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EVIDENCE FOR AN OUTER DISK IN THE PROTOTYPE "COMPACT ELLIPTICAL" GALAXY M32

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ABSTRACT

M32 is the prototype for the relatively rare class of galaxies referred to as *compact ellipticals*. It has been suggested that M32 may be a tidally disturbed $r^{1/4}$ elliptical galaxy or the remnant bulge of a disk-stripped early-type spiral galaxy. This Letter reveals that the surface brightness profile, the velocity dispersion measurements, and the estimated supermassive black hole mass in M32 are inconsistent with the galaxy having, and probably ever having had, an $r^{1/4}$ light profile. Instead, the radial surface brightness distribution of M32 resembles an almost perfect (bulge+exponential disk) profile; this is accompanied by a marked increase in the ellipticity profile and an associated change in the position angle profile where the "disk" starts to dominate. Compelling evidence that this bulge/disk interpretation is accurate comes from the best-fitting $r^{1/n}$ bulge model, which has a Sérsic index of $n = 1.5$, in agreement with the recently discovered relation between a bulge's Sérsic index and the mass of a bulge's supermassive black hole. An index of $n \geq 4$ would also be inconsistent with the stellar velocity dispersion of M32. The bulge-to-disk size ratio r_e/h equals 0.20, and the logarithm of the bulge-to-disk luminosity ratio log (B/D) equals 0.22, typical of Sϕ galaxies. The effective radius of the bulge is 27″ (∼100 pc), while the scale length of the disk is less well determined: owing to possible tidal stripping of the outer profile beyond 220″–250″, the scale length may be as large as 1.3 kpc. M32 is a relatively face-on, nucleated dwarf galaxy with a low surface brightness disk and a high surface brightness bulge. This finding brings into question the very existence of the compact elliptical class of galaxies.

Subject headings: black hole physics — galaxies: bulges — galaxies: dwarf — galaxies: fundamental parameters — galaxies: individual (M32) — galaxies: structure

1. INTRODUCTION

The 32nd object in the catalog of Messier (1850) has come to be known as the archetype of high surface brightness, low-luminosity, *compact elliptical* galaxies (de Vaucouleurs 1961). It has been proposed that they may be the dense cores of tidally truncated, or at least modified, ordinary elliptical galaxies (King 1962; Faber 1973; Nieto & Prugniel 1987; Choi, Guhathakurta, & Johnston 2002 and references therein). It has also been suggested that M32 (NGC 221) may in fact never have been an elliptical galaxy but is instead the bulge of a (partially) stripped disk galaxy (Bekki et al. 2001; see also Nieto 1990).

Using the tight ($r_s = 0.91$) correlation between the central concentration index $C_{r_e}(1/3)$ of a bulge[2] and the mass of its central supermassive black hole (SMBH; Graham et al. 2001a) provides a new constraint capable of determining which proposition, if either, is correct. Simply by modeling M32's surface brightness profile as either a one-component ($r^{1/n}$) elliptical or as a two-component ($r^{1/n}$ bulge+exponential) lenticular or spiral galaxy, and knowing its SMBH mass, allows one to decipher which scenario is more probable.

The Letter is laid out as follows: § 2 introduces M32's surface brightness profile, which is modeled in § 2.1, and § 3 introduces M32's velocity dispersion measurements and SMBH mass estimates into the discussion, supporting the notion that a bulge *and disk* decomposition is required.

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[2] By the term bulge it is meant both an elliptical galaxy and the bulge of a disk galaxy.

2. SURFACE BRIGHTNESS PROFILE OF M32

M32's major-axis, *R*-band surface brightness profile, presented in Kent (1987), is reanalyzed here. The data were obtained using an RCA CCD, attached at different times to three telescopes with different fields of view at the Whipple Observatory on Mount Hopkins. The observing procedures are described in Kent (1983) and the (remarkably standard) reduction procedure given in Kent (1987).

The main complication with this galaxy is its proximity to M31 (Andromeda). It resides (in projection) within the outer disk of M31, and so the disk of M31 had to first be modeled and then subtracted. Kent wrote, "The light from M31 was removed approximately by fitting second-order polynomials to the background light in the frame of M32 obtained with the Bausch & Lomb 8000 [a 20 cm aperture telescope with a 15′ × 25′ field of view], excluding an area about M32 itself." Ultimately, uncertainties in the sky-background level resulted in the termination of the profile at $\mu(r = 280'') \sim 24$ *R* mag arcsec^{-2}.

Further complications and solutions are described in Kent (1987) and are not repeated here for the following reason. After commencing this work, Choi et al. (2002) presented new *B*- and *I*-band surface brightness profiles for M32. These show very good agreement over the radial range in common with Kent (1987) and extend to 420″. This lends confidence that the publicly available data from Kent (1987) are reliable. The profiles of Choi et al. (2002) are referred to here in a qualitative manner.

2.1. *Modeling the Surface Brightness Profile*

Inner components, such as nuclear disks, star clusters, flattened cores, etc., are known to reside within the central ∼1″ of many

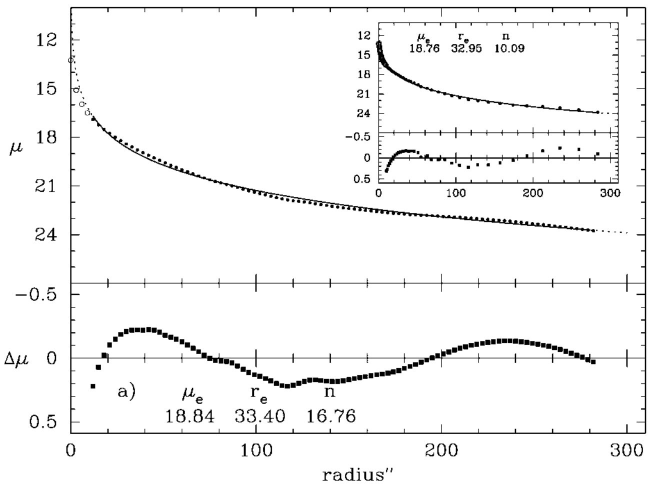

FIG. 1*a*

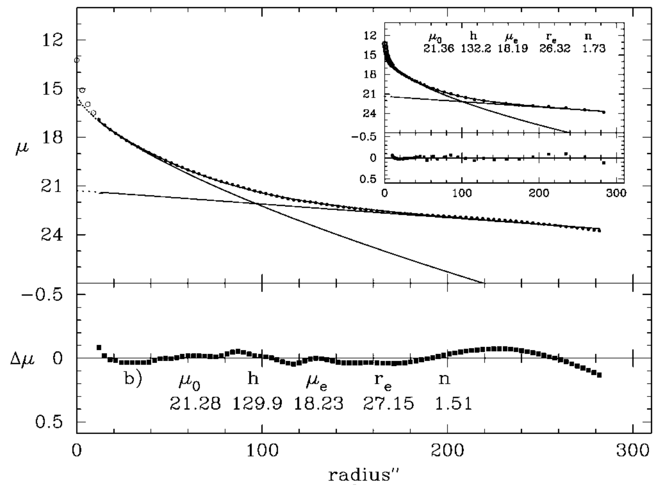

FIG. 1*b*

FIG. 1.—M32's (major axis) *R*-band surface brightness profile from Kent (1987), resampled at equal spacing in radius, is modeled with (*a*) a seeing-convolved $r^{1/n}$-only model and (*b*) a seeing-convolved $r^{1/n}$+exponential model. Following common practice, the inner 10″ have been excluded from the fit. Insets show the results using the logarithmically spaced data from Kent (1987).

galaxies (e.g., Rest et al. 2001; Ravindranath et al. 2001). We wish to avoid such features here, as we are presently concerned only with the bulge (and outer disk, if one exists) of M32. However, typically observed galaxies are considerably more distant than M32. At a distance of 0.8 Mpc, with the exception of the Milky Way, M32 is some 10 times closer than any other galaxy with a positive SMBH detection (Kormendy & Gebhardt 2001; Merritt & Ferrarese 2001b). Its nuclear region is therefore very well resolved: 1″ is equivalent to 3.87 pc. If M32 was located at the distance of the Virgo Cluster, exclusion of its central arcsecond would translate to the removal of the inner ∼60–80 pc (∼15″–20″ at its present location).

Böker et al. (2002) chose to model the central excesses (above that of the bulge) found in *Hubble Space Telescope* (*HST*) images of spiral galaxies with a power law. Tonry (1984) noted that the inner 10″ of M32 displays a power-law shape. This may therefore be a somewhat common feature of bulges.[3] Michard & Nieto (1991) presented evidence that the inner 5″ of M32 contains a nuclear disk; however, this has subsequently been refuted by Lauer et al. (1998), who found no photometric evidence for separate nuclear components in *HST* images. However, the presence of an apparent excess central flux did result in Kent (1987) excluding the inner 15″ from his model fitting and Choi et al. (2002) excluding the inner 10″, which is also done here. Apart from this, the entire surface brightness profile beyond 10″ is modeled. The data from Table 3 of Kent (1987), and also a resampling of Kent's Figure 1 (to give an equal spacing in radius, effectively providing a more even weighting [radially] to the data), are modeled.

Both a seeing-convolved $r^{1/n}$ model and a seeing-convolved $r^{1/n}$+exponential model were fitted. In both cases, all model parameters were simultaneously fitted using the quasi-Newton, nonlinear least-squares algorithm UNCMND (Kahaner, Moler, & Nash 1988) that was iterated until convergence on the optimal solution, giving the smallest χ^2-value. All parameters were allowed to range freely in the fitting process; the only constraint was that they must be positive real numbers. The seeing was reported by Kent (1987) to have an FWHM of 1″.3 and therefore, owing to the exclusion of the inner 10″, has little effect on the results, which are shown in Figure 1. Several truncations of the outer profile were explored, but the overall conclusion was always the same: *M32 cannot be modeled as, that is to say it is not* (*structurally*), *a single-component system*. The curvature in the residual profile of Figure 1*a* is classic evidence of this. Importantly, M32 can be described exceptionally well with the two-component model.[4]

The notably small residuals (Fig. 1*b*) are compelling evidence that this model is likely to be correct. This is, however, not to say that M32 has a rotationally supported disk of stars, it simply has an outer exponential distribution of stars. To help decide whether the disk interpretation is indeed correct, let us look at the resulting structural parameters to see if they are consistent with those of known bulge/disk systems.

The bulge-to-disk size ratio (r_e/h) is 0.20, in good agreement with that of normal disk galaxies (Graham 2001 and references therein), suggesting nothing unusual. The logarithm of the bulge-to-disk luminosity ratio [log (*B*/*D*)] is 0.22, typical of an S0 galaxy. The effective half-light radius of the bulge is 27″, in reasonable agreement with the value of 32″ derived by Kent when modeling the radial interval $15'' < r < 100''$, and it even agrees well with the value of 30″ found by de Vaucouleurs (1953). The effective bulge surface brightness is 18.23 *R* mag arcsec^{-2}, the central bulge surface brightness is 15.31 *R* mag arcsec^{-2}, and the absolute magnitude of the bulge is 16.34 *R* mag.

Further support for the above bulge/disk decomposition comes from the new location of M32 in several structural parameter diagrams for bulges. M32 is a distant outlier in the insightful log n–B_T diagram presented in Jerjen & Binggeli (1997; their Fig. 2). Noting that their value of n corresponds to our value of $1/n$, when $n = 1.5$ (in our notation), M32 moves up into the very center of points and indeed the very center of the relation defined by the dwarf galaxies (see also Graham 2001; his Fig. 14). The reason for this is that the disk had biased Jerjen & Binggeli's one-component $r^{1/n}$ fit to M32's light profile, resulting in a value of n that is ∼5 in our notation. This additionally

[3] In passing, it is noted that this may be a feature that results in the overestimation of the Sérsic index n when modeling ground-based images that have not resolved, or avoided, such central excesses.

[4] Fitting an $r^{1/4}$+exponential model resulted in 86% more scatter than a $r^{1/n}$+exponential model as well as a rather unimpressive fit.

explains the deviant nature of M32 in the log r_0–B_T diagram and most of the discrepancy in the $\mu_{0,\,\mathrm{bulge}}$–B_T diagram.

What of the disk? Kent (1987) remarked that there "seems to be an excess of light at large radii, with the excess having an exponential profile." The ellipticity profile of Kent (1987) also suggests the presence of a distinct outer component in M32, rising from $\epsilon = 0.11$ at 150″ to $\epsilon = 0.19$ by ∼200″ (where the ellipticity was then held constant). This feature is even more clearly evident in the ellipticity profile of Choi et al. (2002), rising steadily from $\epsilon \sim 0.14$ at 100″ to ∼0.35 at 250″. The position angle also changes notably at 100″–150″.

The central disk surface brightness is 21.28 *R* mag arcsec^{-2} (Fig. 1*b*). Applying the standard disk inclination correction $-2.5C \log(1-\epsilon)$, where ϵ is the ellipticity of the disk ($\epsilon \sim 0.3$ from Choi et al. 2002) and $C = 0.5$ in the *R*-band (Tully & Verheijen 1997), would give a face-on central disk surface brightness of 21.48 *R* mag arcsec^{-2}. The definition of a low surface brightness (LSB) galaxy is one in which the central disk surface brightness is more than 1 mag fainter than the canonical Freeman (1970) value of 21.65 *B* mag arcsec^{-2} (which is about 20.5 *R* mag arcsec^{-2}). Thus, M32 would just about qualify as a bulge-dominated LSB disk galaxy (Beijersbergen, de Blok, & van der Hulst 1999; Impey & Bothun 1997). It is, however, because of its size and magnitude, a dwarf galaxy.

The scale length of the disk is 130″, or 0.5 kpc. There is, however, possible evidence of a disturbance in the very outer profile; it turns downward from an exponential profile at around 250″. That is, there appears to be a lack of light, relative to the exponential part of the profile, beyond ∼250″. This behavior is visible in the data of both Kent (1987) and Choi et al. (2002). It is accompanied by a marked change in the behavior of the ellipticity profile of Choi et al. (2002), flattening (or even decreasing slightly) beyond 250″. This may be a sign that material has been stripped away from the outer disk, although it is stressed that this conclusion is largely speculative. However, if true, this turnover would be biasing the surface brightness profile fit, making the disk scale length appear shorter than it was before tidal stripping commenced. Truncating the (equally spaced) profile at 220″, to avoid the potentially stripped outer disk and thereby (possibly) sampling only the original undisturbed profile, gives $h = 336''$ (1.27 kpc) and $\mu_0 = 22.42$ for the disk. For the bulge, $r_e = 29''$ and $n = 1.99$ (see Fig. 2; using the profile that is logarithmically spaced in radius gives $n = 2.08$). Here the value of $\log(B/D) = -0.09$ and $r_e/h = 0.09$, which is again not unreasonable. An $r^{1/n}$-only model fails to provide a convincing fit to this truncated radial range.

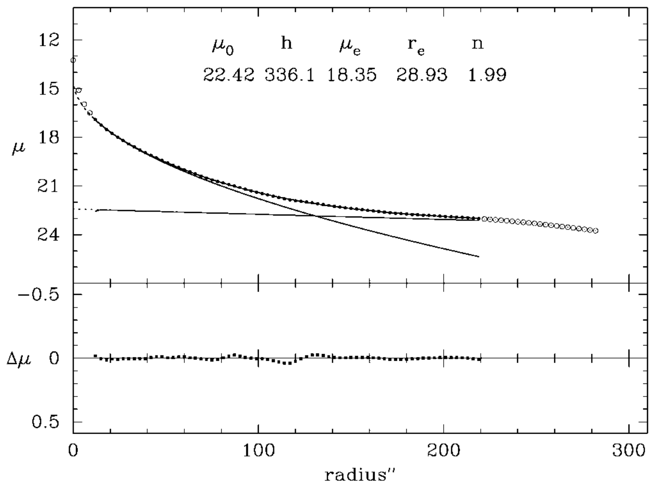

FIG. 2.—M32's (major-axis) *R*-band surface brightness profile from Kent (1987) is modeled here with a seeing-convolved $r^{1/n}$+exponential model. The inner 10″ have been excluded from the fit, as have the data beyond 220″.

3. DISCUSSION

The surface brightness profile of M32 can be modeled remarkably well as a combination of an $r^{1/n}$ bulge and an outer exponential disk of stars. However, could M32's surface brightness profile be so disturbed that the outer exponential envelope is actually due to material pulled off from what was once a one-component $r^{1/4}$ (i.e., $n = 4$) elliptical galaxy? This scenario appears unlikely for the following reasons.

First, somewhat persuasive evidence comes from the central velocity dispersion of M32, which has been measured to be 76 ± 10 km s^{-1} (van der Marel et al. 1998). This figure is in good agreement with the average value of 74 km s^{-1} obtained from numerous estimates listed in Hypercat.[5] It also agrees with Gebhardt et al.'s (2000) estimate of 75 km s^{-1} for the luminosity-weighted velocity dispersion within one effective radius.

Recently, it has been discovered that the central velocity dispersion of a bulge correlates strongly ($r = 0.8$) with the shape of the bulge light profile (as measured with the Sérsic index: Graham, Trujillo, & 2001b; Graham 2002). Galaxies with measured velocity dispersions of less than 100 km s^{-1} are observed to have values of $1 < n < 2$. The measured value of $n = 1.5$ for the bulge of M32 is thus exactly what one would expect from its dynamics, not $n = 4$. Bulges (including elliptical galaxies) with values of $n \gtrsim 4$ have velocity dispersions typically greater than 100 km s^{-1}.

The second, related line of reasoning comes from M32's SMBH mass. From ground-based kinematical data, Tonry (1984, 1987) predicted a SMBH mass of (3–10) $\times\ 10^6\ M_\odot$ at the center of M32. This pioneering work has been confirmed with *HST* data, from which van der Marel et al. (1998) derived a SMBH mass of $(3.4 \pm 0.7) \times 10^6\ M_\odot$, and more recently Joseph et al. (2001) have found a mass of (2–4) $\times\ 10^6\ M_\odot$.

The velocity dispersion (σ) and SMBH mass (M_{bh}) combination of M32 is known to fall on the log M_{bh}–log σ relation for (nondisturbed) ellipticals and bulges (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Merritt & Ferrarese 2001a). Thus, unless the process of tidal stripping modifies both the central velocity dispersion and the SMBH mass in such a way that it preserves the log M_{bh}–log σ relation, the central structure and dynamics of M32 are likely to be that of the original (i.e., undisturbed) galaxy. Indeed, owing to the higher densities at smaller radii, the central velocity dispersion and hence inner mass distribution and therefore inner light profile are expected to remain largely unaffected by the outer stripping process. Taken with the result in the previous paragraph, this strongly suggests that the $n = 1.5$–2.0 bulge profile is the original shape of the bulge.

Figure 3 shows the log M_{bh}–log n relation for bulges. It is a variant of the relation between SMBH mass and central bulge concentration [$C_{r_e}(1/3)$] shown in Graham et al. (2001a). [The parameter $C_{r_e}(1/3)$ is a monotonically increasing function of n; Trujillo, Graham, & Caon 2001.] If M32 did ever have an $r^{1/4}$ profile, then (from Fig. 3) its SMBH mass should have once been and should still be $\sim 10^8\ M_\odot$, and certainly greater than $\sim 10^7\ M_\odot$. Given that the bulge value of $n = 1.5$ agrees with the actual SMBH mass estimate (and with M32's velocity

[5] Hypercat can be reached at http://www-obs.univ-lyon1.fr/hypercat.

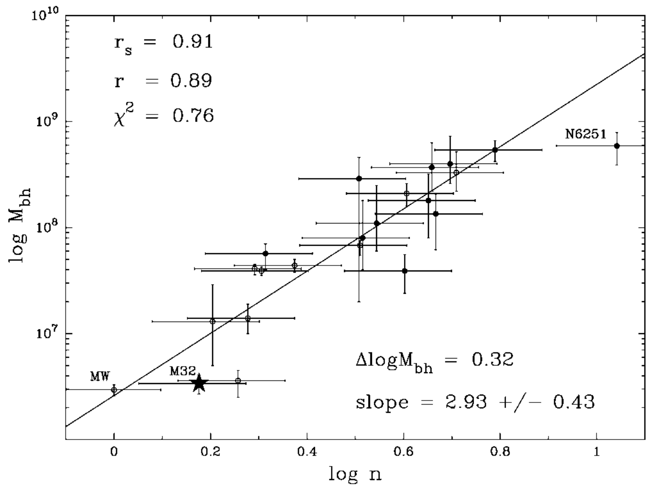

FIG. 3.—Location of M32 is shown in the log M_{bh}–log n diagram by the star. Value of $n = 1.5$ comes from the ($r^{1/n}$ bulge+exponential) model (Fig. 1*c*). Following Graham et al. (2001b), a typical error of 25% for n is shown. The SMBH mass estimate comes from van der Marel et al. (1998). Regression and statistics have been performed excluding M32, so it in no way biases the fit.

dispersion), the stars composing the outer exponential envelope are almost certainly an excess (relative to the bulge) and have not come from a reshaped bulge.[6]

All of this is not to say that the outer profile of M32 has not been disrupted. Indeed, the deficit of stars in the outer profile, causing the downward kink ($r \sim 250''$) in the disk, may have been due to gravitational stripping by M31. This deficit is also visible in the *B*- and *I*-band profiles of Choi et al. (2002) and hence is less likely to be a systematic error in the profile extraction technique of Kent (1987). Indeed, the recently reported tidal stream of metal-rich stars around M31 is thought to have likely come from M32 and/or NGC 205 (Ibata et al. 2001). The presence of a disk may also explain the intermediate-age (5–15 Gyr) stellar population in M32 (e.g., Grillmair et al. 1996; Davidge 2000).

[6] The reason Choi et al. (2002) claimed to be able to fit an $r^{1/4}$ bulge to the inner profile of M32 is likely because of the limited radial range $10'' < r < 30''$ they used to do this.

Perhaps a comment on nomenclature would be beneficial at this point. Kormendy & Gebhardt (2001) used the words "compact" and "fluffy" when referring to bulges. It should be noted that this has no reference at all to varying profile "shape" (or equivalently "concentration," according to the mathematical definition given in Trujillo et al. 2001, their eqs. [5] and [6]). That is, no reference to departures from the $r^{1/4}$ law, or structural homology, are implied by their terms "compact" and "fluffy." The $r^{1/4}$ law has only a horizontal scale term (r_e) and a vertical scale term (μ_e or μ_0); the shape, or concentration, is exactly the same for all $r^{1/4}$ profiles. Kormendy & Gebhardt (2001) discussed variations in μ_e and r_e when they referred to "compact" and "fluffy." Hence, although M32 is regarded as compact, it's central concentration $C_{r_e}(1/3)$ is actually rather low.

Bekki et al.'s (2001) *N*-body/smooth particle hydrodynamic simulations of tidal interactions between M31 and an orbiting early-type spiral galaxy predict either a complete stripping of the satellite's disk or at least a vertical heating of the disk to create a thick disk. As we have seen, it would appear that a faint disk, with very little gas (Welch & Sage 2001), still surrounds M32. Much of the gas and stars may indeed have been stripped away, resulting in the LSB disk. Also possible is the suggestion by Bekki et al. (2001) that tidal interactions with M31 funneled some of M32's gas to its center, forming a massive starburst (see also Noguchi & Ishibashi 1986). This could account for the excess central flux within the inner $\sim 10''$ of M32 having an age of $\sim$4 Gyr (Vazdekis & Arimoto 1999; del Burgo et al. 2001).

Compact elliptical galaxies are a rare class of objects. A closer inspection of such objects seems warranted in order to inspect whether the species is indeed real or simply a case of misclassification.

I wish to thank Peter Erwin for providing me with Kent's (1987) surface brightness profile of M32, resampled with equal spacing in radius, and for useful discussions. I am also grateful to Carme Gallart and Antonio Aparicio for their comments on this work.

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A negative sign was omitted from the absolute magnitude estimate of M32's bulge. In the last sentence of the fifth paragraph of § 2.1, it should read −16.34.