The Astrophysical Journal, 471:L79–L82, 1996 November 10

HUBBLE SPACE TELESCOPE OBSERVATIONS OF THE DOUBLE NUCLEUS OF NGC 4486B[1]

Tod R. Lauer
Kitt Peak National Observatory, National Optical Astronomy Observatories,[2] P.O. Box 26732, Tucson, AZ 85726
Scott Tremaine
CIAR Cosmology Program, Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto, M5S 3H8, Canada
Edward A. Ajhar
Kitt Peak National Observatory, National Optical Astronomy Observatories, P.O. Box 26732, Tucson, AZ 85726
Ralf Bender
Universitäts-Sternwarte, Scheinerstraße 1, München 81679, Germany
Alan Dressler
The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101
S. M. Faber
UCO/Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064
Karl Gebhardt
Department of Astronomy, University of Michigan, Ann Arbor, MI 48109
Carl J. Grillmair
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109-8099
John Kormendy
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822
and
Douglas Richstone
Department of Astronomy, University of Michigan, Ann Arbor, MI 48109
Received 1996 August 1; accepted 1996 August 28

ABSTRACT

Hubble Space Telescope WFPC2 images show that the low-luminosity elliptical galaxy companion to M87, NGC 4486B, has a double nucleus that resembles the one discovered in M31. The NGC 4486B nucleus comprises two peaks separated by $\sim$0$''$.15 or 12 pc. Neither peak is coincident with the galaxy photocenter, which falls between them. The nuclear morphology is independent of color; thus, the double structure is not likely to arise from dust absorption. It is also unlikely that the peaks are a binary stellar system (such as an ongoing merger of the nucleus of a less luminous system with the nucleus of NGC 4486B), since the decay timescale is short ($<10^8$ yr) and the present environment of NGC 4486B should inhibit mergers. We suggest that the nuclear morphology of NGC 4486B may be explained by the eccentric-disk model of Tremaine, which was originally advanced to account for the central structure of M31. This model requires that NGC 4486B contains a central massive dark object, which is suggested by the spectroscopic observations of Kormendy et al. The eccentric disk might be related to the symmetric disk seen at larger radii.
Subject headings: galaxies: nuclei — galaxies: photometry — galaxies: structure

1. INTRODUCTION

The nucleus of M31 is double (Lauer et al. 1993). *Hubble Space Telescope* (*HST*) images reveal that the brighter of the two nuclear components (P1) is separated by only 0$''$.49 (1.8 pc) from the photocenter of the surrounding M31 bulge, which itself coincides with the less luminous peak (P2) to within $\sim$0$''$.05. A key step in understanding the M31 nucleus is to determine how common such structures are. Prior to this work, M31's double nucleus was unique—but then, M31 is among the very few galaxies that we can presently study at subparsec resolution: even *HST* could resolve the P1/P2 components only out to $\sim$5 Mpc. However, *HST* would detect the asymmetry of the M31 nucleus at much larger distances. With this in mind, Lauer et al. (1995) identified a small number of galaxies in their WFPC1 imaging survey whose centers were displaced from their envelopes. One of these was NGC 4486B.

Figure 16 of Lauer et al. (1993) showed the *HST* image of NGC 4486B divided by a model reconstructed from its surface photometry under the assumption of concentric isophotes. This quotient showed a strong dipole pattern; isophotes at large radii were displaced as much as $\sim$12 pc from the central intensity maximum. WFPC2 observations have roughly double the resolution of the WFPC1 images and greatly improved dynamic range; they now show that NGC 4486B has a double nucleus similar to that seen in M31.

In M31, it is tempting to suggest that P1 is the dense remnant of a stellar system cannibalized by M31—but there is no sign that M31 has recently undergone a merger, and the

[1] Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555.

[2] Operated by AURA, Inc., under cooperative agreement with the National Science Foundation.

decay time for P1's orbit is extremely short. It is also unlikely that P1 is a foreground object: the nuclear morphology of M31 is inconsistent with the superimposition of two noninteracting systems, nor does P1 resemble the core of any familiar stellar system. Explaining the double structure by dust absorption is also difficult (Lauer et al. 1993).

Tremaine (1995) has suggested that the M31 nucleus contains a disk composed of stars traveling on aligned, eccentric, Keplerian orbits around the $10^{7.5}$ $M_\odot$ black hole inferred to exist at its center (Dressler 1984; Dressler & Richstone 1988; Kormendy 1988; Richstone, Bower, & Dressler 1990). In this model, P1 is the part of the disk farthest from the black hole, which is bright because the disk stars linger near apapsis. The eccentric-disk model may also explain the nucleus of NGC 4486B.

2. OBSERVATIONS

The NGC 4486B data set consists of three 600 s F555W (V-band) and four 500 s F814W (I-band) WFPC2 images obtained on 1995 November 25. The galaxy was centered in the high-resolution (0.″0455 pixel^{-1}) PC1 camera, with total signal in the central pixel of $\sim 4 \times 10^4 e^-$ in V and $\sim 7 \times 10^4 e^-$ in I. The summed images were deconvolved with 40 Lucy-Richardson iterations. The central 2″ of the deconvolved V and I images are presented in Figure 1 (Plate L9). Both clearly show that the center of NGC 4486B contains two maxima separated by ~3 pixels, or 0.″14. Qualitatively, the center of NGC 4486B strongly resembles the nucleus of M31, with the brighter peak (by analogy designated P1, with the dimmer peak designated P2) offset from the photocenter of the main body of the galaxy. The central surface brightness of P1 is $\mu_I = 12.89$ mag arcsec^{-2}, and that of P2 is $\mu_I = 13.00$; the minimum (PM) between P1 and P2 occurs at $\mu_I = 13.06$.

The V and I images appear to be nearly identical. The color-ratio image (Fig. 1) shows little evidence for dust; further, no dust features are seen at larger radii. A 3 × 3 pixel region centered on P1 has $V - I = 1.29 \pm 0.01$; the same sized region around P2 has $V - I = 1.31 \pm 0.01$, and a 3 × 1 pixel cut at PM, perpendicular to the P1-P2 vector, has $V - I = 1.30 \pm 0.02$. These colors suggest that the double nucleus is not due to a dust lane: in this case, the P1-PM surface brightness difference would imply $A_I \geq 0.18$, or $\Delta(V - I) \geq 0.21$, well in excess of the observed $\Delta(V - I) = 0.01 \pm 0.02$. The brightness profiles (Fig. 2) further show that NGC 4486B has at most a shallow color gradient. We find $V - I = 1.280 - 0.016 \log(r \text{ arcsec}^{-1})$, a gradient that is somewhat shallower than typical for the centers of ellipticals (Lauer et al. 1996).

The major-axis surface brightness profile in Figure 2 can be fitted to the empirical formula (Byun et al. 1996)

$$I(r) = I_b 2^{(\beta-\gamma)/\alpha} \left(\frac{r}{r_b}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_b}\right)^{\alpha}\right]^{-(\beta-\gamma)/\alpha}. \quad (1)$$

This formula fits the surface brightness over only a limited radius range (mainly because the profile curves sharply at *two* distinct radii, near 0.″15 and 4″). Since we are interested in the central behavior, we choose to fit only over $0.''04 < r < 2.''0$, which yields (for the V profile) $I_b = 14.58$ mag arcsec^{-2}, $r_b = 0.''18$, $\alpha = 3.30$, $\beta = 1.36$, and $\gamma = 0.0$. Note that NGC 4486B does not have a distinct nuclear component in its brightness profile, in contrast to M31. The ellipticity of NGC 4486B increases strongly toward the center, as can be seen in

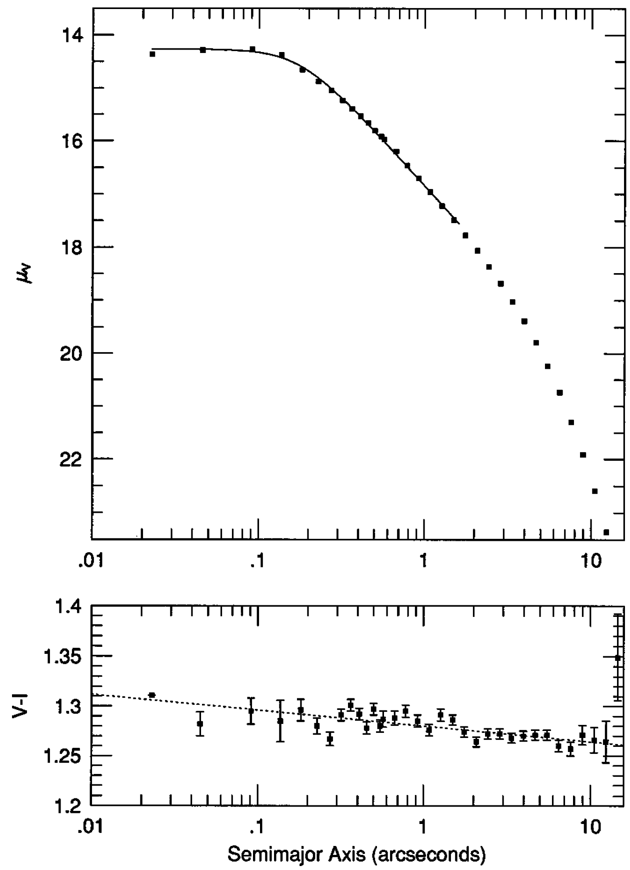

FIG. 2.—Deconvolved V surface brightness and $V - I$ color profiles of NGC 4486B. The solid line in the upper panel shows the empirical formula (1) fitted to the profile for $0.''04 < r < 2''$. The dashed line in the lower panel shows the mean color gradient.

the contour plot (Fig. 3) and isophote ellipticity profile (Fig. 4). The A_4 values are also significantly positive for $1'' < r < 10''$ (the corresponding B_4 are all zero), which suggests that there is a central disk component (Fig. 4).

The precise locations of P1 and P2 are difficult to measure because their separation is close to the limiting resolution and the minimum between them is shallow. The P1-P2 separation measured from intensity centroiding is 0.″13; however, this result may be biased by the steep brightness gradient in the underlying galaxy. We thus attempted to isolate the peaks by filtering the image through a high-pass Gaussian filter with FWHM = 2 pixels. The P1-P2 separation in the filtered image is 0.″16. This latter measurement assumes that the peaks are compact sources, a hypothesis that is probably oversimplified but that does allow us to set lower limits on the light associated with the peaks. The integrated I magnitude of the filtered P1 peak is <20.2 and for P2, <20.7; the total luminosity for the two peaks is $L > 10^6$ $L_\odot$ (for a 16 Mpc Virgo distance). At Virgo, 0.″13–0.″16 corresponds to 10–13 pc. Thus, the P1-P2 separation in physical terms is 5–7 times larger than the 1.8 pc P1-P2 separation in M31.

Another contrast of NGC 4486B with M31 is that the photocenter (PC) of NGC 4486B falls between P1 and P2, rather than at P2 as in M31. The NGC 4486B PC was measured by correlating the inner portions of the V and I images with themselves after rotation by 180° (Djorgovski

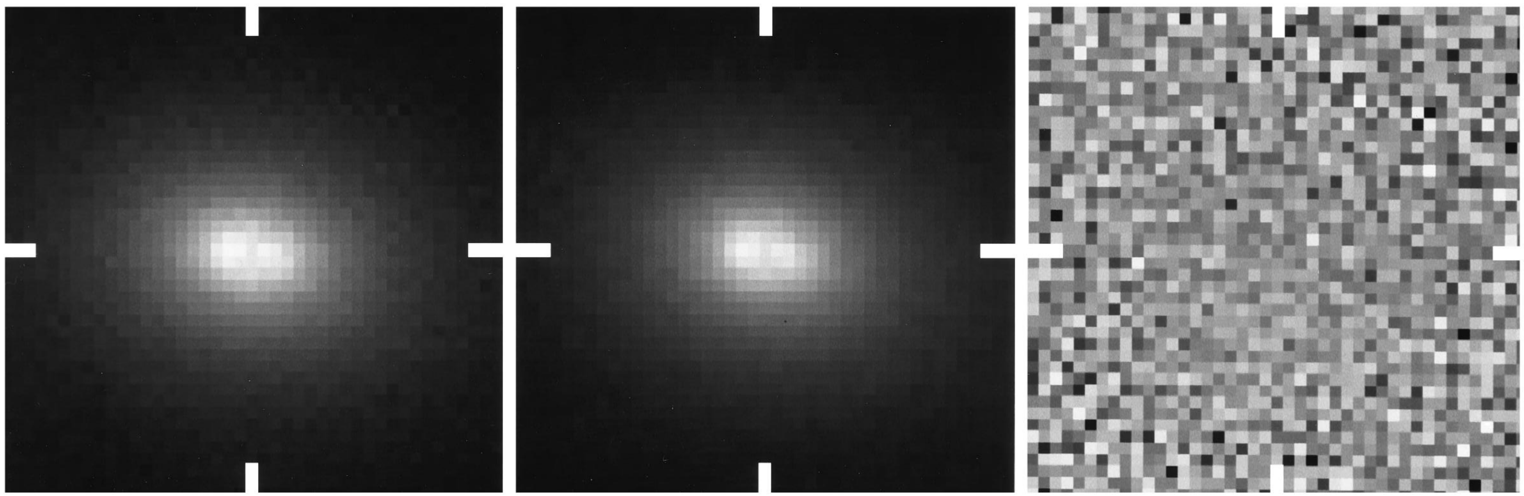

FIG. 1.—NGC 4486B *V*, *I*, and color ratio images. The left two panels show the inner 2″ of the deconvolved *V* (*left*) and *I* (*middle*) images of NGC 4486B. P1 is to the left and P2 is to the right in each image. Tick marks indicate the photocenter (PC) of the galaxy. North is 13°.4 left of vertical. The gray scale is linear but is otherwise arbitrary. The rightmost panel is the color ratio of the *V* and *I* images for the same area. The scale is in magnitudes, covering the range ±0.2 mag about the mean color of NGC 4486B, with white corresponding to bluer colors. Noise increases rapidly toward the edges of the figure owing to the strong decrease in surface brightness from the center.

LAUER et al. (see 471, L80)

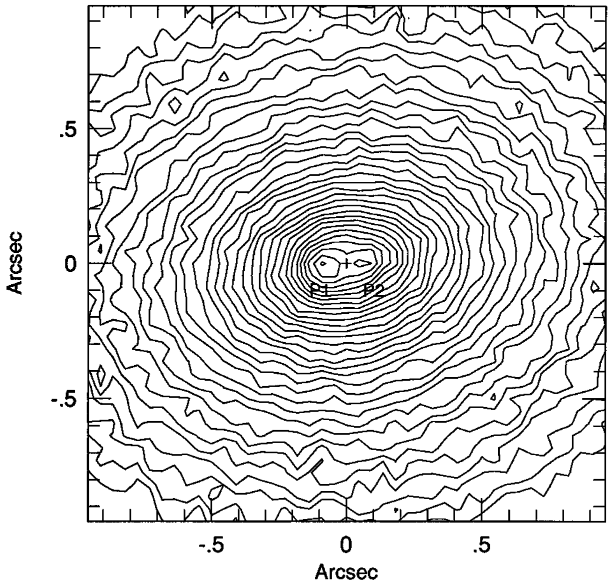

FIG. 3.—Contour map of the deconvolved F814W image of NGC 4486B. The cross marks the photocenter of the galaxy. North is 13°.4 left of vertical. Contours are spaced 0.10 mag apart, with the highest contour in P1 corresponding to $\mu_I = 12.90$ mag s^{-2}.

1988) and is indicated in Figure 3. The PC is accurate to ~0".005. Subtracting the image rotated by 180° about the PC from itself produces a near-zero average residual with no obvious trends beyond $r \sim 0''.5$ from the PC (Fig. 5). Small shifts of 0.1 pixel away from the nominal PC produce a clear dipole pattern outside the nucleus. This test also shows that the P1-P2 asymmetry is limited to the central ~0".5 of the nucleus. The P1-PC separation is 0".084–0".100, and the P2-PC separation is 0".050–0".066, depending on whether the peak centroids are measured from the original or filtered images, respectively. The position angle of the P1-P2 vector is 83° ± 6°, which is not significantly different from the mean central isophote position angle of ~87°.

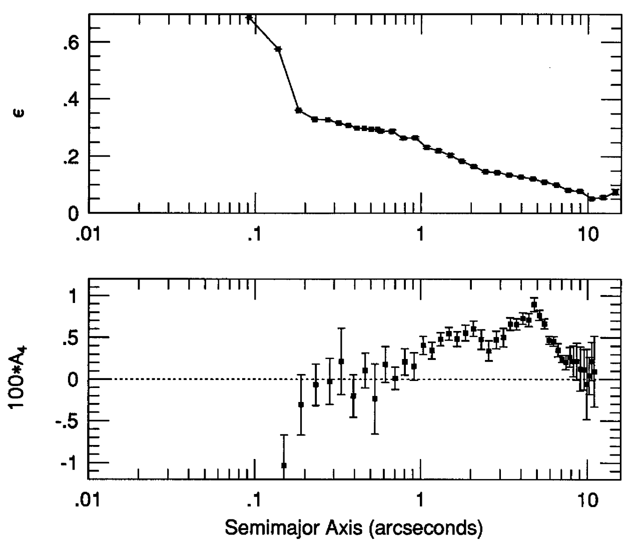

FIG. 4.—Isophote ellipticity and A_4 profiles of NGC 4486B

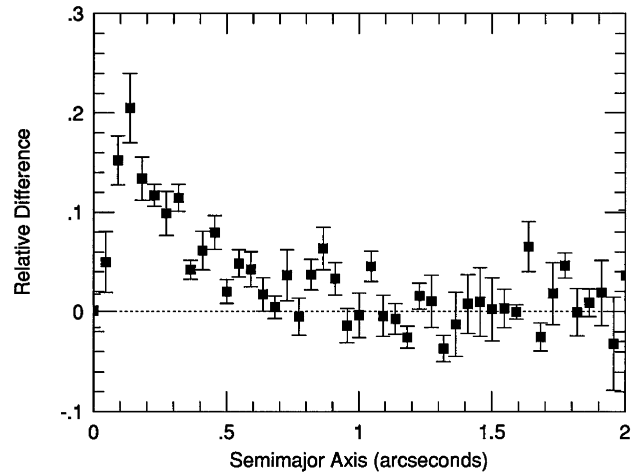

FIG. 5.—Relative differences between the P1 and P2 sides of a 7 pixel–wide cut along the major axis of the deconvolved I-band image.

3. DISCUSSION

Our principal conclusion is that the double nucleus of M31 is not unique. If we can assume that the similar nuclei of M31 and NGC 4486B reflect similar dynamics, then comparing the two offers new insights into their nature and origin:

1. The lack of a clear pattern of reddening correlated with the central morphology of both M31 and NGC 4486B implies that it is difficult to ascribe the double structure to dust absorption, unless for some reason the dust particles are unusually large in both galaxies (Lauer et al. 1993).

2. A double nucleus might be produced when the dense nucleus of a cannibalized small galaxy is dragged into the center of a larger galaxy by dynamical friction. However, there is no independent evidence for a recent merger in either M31 or NGC 4486B. Furthermore, the environment of NGC 4486B is inhospitable to mergers. NGC 4486B is a companion to the giant elliptical galaxy, M87 = NGC 4486, in the heart of the Virgo Cluster. Its projected separation from the center of M87 is 7'.3 or 34 kpc, which places it apparently in the outer envelope of M87. The radial velocity difference between M87 and NGC 4486B is only 204 ± 44 km s^{-1}, which raises the possibility that NGC 4486B is bound to M87. NGC 4486B is a compact, low-luminosity elliptical galaxy ($M_V = -17.6$) with a velocity dispersion of ~130 km s^{-1} (Kormendy et al. 1996) outside its nucleus; it may have been tidally truncated by a previous interaction with M87 (Faber 1973). All these observations suggest that NGC 4486B is within the Virgo Cluster, so most encounters with other Virgo Cluster galaxies will have large relative velocities and will not lead to mergers.

3. A double nucleus could also be produced as globular clusters belonging to NGC 4486B, itself, spiral to the galactic center through dynamical friction (capture of globular clusters from M87 is extremely inefficient). However, in this case (1) it is unlikely that the accreted cluster would match the central color of NGC 4486B, (2) there is no reason that the two peaks should be at similar distances from the photocenter, and (3) we must explain why the central photometry is not dominated by light from the clusters disrupted earlier in the history of the galaxy.

4. An even stronger argument (Dressler & Richstone 1988) that the double structure in M31 is unlikely to be a separate

stellar system orbiting the nucleus is that the timescale for orbital decay from dynamical friction is short—Lauer et al. estimate a few times 10^5 yr, while Tremaine (1995) estimates an upper limit of a few times 10^7 yr owing to the bulge alone. The timescale for decay in NGC 4486B is similarly short:[3] the decay time of P1 due to friction from the background galaxy is $\sim 1 \times 10^8$ $(10^6\ M_\odot/m)$ yr, where m is the mass of P1 (this is an upper limit since the drag from the interaction of P1 and P2 should be much stronger and the mass of P1 is likely to be larger). So long as it was a unique system, the double nucleus in M31 could have been a rare, short-lived configuration. The discovery of a second double nucleus in a WFPC2 survey of only ~30 galaxies suggests that such systems are common and hence likely to be long lived. We also note that if double nuclei are short-lived structures that arise from mergers, there should be many more at larger separations, which would have been detectable from the ground. In summary, neither M31 nor NGC 4486B is easy to explain as infalling or orbiting stellar systems.

5. It is unlikely in either galaxy that P1 or P2 is spatially separated from the galactic center but is seen in projection against it. Three arguments against this hypothesis are (1) the close match in color between the peaks and the surrounding galaxies, (2) the sharply limited spatial extent of the excess light associated with the peaks, and (3) in both galaxies, the isophotal ellipticity increases strongly towards the center at radii well outside the double nucleus.

There are also differences between the two galaxies:

1. The two brightness peaks in NGC 4486B are separated by 10–13 pc, while the peaks in M31 are separated by only 1.8 pc.

2. The two peaks in NGC 4486B are at similar distances from the photocenter ($0\farcs092 \pm 0\farcs08$ for P1, and $0\farcs058 \pm 0\farcs08$ for P2), while in M31, P2 is within $0\farcs05$ of the photocenter and P1 is $0\farcs49$ away.

3. The peaks are more closely matched in central surface brightness in NGC 4486B (within 0.1 mag arcsec^{-2}, compared to a difference of 0.3 mag arcsec^{-2} in M31); they are also more closely matched in total luminosity. It may be significant that in both galaxies the brighter peak is farther from the center, and when the peaks are more closely matched in brightness, they are more closely matched in distance.

4. The nucleus of M31 is a distinct component that rises above the M31 bulge brightness profile. The NGC 4486B brightness profiles show no evidence for a distinct nucleus; however, NGC 4486B is unusual for a galaxy of its luminosity in having a well-resolved core (Faber et al. 1996).

In the eccentric-disk model, as applied to NGC 4486B, the two brightness peaks would be the ansae of a disk or ring of stars orbiting a black hole. The black hole is presumably at or close to the galaxy photocenter; the small differences in separation and brightness of the peaks reflect a modest eccentricity in the disk. The vector connecting the peaks is aligned with the isophotal major axis at larger radii because the disk lies in the equatorial plane of the larger stellar system, which is close to edge-on. The model predicts no color differences between the peaks, consistent with observations.

To maintain an eccentric disk, the potential must be nearly Keplerian. Hence, this model requires that NGC 4486B contains a central dark object whose mass is much larger than the mass of stars inside the disk radius (roughly $1 \times 10^7\ M_\odot$ inside $0\farcs1$). Spectroscopic observations by Kormendy et al. (1996) may be consistent with this prediction. The increasing ellipticity inside 10″ plus the large A_4 values over the same radii (Fig. 4) suggest that the galaxy contains a much larger stellar disk, which is axisymmetric where the force field is non-Keplerian and eccentric where the force field is dominated by the black hole. A thorough understanding of the dynamics of eccentric disks might allow us to estimate the black hole mass directly from the disk shape by relating the scale at which the disk symmetry is broken to the hole mass.

Finally, we note that a poorly resolved disk will appear as a double nucleus only when viewed nearly edge-on, as in M31 and NGC 4486B. Thus, some offset structures near the centers of galaxies (Lauer et al. 1995) may arise from face-on eccentric disks.

We thank the referee for a number of excellent suggestions. We thank the University of Toronto's Fields Institute for Research in Mathematical Sciences for hosting our team during the initial development of this Letter. Our collaboration was supported by *HST* data analysis funds provided through individual grants from STScI. A portion of this research has also been supported by NSERC.

[3] The decay time is $\dot{L}/L$, where L is the angular momentum. The drag is computed using the usual Chandrasekhar formula with $\ln \Lambda = \ln(3.0)$ and local density and velocity dispersion determined from the parametric fit (eq. [1]) assuming a black hole of $2 \times 10^8\ M_\odot$ and stellar $M/L = 4\ M_\odot/L_\odot$.

REFERENCES

Byun, Y.-I., et al. 1996, AJ, 111, 1889
Djorgovski, S. 1988, in IAU Symp. 126, Globular Cluster Systems in Galaxies, ed. J. E. Grindlay & A. G. D. Philip (Dordrecht: Kluwer), 333
Dressler, A. 1984, ApJ, 286, 97
Dressler, A., & Richstone, D. O. 1988, ApJ, 324, 701
Faber, S. M. 1973, ApJ, 279, 423
Faber, S. M., et al. 1996, in preparation
Kormendy, J. 1988, ApJ, 325, 128
Kormendy, J., et al. 1996, in preparation
Lauer, T. R., et al. 1993, AJ, 106, 1436
———. 1995, AJ, 110, 2622
———. 1996, in preparation
Richstone, D., Bower, G., & Dressler, A. 1990, ApJ, 353, 118
Tremaine, S. 1995, AJ, 110, 628