Hubble Space Telescope Planetary Camera Images of NGC 1316
(Fornax A)

Edward J. Shaya, Daniel M. Dowling & Douglas G. Currie
Department of Physics, University of Maryland, College Park, Maryland 20742.
E-mail: shaya@img.umd.edu, dowling@img.umd.edu, currie@img.umd.edu

S. M. Faber
UCO/Lick Observatories, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064.
E-mail: faber@lick.ucsc.edu

Edward A. Ajhar & Tod R. Lauer
Kitt Peak National Observatory, National Optical Astronomy Observatories, P.O. Box 26732, Tucson, Arizona 85726.
E-mail: ajhar@mars.tuc.noao.edu, lauer@noao.edu

Edward J. Groth
Physics Department, Princeton University, Princeton, New Jersey 08544.
E-mail: groth@pupgg.princeton.edu

Carl J. Grillmair
UCO/Lick Observatories, University of California, Santa Cruz, California 95064.
E-mail: carl@lick.ucsc.edu

C. Roger Lynds & Earl J. O’Neil, Jr.
Kitt Peak National Observatory, National Optical Astronomy Observatories, P.O. Box 26732, Tucson, Arizona 85726.
E-mail: rlynds@noao.edu, eoneil@noao.edu

ABSTRACT

We present HST Planetary Camera V and I band images of the central region of the peculiar giant elliptical galaxy NGC 1316. These high resolution

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images reveal that the central surface brightness rises sharply to 12.1 mag arcsec$^{-2}$ in the I band and 13.5 mag arcsec$^{-2}$ in the V band. The inner profile is well fit by a nonisothermal core model with a core radius of 0.41 ± 0.02 (34 pc). At an assumed distance of 16.9 Mpc, the deprojected luminosity density reaches $\sim 2.0 \times 10^3 L_\odot$ pc$^{-3}$.

Outside the inner two or three arcseconds, a constant mass-to-light ratio of $\sim 2.2 \pm 0.2$ is found to fit the observed line width measurements. The line width measurements of the center indicate the existence of either a central dark object of mass $2 \times 10^9 M_\odot$, an increase in the stellar mass-to-light ratio by at least a factor of two for the inner few arcseconds, or perhaps increasing radial orbit anisotropy towards the center. The mass-to-light ratio run in the center of NGC 1316 resembles that of many other giant ellipticals, some of which are known from other evidence to harbor central massive dark objects (MDO’s).

The $V - I$ color of unreddened regions is found to be uniform at 1.55 ± 0.10. The profile does not get significantly bluer near the center as might be expected in a merger, except for perhaps the innermost 0.1. Fits to the unextinguished regions at the center raise concerns that the possible UV-bright point source reported by Fabbiano et al. (1995) is partially or fully explained by dust clouds wrapped around the central line of sight. The smoothness of the underlying stellar distribution allows analysis of the 3-dimensional distribution of the dust. We use two observables; the color excess and the ratio of observed V band flux to that of a symmetric smooth fit. The maximum optical depth is only $A_V \sim 1.5$, and only complexes on the near side of the galaxy are detected.

We also examine twenty globular clusters associated with NGC 1316 and report their brightnesses, colors, and limits on tidal radii. The brightest cluster has a luminosity of $9.9 \times 10^6 L_\odot$ ($M_V = -12.7$), and the faintest detectable cluster has a luminosity of $2.4 \times 10^5 L_\odot$ ($M_V = -8.6$). The globular clusters are just barely resolved, but their core radii are too small to be measured. The tidal radii in this region appear to be $\leq 35$ pc. Although this galaxy seems to have undergone a substantial merger in the recent past, young globular clusters are not detected.

Subject headings: galaxies: nuclei — galaxies: photometry — galaxies: structure — clusters: globular
1. Introduction

NGC 1316, in the Fornax Cluster, is a giant Morgan type D elliptical with a NW-SE dust lane. It has a strong double-lobed radio source, Fornax A, and an unresolved radio core (Geldzahler & Fomalont 1978, 1984). Fabbiano et al. (1995) report a possible unresolved bright point source at $\lambda 1750\AA$ at the center. The outer region has shells, loops, ripples and possibly a tidal tail (Schweizer 1980), evidence of a recent merger event. The brightness profile at the center rises quite sharply. These assorted observations make NGC 1316 a likely candidate for hosting an active supermassive black hole. Unfortunately, the inner region is partially obscured by the dust lane, and this complicates the determinations of the brightness profile at the center. We report here on information at additional wavelengths, the V and I bands, that help to sort out some of the extinction difficulties and determine the profile in the inner few arcseconds.

Schweizer (1981) found a central velocity dispersion of 248 km sec$^{-1}$ and a core radius, $r_c$, of $0\arcsec 6 \pm 0\arcsec 2$ after correction for the $FWHM = 0\arcsec 90$ seeing. He derived a mass-to-light ratio in the V band of 2.5 (correcting to a distance of 16.9 Mpc). This low value would appear to be contrary to the idea that a supermassive object resides at the center. In §3, the core size is found to be $\sim 0\arcsec 41$. Hydrostatic models, presented in §4, indicate a mass-to-light ratio of $2.2 \pm 0.2$ outside of the inner few arcseconds, but at the center, additional dark mass appears to be required.

In §5, estimates are made of the amount of extinction present and a rough determination is attempted of where along the line of sight the extinction resides. We arrive at estimates of extinction at the center and re-evaluate the photometry of the central region.

We examine, in §6, the brightest globular clusters in this galaxy to determine whether the merger resulted in the formation of young clusters similar to those in NGC 1275 (Holtzman et al. 1992), NGC 3597, NGC 6052 (Holtzman et al. 1996), NGC 7252 (Whitmore et al. 1993), and NGC 4038/4039 (Whitmore & Schweizer 1995). No such bright young clusters are detected. Limits are placed on the cluster tidal radii assuming King (1966) models.

Although NGC 1316 lies at the outskirts of the Fornax Cluster, it has been established to be a member of Fornax by both the surface brightness fluctuation method (Tonry 1996, personal communication) and its planetary nebulae brightness distribution (McMillan et al 1993). To obtain the distance to the Fornax Cluster, we average the differences between distance moduli measured for the Virgo Cluster and the Fornax Cluster from: the planetary nebulae brightness distribution, $\mu_{\text{Fornax}} - \mu_{\text{Virgo}} = 0.24 \pm 0.10$ (McMillan et al 1993); the $D_n - \sigma$ relation, $\mu_{\text{Fornax}} - \mu_{\text{Virgo}} = 0.25 \pm 0.31$ (Faber et al. 1989); and
the surface brightness fluctuation method, $\mu_{\text{Fornax}} - \mu_{\text{Virgo}} = 0.08 \pm 0.11$ (Tonry 1991).
The average $\mu_{\text{Fornax}} - \mu_{\text{Virgo}} = 0.176$ can be added to the distance determination of the Cepheids in the Virgo Cluster of 30.96 ($d_{\text{Virgo}} = 15.6$ Mpc) (Freedman et al. 1996) to derive $\mu_{\text{Fornax}} = 31.14 \pm 0.40$ (16.9 Mpc). This distance is in relatively good agreement with peculiar flow model calculations (Tully, Shaya, & Pierce 1992) of 19 Mpc. The redshift of 1635 km s$^{-1}$ is substantially increased by reflection of our own peculiar velocity toward the Virgo Cluster direction. Most of the previous studies of this galaxy assumed distances that are too large because the distances were based on unperturbed Hubble flow and a lower value for $H_0$. At the closer distance, the galaxy fits well to the Faber & Jackson (1976) relation between central velocity dispersion and absolute brightness. However, the central surface brightness is 3 mag arcsec$^{-2}$ brighter than expected for a galaxy of total absolute magnitude of $M_B = -21.80$ (Sandage & Tammann), according to the relations of Kormendy (1987) and Faber et al. (1996).

2. Observations and Reduction

As part of a WF/PC-1 GTO investigation of galaxies with interesting nuclei, optical images were taken with the HST Planetary Camera (PC) on 1991 July 2. The telescope was affected by spherical aberration during this period. The PC is composed of four 800 x 800 pixel CCDs. The pixels subtend 0$''$0437 and the total field of view is 70$''$. The center of NGC 1316 appears in PC6. Data were obtained with the F555W and F785LP filters, corresponding roughly to Johnson V and I. Two 260 second images were taken in each filter. Observations in both filters of a bright star, exposed on the same day as the galaxy observations, were used as the point spread functions (PSF). The F785LP exposure time was 0.26 s and the F555W exposure was 0.11 s. The guiding mode during all exposures was coarse track. The rms jitter from telescope guiding errors, according to the log of guide star motions obtained from the OMS branch of STScI, was $\approx 30$ mas in each N 1316 image. When the PSFs are convolved with gaussians with rms of 30 mas their radial profiles become similar to that of the bright Galactic star in the galaxy image. This is consistent with there being negligible jitter in the short exposure PSF images.

Images were processed according to the procedure outlined by Lauer (1989). Shifts between images could be accurately determined from the position of the nucleus and several bright knots scattered through the images, which we identify as globular clusters. Individual images for a single filter shifted by $< 0.1$ pixel in position, so we simply co-added these. There was a shift between the V and I filters by 9 columns and one row. The galaxy was detected to the edges of all four chips. We present deconvolved images from the PC
(Figure 1) with wide logarithmic stretch. The dust lane is clearly evident in the F555W filter, but barely noticeable in the F785LP image. A few weakly visible features due to dust grains in the optical path of the WFPC-1 camera were patched by interpolation.

When the V and I summed images are divided by one another there is a very faint, thin ellipse discernable with a semimajor axis of 130 pixels. This feature occurs at locations where the count level is 256 ADU. It is almost certainly an artifact of the dropouts of A-to-D codes at the 256-bit transition (Lauer 1989) of the A-to-D converter in the WFPC-1 camera. This feature is easily ignored.

Sixty iterations of the Lucy-Richardson deconvolution procedure (Lucy 1974) were applied to the inner 512 by 512 pixel region to partially correct for the spherical aberration introduced by the HST optics. When more than sixty iterations were applied, the noise was amplified to undesirable levels. Since the signal-to-noise is high ($\approx 130$) in the central region, we also deconvolved using a Weiner filter modified to further reduce noise. The two methods agreed exceedingly well (average rms deviation was $\approx 1\%$ within 50 pixels of the nucleus).

Recalibration of the zero-points in the conversion to Johnson V and I bands was accomplished by referring to ground-based aperture photometry (Poulain 1988). We used Bessel’s (1979) transfer equation $(V - I)_C = 0.778(V - I)_I$ to convert the ground based Cousins I to Johnson I. Comparisons were made to apertures of 22$''$87 for V and 31$''$21 for I. Our calibrations give 23.11 and 21.60 for V and I band zero points; the WF/PC Science Verification Report (WF/PC Team 1992) values for PC6, based on individual stars, are 23.05 and 21.55 respectively.

3. Brightness Profile

The dust lane presents a problem in attempting to measure the brightness profile in the central few arcseconds. Penereiro et al. (1994) measured the Gunn-Thuan $g - r$ color profile of this galaxy and found that it is quite constant from 7$''$ to 25$''$. Interior to 7$''$ there is a rapid rise in $g - r$ of 0.2 mag. With HST resolution we can clearly see that this rise is due entirely to the dust lane. Apart from regions belonging to the dust lane and the central few pixels, the $V - I$ color in the PC chip is uniform at 1.55 $\pm$ 0.10 (Figure 2). Much of the quoted uncertainty in the color can be ascribed to the precision of the flat fields.

We can make an estimate of the amount of dust extinction for the central pixels. The contours of the $V - I$ image (Figure 3) indicate that $V - I < 1.8$ for the central 5 pixels in radius. There are two possible situations by which dust extinction can result in low color
excess; either the extinction is so complete that almost none of the light from the center or behind it is transmitted, or the extinction is very light. There is also the possibility that the bluing trend toward the center is due to blue stars near the nucleus. The key to deciding between these possibilities is to note that the dust is definitely not distributed elliptically like the light. Since the I band light is distributed fairly smoothly in elliptical isophotes near the center and the I band and V band give consistent centroids that are aligned with elliptical contours at larger radii, we conclude that the center has only a small amount of extinction, with upper limit values of \( A_V < 0.4 \) mag and \( A_I < 0.2 \) mag.

To compute brightness profiles, we solved for the intensity and ellipse shape which gave the minimum square deviation from median intensity for each chosen semimajor axis. Two gaussians were fit, one along columns and one along rows, to the inner 7 pixels in radius to determine the centers. The centers of the ellipses were not varied, but the eccentricity and orientation did vary. Dusty regions were excluded from the calculation by ignoring pixels with \( V - I > 1.6 \). Figure 4 and Table 1 present brightness as a function of semimajor axis for the raw and deconvolved images of both bands. The large swing in position angle of the major axis within 0\( \prime \)5 is probably just an artifact of dust obscuration that was not fully removed.

The central pixel of the \( V - I \) map before deconvolution is bluer by about \( \approx 0.1 \) mag, and by \( \approx 0.2 \) mag in the deconvolved image (Fig. 3). The blue region appears to be only about 3 pixels in radius. However, this can be ascribed entirely to the higher resolution at shorter wavelengths. When we convolve the deconvolved F555W image with the F785LP PSF the central pixel does not appear to be bluer than the rest of the image. In other words, the deconvolved V profile is also a deconvolution solution for the I profile within the errors. Thus, the inner 0\( \prime \)04 of this galaxy may be bluer by \( \approx 0.2 \) mag, but we do not have sufficient information at this scale to make that claim.

We now fit the deconvolved I band surface brightness profile. It should be recognized that the deconvolution process does not produce an image of infinite resolution. The central pixel may still be underestimated by \( \approx 0.4 \) mag due to the finite resolution and reddening. We use the functional form

\[
\Sigma(r) = 2^n \Sigma_b \left[ 1 + \left( \frac{r}{r_b} \right)^\gamma \right]^{-\eta},
\]

This form is the \( \gamma = 0 \) case of the function used by Byun et al. (1996) and Lauer et al. 1996) to represent surface brightness profiles for several elliptical galaxies observed with \textit{HST}. In the general form, \( r_b \) is considered to be the breakpoint from an outer slope to an inner slope, \( \gamma \). The \( r_b \) parameter can be considered to be a core size. We determined
least-squares values of the parameters for the deconvolved I band profile. Best fit is found with parameters \( r_b = 0'41 \pm 0.02, \alpha = 1.16 \pm 0.02, \eta = 1.00 \pm 0.02, \) and \( \Sigma_b = 12.88 \pm 0.06 \) I mag arcsec\(^{-2}\), where the errors are determined by holding the other parameters fixed. The fit is shown as the top solid line in Figure 4. We also plot as a solid line on this figure the I band fit increased by a constant 1.55 which fits the V band profile quite well, except, perhaps, for the central pixel or two. Thus the \( \Sigma_b \) value in V is 14.44 mag arcsec\(^{-2}\) which, at 16.9 Mpc is equivalent to 5.37 \( \pm 0.30 \times 10^4 \) \( L_\odot \) pc\(^{-3}\).

### 3.1. Deprojected Density Profile

We use the Abel deprojection scheme (Bracewell 1978) to deduce the three dimensional density profile from the projected major axis profile. When the swings in position angle are small, this procedure implicitly assumes that the figure of the galaxy is an oblate spheroid (solid line in Figure 3). The procedure was repeated using the profile along the minor axis, which is equivalent to assuming that the galaxy is prolate (dashed line). The galaxy has substantial rotation about the minor axis, so it is unlikely to be fully prolate, but by calculating the density run for both prolate and oblate we bracket a wide range of spheroidal shapes and demonstrate that the range of variation in densities is small. The three dimensional luminosity density falls off as \( r^{-2.0} \) for radii \( r > 1'' \), and the central density reaches \( \geq 2000 \) \( L_\odot \) pc\(^{-3}\). This range of densities is now becoming quite common in HST observations of nearby galaxies (Lauer et al. 1996).

The deprojected density profile is also well fit by Equation 1. The values of the parameters of the best fit to the oblate shape are: \( r_b = 0'265 \pm 0.015, \alpha = 1.80 \pm 0.03, \eta = 1.13 \pm 0.03, \) and \( \Sigma_b = 654 \pm 25 \) \( L_\odot \) pc\(^{-3}\). It is noteworthy that based on the projected and deprojected profiles, NGC 1316 has one of the flattest interior density cusps, compared to the sample of Lauer et al. (1996).

### 4. Mass-to-Light Ratios

Schweizer (1981) measured a line of sight central velocity dispersion of \( \sigma_v = 248 \pm 6 \) km sec\(^{-1}\) that refers to a region \( 6''7 \times 1''.1 \). Jenkins & Scheuer (1980) measured \( \sigma_v = 262 \pm 6 \) km sec\(^{-1}\) in a region \( 2''0 \times 2''.5 \). Based on these observations, an assumed core radius of \( R_{hb} = 0''.6 \pm 0''.2 \), a central surface brightness of \( \Sigma_{V,0} = 13.3 \pm 0.3 \) mag arcsec\(^{-2}\), and the standard equation for the mass-to-light ratio in a galactic core,
\begin{align}
M/L &= \frac{9\sigma^2}{2\pi G\Sigma_0 R_{hb}},
\end{align}

where \( R_{hb} \) is the half-maximum brightness radius, Schweizer quoted a V band mass-to-light ratio for the inner core of \( 1.3 \pm 0.2 \) \( (H_0 = 50) \). When converted to our adopted distance this corresponds to a mass-to-light ratio of 2.5. However, Equation 1 is appropriate only for an isothermal core. For example, a brightness profile that follows the de Vaucouleurs’ law will have its mass-to-light ratio underestimated by a factor of 7 (Richstone & Tremaine 1986). There is a more general procedure to determine mass-to-light ratios which we shall now describe.

The light profile is distinctly different from that of an isothermal distribution. However, the velocity dispersion profile is, as we shall see, fairly constant. Either a varying mass-to-light ratio or a strongly anisotropic velocity dispersion is required to explain the shape of the light profile. We take an approach toward constraining the mass-to-light ratio by modeling the run of kinematic pressure with radius assuming an isotropic velocity dispersion.

We can combine the new light profile with previously published velocity profiles to determine the distribution of total mass and mass-to-light ratios in the central 1 kpc. Bosma et al. (1985) measured the run of velocities with radius. They found the velocity dispersion falls linearly from \( 232 \pm 13 \text{ km s}^{-1} \) at the center to about \( 150 \pm 50 \text{ km s}^{-1} \) at \( 100'' \). The rotational velocity rises linearly from \( 0 \pm 5 \text{ km s}^{-1} \) at the center to about \( 150 \pm 50 \text{ km s}^{-1} \) at \( 100'' \). Their slit was aligned along \( pa = 60^\circ \), which is very close to our estimates of the major axis position angle (Table 1).

The expected run of velocity dispersion \( \sigma \) required for hydrostatic equilibrium can be calculated from the light distribution and some assumed profile of the mass-to-light ratio by calculating the pressure at each radius arising from the material outside that radius. NGC 1316 is substantially flattened, so the potential for oblate spheroidal shells of eccentricity \( e \) is used (Binney & Tremaine 1987, P52):

\[ \Phi(a') = -\frac{G\delta M}{ea} \arcsin \left( \frac{ea}{a'} \right). \]

Here the major-axis radius of the shell is \( a \), and the mass of the shell is \( \delta M = 4\pi \rho a^2 (1 - e^2)^{1/2} \delta a \). The acceleration contributed by each shell to a point on the equatorial plane at radius \( a' \) is:
\[ g(a') = -\frac{\partial \Phi}{\partial a'} = -\frac{-G\delta M}{a'^2[1 - \left(\frac{ea}{a'}\right)^2]^{1/2}}. \quad (4) \]

The acceleration at \( a' \) is reduced by rotation in the amount \( V^2_{\text{rot}}(a')/a' \).

For the overpressure exerted on our outermost radius, we simply assume a power law exponent of \( \beta = 2 \) for the density beyond the outer radius. We assume a constant rotational velocity of 150 km \( s^{-1} \) outside the last measured data point. Integrating density times gravitational acceleration from outer radius \( r_m \) to infinity leads to the radial pressure at \( r_m \):

\[ P_r(r_m) = \frac{2\pi G\rho_m^2 r_m^2}{\beta^2 - 1} + \frac{GM(< r_m)\rho_m}{r_m(\beta + 1)} - \rho_m V^2_{\text{rot}}/\beta. \quad (5) \]

Working inward, one shell at a time, the additional weight is calculated and pressure equilibrium establishes the required radial velocity dispersion, \( \sigma_r \), of each shell. The eccentricities of the projected image were used to approximate the true cross-sectional eccentricities. Figure 6 presents \( \sigma_r(r) \) assuming a constant \( V \) band mass-to-light ratio of 2.2. If no rotation is assumed (dashed line), the expected velocity dispersion rises slowly with radius. The inclusion of rotation (solid line) reduces some of the pressure and we find \( \sigma_r \) turns over at several hundred pc.

To compare a model with observations along a slit, it is necessary to integrate \( \sigma_r^2 \) through the line of sight and weight by the density at each position along the path. For the observations near the center, one must also integrate over all lines of sight within the aperture. Figure 7 shows the resultant projected velocity dispersion along a slit assuming the dispersion is isotropic. The fit to the data points of Bosma et al. (1985) beyond 2'' is quite good for a model with a constant mass-to-light ratio of 2.2 (solid line). The central pixel data points of Jenkins & Scheuer (1980) (square), Schweizer (1981) (triangle) and Bosma et al. (1985) (plus) are shown on Figure 8 for equivalent circular apertures. They all lie substantially above the curve established by data at larger radii. The effective apertures in each case were limited by the quoted seeing. The Jenkins & Scheuer dispersion measures run about 10% higher than the Bosma et al. measurements at all radii on this galaxy, and so there may need to be a slight adjustment to one or the other.

One obvious possibility that would raise the model velocities at \( \sim 1'' \) to better match the observations is the addition of a massive central point mass. The dotted lines in Figures 6, 7, and 8 show model velocity runs when point masses of \( 3 \times 10^8, 1 \times 10^9, \) and \( 3 \times 10^9 M_\odot \) are added to the above model with mass-to-light ratio of 2.2. It is seen that a \( 2 \times 10^9 M_\odot \) dark compact object would give a reasonable fit to the central velocity dispersion.
measurements. Of course, there is an obvious prediction of substantially higher velocities at smaller radii, but we are unaware of published data with better spatial resolution.

Another way to explain the excess in observed velocity dispersion at the center is to allow stellar mass-to-light to vary. An easy way to proceed becomes apparent when one realizes that the total velocities, from 1'' to 100'', are not significantly different from a constant value of 240 km s^{-1} if one takes into account that much of the dropoff in velocity dispersion is compensated by rotation. Thus, we may use the well known isothermal density distributions to arrive at a good approximation. At large radii, the luminosity density falls as 1/r^2, as does an isothermal distribution. But in isothermal distributions, the profile steepens below an inverse square law, just outside the core radius. Since the density distribution of NGC 1316 does not follow this, significant mass-to-light variation is required to obtain constant $\sigma$. If one simply divides the luminosity density into the family of King isothermal profiles that result in $\sigma_v = 240$, one gets the family of mass-to-light runs shown in Figure 9, where the choices of core radii were 0''.2, 0''.4, 0''.8, and 1''.6, corresponding to 16.8, 33.6, 67.2, and 134 pc.

Certain cases can be excluded as being unreasonable. The largest of these core radii can be excluded because it has mass-to-light rising, at first, as one moves inward and then dropping below unity near the center. Given the lack of color gradients, this behavior does not seem reasonable. The next largest core radius is also unattractive because it has a mass-to-light bump at a random radius in the galaxy; one would be hard pressed to explain such behavior. The other two cases are both fairly acceptable. They contain higher mass-to-light with decreasing radius, except at radii smaller than the resolution limit. The conclusion is that the stellar mass-to-light ratio is 2.2 ± 0.2 at large radii and rises rapidly within a 2'' to values of at least 5. A massive dark compact object would not then be required.

NGC 1316 is typical of many spheroidal galaxies in showing a modest rise of 10 – 20% in central velocity dispersion at groundbased resolution. It was this behavior in M87 that inspired the suggestion that it contained a central dark object of mass $3 \times 10^9 M_\odot$ (Sargent et al. 1978). This argument subsequently was disputed when it was realized that velocity anisotropies could also match the data (Binney & Mamon 1982). This same explanation can clearly be invoked for NGC 1316 as well. However, subsequent observations of promising dark mass candidates at high resolution (including M87) have invariably revealed further increases in central velocity dispersion (and rotation) that are fully consistent with actual central dark masses. The accumulating number of such cases (see Kormendy & Richstone 1995 for a review) plus the known non-thermal nuclear activity in NGC 1316 suggest that it, too, contains a dark mass. High resolution velocity dispersion measurements with HST,
planned for late 1996 or early 1997 with the Faint Object Spectrometer, should test this possibility.

Finally, a few words on the global mass-to-light ratio, $M/L_V = 2.2 \pm 0.2$ or $M/L_R = 1.0$, assuming $V - R = 0.7$. This is remarkably low compared to normal ellipticals of comparable luminosity, which have an average $M/L_R \sim 4.0$ (van der Marel 1991, adjusted to $H_0 = 80$). This low value might be associated with star formation triggered by the recent merger. More insight might come from comparing global parameters such as radius, surface brightness, dispersion, and colors versus those of normal ellipticals of comparable mass.

4.1. Core Collapse

One might be persuaded that a black hole could have formed via gravothermal collapse in the center if the collapse time of the core were shorter than a Hubble time. Assuming an isotropic velocity dispersion and stars of about one solar mass, the relaxation time is (Binney & Tremaine 1987, P. 514),

$$t_r = 3.7 \times 10^{12} yr \left(\frac{\sigma}{250 \text{ km s}^{-1}}\right)^3 \left(\frac{4 \times 10^2 M_{\odot} \text{ pc}^{-3}}{\rho}\right) \ln \left(0.4 \frac{N}{5.2 \times 10^8}\right)^{-1}. \quad (6)$$

Fokker-Planck based simulations have shown that single-mass systems collapse after $\approx 15$ relaxation times of the core (Cohn 1980) and multi-mass models can collapse in as short as 2 relaxation times (Inagaki & Saslaw 1985). Thus the core collapse time is $10^{13}$ yr. If a supermassive black hole developed in NGC 1316, it must have formed by gaseous dissipation.

5. Color Analysis and Dust

5.1. The Smoothed Fit, $V_{fit}$

We also attempted to fit the deconvolved V band image, ignoring regions of dust obscuration. The purpose is to measure the amount of light removed along the lines of sight by the dust clouds, independent of the reddening determination. In the inner regions of this galaxy, a large fraction of each isophote includes dust clouds, rendering the eccentricity and position angles of ellipse fitting uncertain. We therefore refit with a more elaborate procedure that permits control of the degree of fit and requires a minimum amount of interpolation. The brightness profile was remapped to make the isophotes circular, and the resulting image was fit along circles by sine series. Each sine term had an independent
amplitude and reference angle. Pixels with $V - I > 1.6$ were masked out. The degree of the fit was varied according to the fraction of pixels unmasked at each radius. For the inner 25 pixels, the fit was only to a constant surface brightness. From 26 pixels to 40 pixels, a constant and the first sine term were used. Beyond 40 pixels, the fit contained a constant and two sine terms. Upon completion of this fitting, it was apparent that there were dust regions of low color excess. Therefore, the mask was augmented by pixels that were below the fit by 50 ADU or more, and the process was repeated. This process smoothly filled in regions with evident dust absorption. The difference between the observed V band image, $V_{\text{obs}}$, and the fit, $V_{\text{fit}}$, is shown in Figure 10.

There is a region of negative values in the difference in the inner 25 pixels but these are all less than 10% of the flux. A cut down the major axis of this fit gives a very similar profile as the ellipse fitting of §3 (Figure 11). This gives us additional confidence that our fitting of the brightness profiles correctly gives the unextinguished profiles to within about 0.2 mag in the I band in the inner arcseconds. This central region has an incomplete loop of absorption going around the central 5 – 10 pixels. In the I-band image, the absorption band is just barely discernible. However, at $\lambda 1750{\text{Å}}$ the absorption is an order of magnitude greater, and one should be wary, as Fabbiano et al. (1995) are, that the UV bright point source reported by them may be merely an artifact of the details in the dust distribution.

Figure 12 presents an overlay of a radio map at 1.5 GHz produced by Geldzahler & Fomalont (1984) on the $V - I$ grayscale image. We note that the SE jet terminates at one of the thick clouds. This indicates that the SE jet is pointing toward us since we find that the detected dust clouds are in front of the midplane. Presumably the gas or dust has sufficient density to stop the charged particles responsible for the radio emission. The NW jet extends farther, apparently missing any region of high gas and dust density. If this geometry is correct, it suggests that the jet is not highly relativistic, as the side away from us is visible.

5.2. Color Excess - $\frac{V_{\text{obs}}}{V_{\text{fit}}}$ Relation

The smoothness of the underlying elliptical galaxy allows measurements of the dust distribution to be made that are rarely possible. We compare the color excess, $E(V - I)$, to the ratio of observed to flux to the fit flux of the previous section, $\frac{V_{\text{obs}}}{V_{\text{fit}}}$. A simple starting model assumes that each line of sight passes through a single discrete cloud within the galaxy that dominates the extinction. We define $V_{\text{front}}$ to be the flux emanating from stars in the galaxy between the observer and the single cloud along the line of sight. We define $V_{\text{back}}$ to be the flux emanating from stars directly behind the cloud as seen by the observer,
and similarly for $I_{\text{front}}$ and $I_{\text{back}}$. We assume constant intrinsic color along the line of sight. The ratio of the two fluxes is designated $s$:

$$s \equiv \frac{V_{\text{front}}}{V_{\text{back}}} = \frac{I_{\text{front}}}{I_{\text{back}}}.$$ 

(7)

The expressions for color excess and $\frac{V_{\text{obs}}}{V_{\text{fit}}}$ are then,

$$E(V - I) = -2.5 \log \left[ \frac{s + 10^{-0.4A_V}}{s + 10^{-0.4A_I}} \right].$$ 

(8)

and

$$\frac{V_{\text{obs}}}{V_{\text{fit}}} = \frac{s + 10^{-0.4A_V}}{1 + s}.$$ 

(9)

For Figure 13, we also define the ‘depth of cloud’,

$$s_2 = \frac{V_{\text{front}}}{V_{\text{total}}} = \frac{s}{s + 1}.$$ 

(10)

Planck functions and stellar spectra have been multiplied by standard reddening curves and then multiplied by HST/WFPC-1 throughput curves to derive the relation $A_V = 2.0A_I$ (Shaya et al. 1994). Curves of constant $s_2$ (dashed lines) and constant $A_V$ (solid lines) are plotted in the $E(V - I)$ versus $\frac{V_{\text{obs}}}{V_{\text{fit}}}$ plane in Figure 13 along with the data for all pixels within 7″ but outside of 1″ from the center.

Most of the data points lie in a region in Figure 13 that should be impossible for dust with $A_V = 2.0A_I$. At first, we suspected that this galaxy may have unusual dust optical properties, and found that $A_V = 1.6A_I$ would fit quite well. However, if the extinction has substantial variations on smaller scales than the resolution, there could be a small shift of the data points on this type of plot. Light scattered into the line of sight by resolution blurring has a greater effect on the $V_{\text{obs}}/V_{\text{fit}}$ than on the color. We suspected that a shift of this nature could be caused by incomplete deconvolution. We ran simulation tests in which we started with a constant intensity image and then decreased the intensity in disks to simulate variously sized disks of dust with a variety of optical depths. The image was convolved using the HST PSF, noise was added, and then the image was deconvolved using 60 Lucy-Richardson iterations. We found the distribution of points tended to move in the correct direction. A few examples of the test results are shown in Figure 14. The dust model that most resembled the observations had $A_V = 1.0$, radius of cloud = 10 pixels, and $s_2 = 0.0$ (completely in front).

None of the points in Figure 13 lie in the region of very high extinction. High extinction would appear as a large drop in surface brightness but with little reddening because most
of the observed light arises in front of the absorbing region. If there were much dust at the midplane with large values of extinction, then one would expect to find many pixels along the dust lane with about 50% of the light missing \((A_V = 0.7)\) and \(E(V - I) < 0.2\), but no redder. However, values near this range occur for only two pixels. The vast majority of pixels show large color excess and relatively little absorption. This is the signature of low extinction and low depth along the line of sight.

In addition, near the centers of each of the prominent complexes there are regions with nearly 80% of the total light removed and very large reddening \((E(B - V) \sim 0.6)\). This suggests that all of the prominent complexes are in front of at least 80% of the projected starlight (30% of the light in front of the midplane). And, the extinction of the clouds all have \(A_V < 1.5\). That the extinctions are typically so small is actually quite obvious from the I band image alone because the dust, in that image (Figure 1b) is fairly difficult to perceive. The dust is probably distributed in a patchy ring. We do not detect the dust on the far side because the fraction of light removed from the line of sight is too small. It is even possible for the clouds to be randomly distributed within a plane. With a steep stellar density distribution, a cloud does not need to be far in physical distance from the midplane to be outside of 70 percent of the light.

6. Globular Clusters

We identify 20 bright knots apparent in both bands around NGC 1316 as globular clusters. One much brighter object has been shown to be a Galactic foreground star (Schweizer 1980). Cluster locations are given in Figure 15. In Table 2 we also report the coordinate locations, apparent brightnesses, and \(V-I\) colors. Brightnesses were determined by aperture photometry with a 3 pixel radius and an aperture correction, based on a star in the field, measured in the same manner. Since the clusters are extended the total brightnesses will be somewhat greater. Only the extreme bright end of the globular cluster luminosity distribution is detected.

For the purpose of determining if the clusters are resolved, we measured the fraction of encircled energy at the 3 pixel radii relative to the 6 pixel radii for each cluster and compared these to the same quantity for the Galactic foreground star. This can be written:

\[
\Delta \equiv 2.5 \log \left( \frac{F(6)F^*(3)}{F(3)F^*(6)} \right)
\]  

(11)

Figure 16 presents the \(\Delta\) values for all the globular clusters in Table 2 plotted against
absolute magnitude. In nearly all cases the value of $\Delta$ is positive, indicating larger measurable extent than the star, but the error bars, taken from the DAOPHOT photometry package, are large. A weighted average value for $\Delta$ is 0.075 mag (0.06 for V band and 0.09 for the I band).

To determine if this is consistent with typical globular cluster light distributions at the distance of NGC 1316, we created simulated images of self-consistent King models (1966) with a range of core radii and tidal radii $r_t = 25$ pc, 50 pc, and 75 pc. The values of $\Delta$ for these models are shown in Figure 17. The solid horizontal line is placed at the measured mean value for $\Delta$ of 0.075. It appears that we do not measure core radii for any of the clusters, but we can put limits on the tidal radii. A finite tidal radius is required by the measured value of $\Delta$ because an infinite tidal radius gives a larger value at all core radius values. It appears that the tidal radii in the region examined are typically < 35 pc. For comparison, the tidal radii of the four M31 globular clusters studied by Grillmair et al. (1996) range from 35 – 60 pc. For Galactic globular clusters, 35 pc is in the middle of the range of tidal radii (Trager et al. 1993; Djorgovski 1993).

The mean $V - I$ color of the globular clusters is about 0.3 mag bluer than the galaxy itself within the WFPC field, but that is still 0.2 mag redder than the mean of Galactic globular clusters and 0.1 to 0.3 mag redder than the ten globular cluster systems in Virgo measured by Ajhar et al. (1994). The brightest globular cluster, with $M_V = -12.7$, is the most luminous red globular cluster to be resolved that the authors are aware of, although, in other galaxies, there are brighter candidate clusters that have not been confirmed to be non-stellar.

Couture, Harris & Allwright (1991) present BVI CCD photometry of 230 globular clusters in NGC 4472. Located in the Virgo cluster, NGC 4472 is a giant elliptical galaxy at a similar distance. In Figure 18 we compare the two globular cluster systems. The distribution of globular cluster colors are similar. The distribution of brightest magnitudes in NGC 1316 is also not remarkable, provided that the total population is comparable in numbers to that in NGC 4472. Apparently, although NGC 1316 shows all the signs of a recent merger with gas rich companion(s), the young, bright, blue globular clusters seen in other merger events, such as NGC 1275 (Holtzman et al. 1992) are not seen in NGC 1316. Either they did not form, or perhaps, they did form but have since evaporated.
7. Conclusions

Although there is extinction near the line-of-sight to the center of NGC 1316, it is sufficiently weak at I band ($A_I < 0.2$ mag) to permit accurate profile determination. The central surface brightness is unusually bright, for a galaxy of this magnitude, and has a very small projected core radius of $0.41'' = 34$ pc. The shape of the luminosity profile is distinctly nonisothermal. The deprojected density reaches $2000 \, L_{\odot} \, pc^{-3}$ in the central $0.05''$. The predicted velocity dispersion calculated from the deprojected density profile and assuming constant mass-to-light ratio rises with radius. However, the observed velocity dispersion is roughly constant (allowing for the increasing rotation with radius). To reconcile the observed dispersion with the brightness distribution requires either a single dark object of mass $\approx 2 \times 10^9 M_{\odot}$ at the center, a strongly varying stellar mass-to-light ratio in the inner 100 pc, or a radially varying velocity anisotropy. There has been insufficient time for the steep inner slope or a black hole to have evolved through stellar dynamical interactions from a larger initial central core distribution. The V band mass-to-light ratio determined outside of 100 pc is $2.2 \pm 0.2$.

Away from the dust lane, NGC 1316 has a fairly uniform $V - I$ color. The uniform, very red color precludes a significant young cluster from explaining the brightness and cuspiness of the inner region. The maximum extinction regions have $A_V$ of only $\sim 1.5$. Most of the deep dust regions detected are found to be in front of at least 80% of the light along the line of sight. This is not very surprising because within $10''$ of the center, the position in front of 80% of the light occurs within 100 pc of the midplane. It is difficult, in these images, to discern dust past the midplane from its absorption properties.

Most of the globular clusters associated with NGC 1316 are barely resolved. Overall, they appear to be normal in luminosity and color, if the distance to NGC 1316 is $\approx 17$ Mpc and the total population is reasonably large. The one exception is the brightest globular which has $M_V = -12.7$. This is more than a magnitude brighter than the previous brightest resolved globular cluster known. The tidal radii of the globular clusters seen in the inner 60'' appear to be less than or equal to 35 pc. There are no bright young globular cluster despite the clear evidence of a recent significant merger. Either globular clusters were not formed during the merger or they have since evaporated in the strong tidal field at the center.

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Fig. 1.— Deconvolved Images of N 1316. The whole PC2 chip of WFPC-1 are shown after pairs of exposures in each filter have been cleaned of cosmic rays and coadded. Insert at the lower right are $3 \times$ blowups of the central 64 x 64 pixels. The logarithm of the images is displayed and the stretch ranges from: a) 40 to 3162 ADU in the F555W image (251 to 10000 ADU for the insert) and b) from 50 to 3162 ADU in the F785LP image (398 to 10000 ADU for the insert). A few of the globular clusters can be seen in this reproduction.

Fig. 2.— Color Map of NGC 1316. $V - I$ image after 60 iterations of the Lucy-Richardson deconvolution procedure were applied to the V and I images. All 4 PC chips are shown. Orientation is the same as Figure 1. The dust lane is clearly visible with many interesting filaments and swirls.

Fig. 3.— Inner region color map. Grayscale image of $V - I$ for just the central 128 by 128 pixels. Pixels have been rebinned 2 by 2. Contours of $V - I$ are superimposed. The bluest point near the middle is the central pixel. Orientation is the same as Figure 1.

Fig. 4.— Brightness profiles as a function of semimajor axis. Plus signs refer to both the pre-deconvolved and to 60 iterations of Lucy-Richardson deconvolved I band images and diamonds refer to the same for the V band image. Pixels with $V - I > 1.6$ were not included in the ellipse fitting procedure. The line on the deconvolved I band data is the fit using Equation 1. The line on the deconvolved V band data is the I band fit plus 1.55.

Fig. 5.— Deprojected luminosity density profile. Abel inversion of the fit to the deconvolved I band profile, converted to solar luminosities pc$^{-3}$. Solid line is the result of assuming that the galaxy is an oblate spheroid (i.e., inversion of major axis), and dashed line is the result of assuming galaxy is a prolate spheroid (i.e., inversion of minor axis).
Fig. 6.— Radial velocity dispersion at each deprojected radius. Hydrostatic equilibrium was assumed, and a mass-to-light of 2.2 was applied to the luminosity density profile (previous figure). The observed rotation curve of Bosma et al. (1985) and the ellipticity measures of the profile fitting were used to determine the weight of each oblate shell. Solid line refers to simple single mass-to-light ratio. Dashed line is obtained if no rotation is assumed. Dotted lines result from adding a compact dark object of either $3 \times 10^8$, $1 \times 10^9$, or $3 \times 10^9 M_\odot$.

Fig. 7.— Velocity dispersion along a slit. The radial velocity dispersions (squared) from Figure 6 were integrated along the line of sight and weighted by the local densities assuming $\sigma$ is isotropic. Line styles are the same as the previous figure. The velocity measurements of Bosma et al. (1985) along $pa = 60^\circ$ are plotted with their error bars.

Fig. 8.— Velocity dispersion within a circular aperture. The profiles of velocity dispersions squared were integrated along the line of sight and weighted by the local densities and then averaged over a circular aperture of radius $R_{\text{circ}}$. Line styles are the same as Figure 6. The central velocity measurements of Bosma et al. (1985) (plus sign), Schweizer (1981) (triangle) and Jenkins & Scheuer (1980) (square) are plotted with their error bars.

Fig. 9.— Mass-to-light ratio variation. Velocity measurements indicate a nearly isothermal velocity profile. This does not agree with the brightness profile. The curves here give several possible runs of mass-to-light with radius that would result in isothermal distributions. The numbers next to each curve give the core radii in parsecs of the corresponding isothermal sphere.

Fig. 10.— Extinction Map. A fit to the pixels with little or no reddening is subtracted from the inner 256 by 256 pixel subimage of the deconvolved V band image. The resulting image vividly portrays the dust distribution by the amount of light removed from the line of sight. The figure gives reassurance that away from dusty regions the model fit is reasonably good. Orientation is the same as Figure 1.
Fig. 11.— A cut along the major axis of the V band fit of § 5.1 (pluses) compared to I band ellipse fitting model of § 3 (asterisks), offset by 1.55 mag.

Fig. 12.— Radio map contours at 1.5 GHz (Geldzahler & Fomalont 1984) are overlayed on the $V - I$ color map shown as a grayscale (darker is redder). Most of the PC2 chip plus parts of PC1 and PC3 are shown. Note the abrupt termination of the radio jet at the absorption features to the South. North is up.

Fig. 13.— Scatter plot of $E(V-I)$ versus $V_{fit}$ for all pixels in annulus from 1" to 7". Curves of constant depth of the position of the cloud, $s_2$, but varying extinction $A_V$ are indicated by dashed lines. Curves of constant $A_V$ but varying depth of the cloud is indicated by solid lines. $A_V = 2.0$ $A_I$ has been assumed.

Fig. 14.— Scatter plots of models of dust regions after being convolved with the PSF, noise added to data and PSF, and 60 iterations of Lucy-Richardson deconvolution. a) $A_V = 1$, radius of dust cloud = 10 pixels, depth $s_2 = 0$, b) $A_V = 1$, radius of dust cloud = 10 pixels, depth $s_2 = 0.25$, c) $A_V = 1$, radius of dust cloud = 20 pixels, depth $s_2 = 0$, d) $A_V = 2$, radius of dust cloud = 10 pixels, depth $s_2 = 0$.

Fig. 15.— Cluster Locations relative to the center of NGC 1316. We have included contours from V band for reference. Cluster locations are indicated by '*'-sign. Orientation is the same as Figure 1.

Fig. 16.— Globular cluster deviation of aperture photometry from expectations for a point source. Fraction of light within an aperture of 3 pixel radius relative to 6 pixel radius for globular clusters divided by same quantity for a star in the image, $\Delta$ in the text. The amplitude is displayed in astronomical magnitudes. Top figure is for V band and bottom figure is for I band. The brightest cluster in the I band is excluded because it fell on the CCD chip boundary, of course. Horizontal lines are drawn at the weighted average for each filter.

Fig. 17.— Degree of resolution for simulated King (1966) isothermal models, scaled to the NGC 1316 distance, as a function of the core radius of the model. The tidal radii used were 25 pc (dashed), 50 pc (dotted), and 75 pc (solid). Solid horizontal line is placed at measured mean value for the globular clusters.

Fig. 18.— Comparison between clusters of NGC 1316 and NGC 4472. The histogram of number of globular clusters at each 0.2 mag bin in $V - I$ of a) NGC 1316 and b) NGC 4472. Scatter plot of $V - I$ vs. $V$ for clusters in c) NGC 1316 and d) NGC 4472.