THE ASTRONOMICAL JOURNAL, 000:00–00, 2001

THE NUCLEAR DISK IN THE DWARF ELLIPTICAL GALAXY NGC 4486A[1]

John Kormendy[2] and Karl Gebhardt[2]
Department of Astronomy, University of Texas, Austin, TX 78712

AND

F. Duccio Macchetto and W. B. Sparks
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218
Received 2001 July 4

ABSTRACT

Many ellipticals contain nuclear disks of dust and gas. Some ellipticals contain nuclear disks of stars that are distinct from the rest of the galaxy. We show that the dwarf E2 galaxy NGC 4486A contains both – it is a "Rosetta stone" object that tells us how nuclear disks evolve. Its properties suggest that, as accreted gas dissipates and settles toward the center, it forms stars and builds a stellar disk. Secular growth may explain not only the most distinct nuclear disks such as those in NGC 4486A but also some of the disky distortions that are commonly seen in elliptical galaxies. That is, density distributions may grow secularly cuspier. This would result in chaotic mixing of stellar orbits in phase space and would tend to make an elliptical galaxy evolve toward a more nearly axisymmetric shape.

1. INTRODUCTION

The fraction of all elliptical galaxies that are known to contain dust has risen dramatically as the resolution of our observations has improved and as digital detectors have made it possible to see subtle absorption features superposed on steep brightness gradients. Kormendy & Djorgovski (1989) review ground-based observations that reveal dust, often in well defined disks, in at least 20 – 40 % of all ellipticals (Hawarden *et al.* 1981; Sadler & Gerhard 1985a, b; Sparks *et al.* 1985; Ebneter & Balick 1985; Djorgovski & Ebneter 1986; Kormendy & Stauffer 1987; Ebneter *et al.* 1988). More recent ground-based surveys find dust in even higher fractions of early-type galaxies (e. g.,Ferrari *et al.* 1999). The *Hubble Space Telescope* (*HST*) reveals dust disks in spectacular detail. It has been used to discover additional dust disks that are too small to be seen from the ground (see Jaffe *et al.* 1994; van Dokkum & Franx 1995, Ford *et al.* 1998, Jaffe *et al.* 1999, Tomita *et al.* 2000, Tran *et al.* 2001 for reviews). Also, even prototypical bulges like M 31 are frequently riddled with dust (Johnson & Hanna 1972; Kent 1983; McElroy 1983) and ionized gas (Ciardullo *et al.* 1988). Kinematic axes that are misaligned with respect to photometric axes show that many of these disks are accreted (see Kormendy & Djorgovski 1989 for a review).

Nuclear disks of stars are also seen in some ellipticals and bulges. Examples in bulges are found in NGC 3115 (Kormendy *et al.* 1996a) and NGC 4594 (Kormendy *et al.* 1996b). Ellipticals with stellar nuclear disks include NGC 4570 (van den Bosch *et al.* 1994) and, most spectacularly, NGC 3706 (Lauer *et al.* 2001). Clues to the formation of these disks are the main subject of this paper.

The E3 galaxy NGC 5845 contains both a dust disk and an associated, nuclear stellar disk. Kormendy *et al.* (1994) emphasize that it provides clues to how dust disks evolve. They suggest that, as accreted gas dissipates and settles toward the center, it forms stars and builds a stellar disk. Secular growth may explain not only the most distinct nuclear disks such as those in the above galaxies but also some of the disky distortions that are commonly seen in elliptical galaxies (e. g., Bender *et al.* 1989). That is, density distributions may grow secularly cuspier. This is important because it means that the distribution of orbits and hence the degree of triaxiality can evolve (see Merritt 1999 for a review).

NGC 4486A now provides a second example of associated dust and stellar disks. At a distance of 16 Mpc, it is an absolute magnitude $M_B \simeq -17.6$ dwarf elliptical companion of M 87 (NGC 4486). Binggeli, Sandage, & Tammann (1985) classify it as E2. The galaxy is rarely studied because there is a bright star only $2\farcs5$ from its center. This star is ideal for ground-based adaptive optics (AO) correction. JK and KG obtained K-band AO images using the Canada-France-Hawaii Telescope (CFHT) as part of a general investigation of Virgo Cluster ellipticals and found that the galaxy contains an edge-on nuclear disk. In the infrared, there is no obvious dust, but the center is offset from the outer isophotes by $\sim 0\farcs05$ along the minor axis. This suggested that there may be a dust lane. Fortunately, FDM and WBS had obtained *HST* V- and I-band WFPC2 images as part of an unrelated program. These images show an edge-on dust disk. The following sections discuss the properties and implications of the nuclear disks of NGC 4486A.

[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] Visiting Astronomer, Canada–France–Hawaii Telescope, operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique of France, and the University of Hawaii.

2. CFHT ADAPTIVE OPTICS IMAGE

Figure 1 shows a K-band AO image obtained with the CFHT Adaptive Optics Bonette (PUEO) and KIR camera (Rigaut *et al.* 1998). The image scale is $0\farcs035$ pixel^{-1}. The images were obtained on 1999 March 6 in photometric conditions. The total exposure time was 24 min, taken in three groups of 24, 20 s exposures interleaved with sky exposures. The uncorrected seeing was $\sim 0\farcs7$ FWHM. Given the very bright guide star only $2\farcs5$ from the galaxy, the AO compensation is excellent; the stellar FWHM is $\sim 0\farcs12$ and the Strehl ratio is 0.6. Two diffraction rings are visible around the star in Figure 1. A galaxy-subtracted image of this star was used as a point-spread function (PSF) for Lucy-Richardson deconvolution; 40 iterations eliminated most of the diffraction pattern and reduced the FWHM to $0\farcs07$. Further details of the observations are given in Gebhardt & Kormendy (2001).

Figure 1 shows a surprising result: this elliptical galaxy contains a prominent, almost edge-on nuclear disk of stars. This does not mean that the galaxy is an S0. S0 disks are at large radii, outside most of the bulge (Sandage, Freeman, & Stokes 1970). There is no evidence for an outer disk here. In contrast, the disk in NGC 4486A is similar to the nuclear disks that are found interior to and not connected with the outer disks in the S0 galaxy NGC 3115, the Sa galaxy NGC 4594, and some giant ellipticals (§ 1).

The outer part of the disk is symmetric, but the brightest pixels near the center are displaced by $\sim 0\farcs05$ along the minor axis. This suggested that the galaxy may contain a dust lane that is almost negligible in the infrared.

3. *HUBBLE SPACE TELESCOPE* WFPC2 IMAGES

The presence of dust is clearly established by Figure 2, which shows WFPC2 images obtained in the V and I bandpasses (F555W and F814W). These images were processed using the standard STScI calibration pipeline. Each is the sum of two, 500 s exposures that were combined using the iraf/stsdas task “crrej” to eliminate cosmic rays.

These images were obtained for an unrelated program, but NGC 4486A is fortuitously positioned close to the center of the PC. Figure 2 shows that the dust lane is very well defined and has a sharp outer edge. It is embedded in the inner part of the stellar disk, but the stellar disk extends to twice the radius of the dust disk.

4. ORIGIN OF NUCLEAR DISKS OF STARS

The morphology of the nuclear disk is best illustrated by constructing a three-color image from the V-, I-, and K-band exposures (Figure 3). NGC 4486A is important because it contains both a stellar and a dust disk. They are regular and clearly associated. As in NGC 5845, this provides a key clue toward our understanding of how nuclear disks evolve. It does not tell us how the dust originates. Other evidence demonstrates that dust is commonly accreted (Kormendy & Djorgovski 1989), but it does not exclude that it sometimes has an internal origin. For convenience, we refer to the dust as accreted material. Whatever its origin, it migrates quickly toward the center. There, gas and dust settle into a disk that, in equilibrium, is oriented perpendicular to the short axis if the object is a spheroid or perpendicular to the shortest or longest axis it the object is triaxial (Heiligman & Schwarzschild 1979). Objects like NGC 4486A and NGC 5845 illuminate what happens next. Gas likes to make stars when it gets crunched, and funneling the gas into the compact center is a natural way to crunch it. With Kormendy *et al.* (1994), we suggest that the gas and dust turn into stars and build a stellar disk.

The possible caveat is this: if the nuclear disk of stars predates the accretion event because it formed with the galaxy, then it helps to define a gravitational potential that will make newly acquired gas settle into the same disk plane and look like it is associated with the stellar disk. On the other hand, if the stellar disk formed recently from the accreted material, then it may be observably younger than the rest of the galaxy. The best way to test this is spectroscopy. This is in progress. Here, we can look for a color difference between the nuclear disk and the bulge.

Figure 4 shows a $V - I$ color image of NGC 4486A. The blue PSF halo produced by scattered light clobbers the southern part of the stellar disk. But Figure 4 shows (1) that light from the dust lane is very red, and (iii) that the stellar disk outside the dust lane is marginally bluer than the rest of the galaxy. After a convolution of the V image to match it to the spatial resolution of the I image, the difference in color is $\Delta(V - I) = 0.06$ mag. Broad-band colors are not a unique indicator of age, but this result supports the hypothesis that gas disks build stellar disks near the centers of bulges and elliptical galaxies.

5. SECULAR GROWTH OF CUSPY DENSITY DISTRIBUTIONS IN BULGES AND ELLIPTICAL GALAXIES

The implication of these results is that the density distributions of bulges and elliptical galaxies grow cuspier even after the events that formed them. This has practical consequences; it makes the search for supermassive black holes easier (because the brightness is higher) and more reliable (because the dynamics are dominated by rotation, so velocity anisotropy is less important). It also adds noise to the correlations between central and global properties of elliptical galaxies. These suggest that there are two kinds of ellipticals, (1) slowly rotating, anisotropic, triaxial, boxy-distorted ellipticals with cuspy cores and (2) rapidly rotating, nearly isotropic and spheroidal, disky-distorted, coreless ellipticals (Bender 1988; Bender *et al.* 1989; Nieto, Bender, & Surma 1991; Kormendy *et al.* 1994; Kormendy & Bender 1996; Faber *et al.* 1997; Tremblay & Merritt 1996). In particular, it may account for exceptions to the dichotomy, like NGC 1316 = Fornax A (Schweizer 1980; Kormendy 1987; Faber *et al.* 1997) and NGC 4621 (Kormendy *et al.* 1994). Both galaxies are unusually cuspy for their high luminosities.

However, the main reason why the growth of cuspiness is important is that it results in secular evolution of the overall structure of elliptical galaxies. Merritt and collaborators (see Merritt 1999 for a review) have shown that the growth of cuspy density distributions makes the orbit structure evolve even at radii substantially outside the radius out to which the cusp dominates the potential. Stars on box orbits pass close to the center and scatter off of the density cusp. This results in chaotic mixing, which redistributes the orbits in phase space and makes the galaxy evolve rapidly toward axisymmetry. One driving agent is the growth of nuclear black holes. Increasing the cuspiness of the stellar mass distribution is another.

What the present observations do not tell us is how much growth in density is typical. The frequent observation of dust disks suggests that some evolution happens to nearly every elliptical. But timescales and mass deposition rates are unknown. We need to know how much gas and dust is observed and to investigate the ages of nuclear disk stars to constrain the timescale of disk growth.

What the present results provide is a proof of concept. They imply that evolution does take place, and that the fate of the gas and dust disks that we see in so many elliptical galaxies is to turn into nuclear disks of stars.

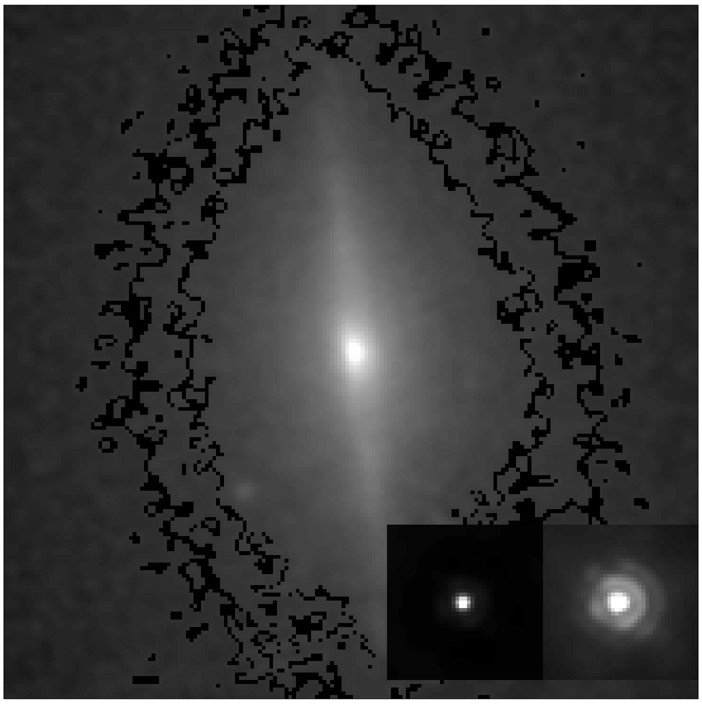

Fig. 1. – NGC 4486A: K-band adaptive optics image obtained with the CFHT after 40 iterations of Lucy deconvolution. The field size is 6.″4; north is up and east is at left. Brightness is proportional to the square root of intensity, and two isophotes are blacked out. For display purposes, a region around the bright star has been divided by 100 to approximately match the peak brightness in the galaxy. The FWHM is 0.″07. To its right, an inset shows the star before deconvolution.

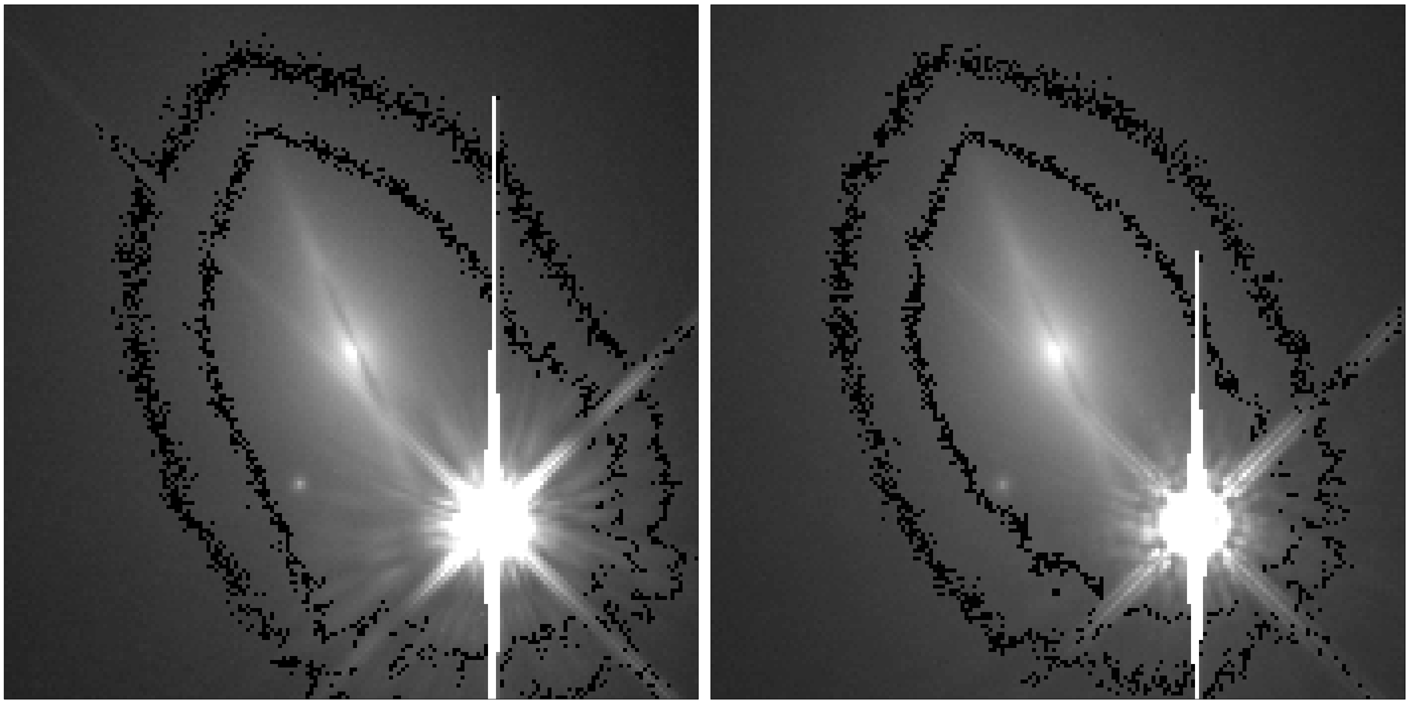

Fig. 2. – NGC 4486A: WFPC2, V-band (*left*) and I-band (*right*) images. The field size is 8″. Brightness is proportional to the square root of intensity, and two isophotes are blacked out.

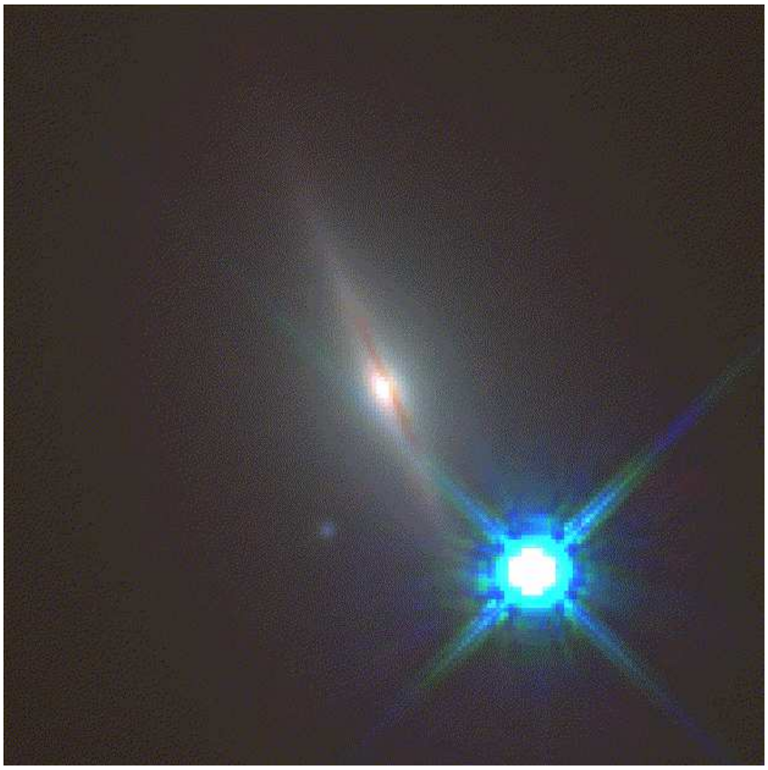

Fig. 3. – Three-color image of NGC 4486A constructed by coding the V image as blue, the I image as green, and the K image as red. The field size is $8''$. The intensity stretch is linear.

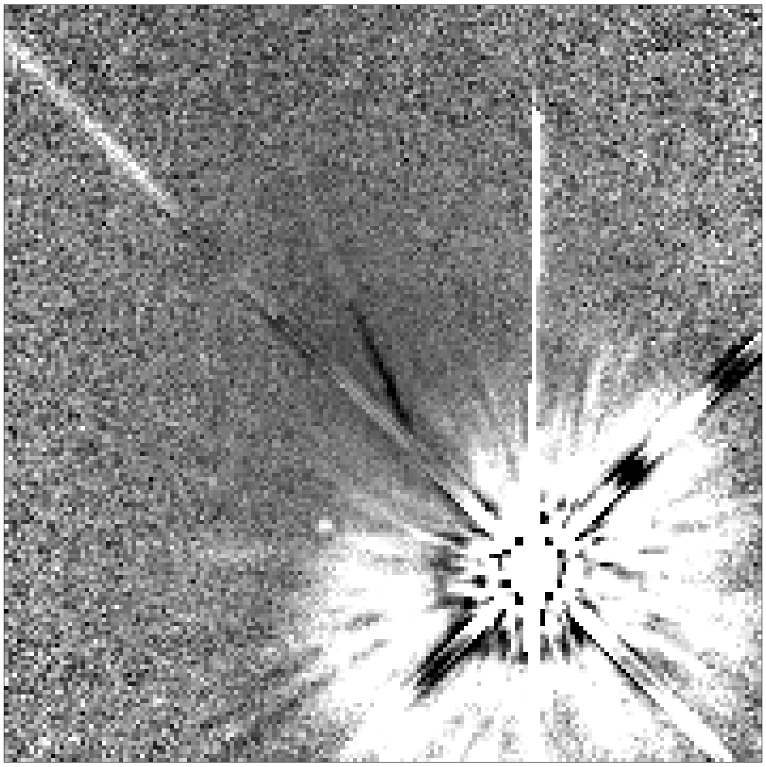

Fig. 4. – $V-I$ color image of NGC 4486A. Black corresponds to $V-I=1.7$ and white corresponds to $V-I=1.2$. The bulge color is $V-I\simeq 1.41$ The stellar disk is $\Delta(V-I)=0.06$ bluer than the bulge. The field size is $8''$.

REFERENCES

Bender, R. 1988, A&A, 193, L7
Bender, R., *et al.* 1989, A&A, 217, 35
Binggeli, B., Sandage, A., & Tammann, G. A. 1985, AJ, 90, 1681
Ciardullo, R., Rubin, V. C., Jacoby, G. H., Ford, H. C., & Ford, W. K. 1988, AJ, 95, 438
Djorgovski, S., & Ebneter, K. 1986, in IAU Symposium 118, Instrumentation and Research Programmes for Small Telescopes, ed. J. B. Hearnshaw & P. L. Cottrell (Dordrecht: Reidel), 277
Ebneter, K., & Balick, B. 1985, AJ, 90, 183
Ebneter, K., Djorgovski, S., & Davis, M. 1988, AJ, 95, 422
Faber, S. M., *et al.* 1997, AJ, 114, 1771
Ferrari, F., Pastoriza, M. G., Macchetto, F., & Caon, N. 1999, A&AS, 136, 269
Ford, H. C., *et al.* 1998, in IAU Symposium 184, The Central Regions of the Galaxy and Galaxies, ed. Y. Sofue (Dordrecht: Kluwer), 377
Gebhardt, K., & Kormendy, J. 2001, to be published
Hawarden, T. G., Elson, R. A. W., Longmore, A. J., Tritton, S. B., & Corwin, H. G. 1981, MNRAS, 196, 747
Heiligman, G., & Schwarzschild, M. 1979, ApJ, 233, 872
Jaffe, W., Ford, H. C., O'Connell, R. W., van den Bosch, F. C., & Ferrarese, L. 1994, AJ, 108, 1567
Jaffe, W., *et al.* 1999, in Galaxy Dynamics, ed. D. Merritt *et al.* (San Francisco: ASP), 13
Johnson, H. M., & Hanna, M. M. 1972, ApJ, 174, L71
Kent, S. M. 1983, ApJ, 266, 562
Kormendy, J. 1987, in Nearly Normal Galaxies: From the Planck Time to the Present, ed. S. M. Faber (Berlin: Springer-Verlag), 163
Kormendy, J., & Bender, R. 1996, ApJ, 464, L119
Kormendy, J., & Djorgovski, S. 1989, ARA&A, 27, 235
Kormendy, J., & Stauffer, J. 1987, in IAU Symposium 127, Structure and Dynamics of Elliptical Galaxies, ed. T. de Zeeuw (Dordrecht: Reidel), 405
Kormendy, J., *et al.* 1994, in ESO/OHP Workshop on Dwarf Galaxies, ed. G. Meylan & P. Prugniel (Garching: ESO), 147
Kormendy, J., *et al.* 1996a, ApJ, 459, L57
Kormendy, J., *et al.* 1996b, ApJ, 473, L91
Lauer, T. R., *et al.* 2001, in preparation
McElroy, D. B. 1983, ApJ, 270, 485
Merritt, D. 1999, in Galaxy Dynamics, ed. D. Merritt *et al.* (San Francisco: ASP), 164
Nieto, J.-L., Bender, R., & Surma, P. 1991, A&A, 244, L37
Rigaut, F., *et al.* 1998, PASP, 110, 152
Sadler, E. M., & Gerhard, O. E. 1985a, in New Aspects of Galaxy Photometry, ed. J.-L. Nieto (New York: Springer-Verlag), 269
Sadler, E. M., & Gerhard, O. E. 1985b, MNRAS, 214, 177
Sandage, A., Freeman, K. C., & Stokes, N. R. 1970, ApJ, 160, 831
Schweizer, F. 1980, ApJ, 237, 303
Sparks, W. B., Wall, J. V., Thorne, D. J., Jorden, P. R., van Breda, I. G., Rudd, P. J., & Jorgensen, H. E. 1985, MNRAS, 217, 87
Tomita, A., Aoki, K., Watanabe, M., Takata, T., & Ichikawa, S.-I. 2000, AJ, 120, 123
Tran, H. D., *et al.* 2001, AJ, 121, 2928
Tremblay, B., & Merritt, D. 1996, AJ, 111, 2243
van den Bosch, F. C., Ferrarese, L., Jaffe, W., Ford, H. C., & O'Connell, R. W. 1994, AJ, 108, 1579
van Dokkum, P. G., & Franx, M. 1995, AJ, 110, 2027