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DOI: <https://doi.org/10.1088/0004-637X/750/2/121>

Posted at the Zurich Open Repository and Archive, University of Zurich
ZORA URL: <https://doi.org/10.5167/uzh-70060>

Originally published at:

Graham, Alister W; Spitler, Lee R; Forbes, Duncan A; Lisker, Thorsten; Moore, Ben; Janz, Joachim (2012). LEDA 074886: a remarkable rectangular-looking galaxy. *Astrophysical Journal*, 750(2):121-126.
DOI: <https://doi.org/10.1088/0004-637X/750/2/121>

LEDA 074886: A REMARKABLE RECTANGULAR-LOOKING GALAXY

ALISTER W. GRAHAM¹, LEE R. SPITLER, DUNCAN A. FORBES

Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia.

THORSTEN LISKER

Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstraße 12-14, 69120 Heidelberg, Germany.

BEN MOORE

Institute for Theoretical Physics, University of Zurich, Zurich, Switzerland.

JOACHIM JANZ

Division of Astronomy, Department of Physics, University of Oulu, P.O. Box 3000, FI-90014 Oulun Yliopisto, Finland. and
Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstraße 12-14, 69120 Heidelberg, Germany.

Draft version March 19, 2012

ABSTRACT

We report the discovery of an interesting and rare, rectangular-shaped galaxy. At a distance of 21 Mpc, the dwarf galaxy LEDA 074886 has an absolute *R*-band magnitude of -17.3 mag. Adding to this galaxy's intrigue is the presence of an embedded, edge-on stellar disk (of extent $2R_{e,disk} = 12'' = 1.2$ kpc) for which Forbes et al. reported $v_{rot}/\sigma \approx 1.4$. We speculate that this galaxy may be the remnant of two (nearly edge-on) merged disk galaxies in which the initial gas was driven inward and subsequently formed the inner disk, while the stars at larger radii effectively experienced a dissipationless merger event resulting in this 'emerald cut galaxy' having *very* boxy isophotes with $a_4/a = -0.05$ to -0.08 from 3 to 5 kpc. This galaxy suggests that knowledge from simulations of both 'wet' and 'dry' galaxy mergers may need to be combined to properly understand the various paths that galaxy evolution can take, with a particular relevance to blue elliptical galaxies.

Subject headings: galaxies: formation — galaxies: individual (LEDA 074886) — galaxies: kinematics and dynamics — galaxies: peculiar — galaxies: structure

1. INTRODUCTION

In the universe around us, the overwhelming majority of bright galaxies exist in one of three main forms (Sandage 1961). Many, including our own Milky Way galaxy, are in the shape of a flattened circular disk, typically hosting a spiral pattern of stars and a central bulge. A significant number of galaxies are shaped something like an ellipsoidal football, while the remaining few are lumpy and irregular in appearance. Pushing into the dwarf galaxy regime, while many elliptical and lenticular dwarf galaxies exist, the spiral galaxies tend to give way to more irregular looking galaxies without a clear symmetry or form.

We have discovered an exceedingly rare example of a rectangular-shaped galaxy, which may be unique for its luminosity. LEDA 074886 ($\alpha = 03^{\text{h}} 40^{\text{m}} 43.2^{\text{s}}$, $\delta = -18^{\circ} 38^{\text{m}} 43^{\text{s}}$: J2000) resides within the hot gas halo of the massive, spherical galaxy NGC 1407 (E0), with a projected separation of ~ 50 kpc from this giant galaxy's core. LEDA 074886, which we affectionately call the "emerald cut galaxy" given its striking resemblance to an emerald cut diamond, is the 25th brightest galaxy within the NGC 1407 Group of over 250 galaxies (Trentham, Tully, & Mahdavi 2006).

2. DATA AND ANALYSIS

¹ Corresponding Author: AGraham@astro.swin.edu.au

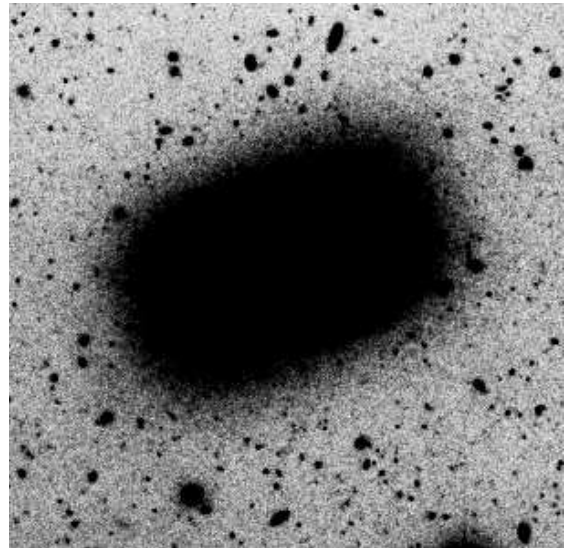


FIG. 1.— A 120×120 arcsecond ($\sim 12 \times 12$ kpc) *i*-band image of LEDA 074886. North is up and East is left. NGC 1407 is located ~ 50 kpc to the NW.

At a distance of 21 Mpc (Spolaor et al. 2008), LEDA 074886 has an apparent (and absolute) *R*-band brightness of 14.3 (and -17.3) mag (Trentham et al. 2006), roughly corresponding to a stellar mass of $10^9 M_{\odot}$ (see Forbes et al. 2011, their section 9.1). The associated spatial scale is such that $1'' = 101$ pc.

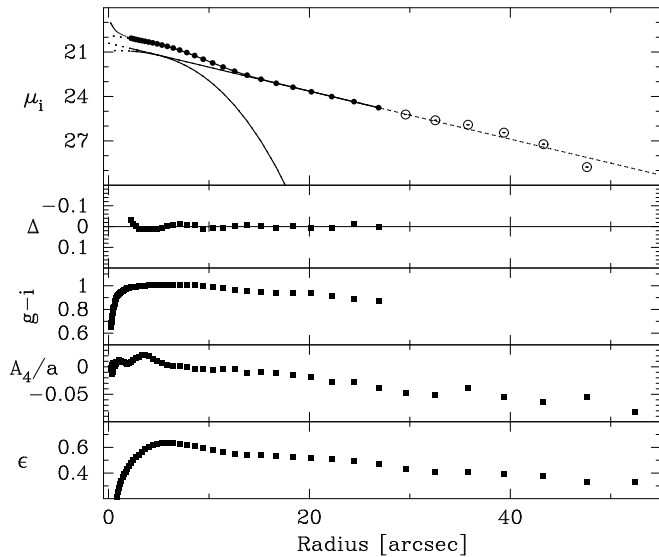


FIG. 2.— Major-axis, i' -band light-profile for LEDA 074886 fit with a Sérsic model ($n_{\text{inner}} = 0.4$, $R_{\text{e,inner}} = 5.9''$, $\mu_{\text{e,inner}} = 21.4$ mag arcsec $^{-2}$) for the inner embedded disk, plus an exponential model for the outer host galaxy ($h_{\text{outer}} = 6.7''$, $\mu_{0,\text{outer}} = 20.4$ mag arcsec $^{-2}$ $\rightarrow R_{\text{e,outer}} = 11.2''$, $\mu_{\text{e,outer}} = 22.2$ mag arcsec $^{-2}$). An additional nuclear component is present, but has been excluded from the fit over the inner $2''$. The residuals Δ about the fit are shown in the second panel. The $g' - i'$ colour, A_4/a boxiness parameter, and ellipticity are shown in the subsequent panels. The scale is such that $10'' = 1.01$ kpc, which is roughly the galaxy's major-axis half-light radius.

The unusual shape of LEDA 074886 was discovered by us in deep i' -band exposures acquired with the Suprime-Cam imager (Miyazaki et al. 2002) on the Subaru 8 m Telescope. Figure 1 reveals the remarkable rectangular nature of the periphery of this galaxy.

The ELLIPSE task in IRAF was used to extract this galaxy's major-axis surface brightness profile. In so doing, the centre was held fixed while the ellipticity and position angle were allowed to vary. Due to the background gradient of halo light from the nearby giant galaxy NGC 1407, the light from NGC 1407 was first modelled and subtracted from the Suprime-Cam image. This was achieved by first subtracting a constant sky-background level determined from galaxy-free regions of the image, then masking objects around NGC 1407 before running ELLIPSE on NGC 1407, and then subtracting this model of NGC 1407 prior to modelling LEDA 074886 itself. The resultant light profile for LEDA 074886 is shown in Figure 2, where it is apparent that this is not a simple one-component galaxy that can be described by a single-component Sérsic model. As revealed by Forbes et al. (2011), the galaxy possesses an embedded, edge-on stellar disk extending to $\sim 12''$. We have therefore modelled the galaxy's distribution of light with an extended inner and outer component. We avoided the inner three seeing disks ($3 \times 0''.7$) because the galaxy is additionally nucleated (see Forbes et al. 2011). Although we have modeled the light profile from 2 – $27''$, the extrapolated fit provides a good description to at least $\approx 45''$ where $\mu_{i'} = 28$ mag arcsec $^{-2}$ (see Figure 2).

Figure 2 also reveals that the inner disk component is well described with a Sérsic $R^{1/n}$ model. However, as this disk is highly inclined, and given the tendency for dust to be centrally-concentrated in at least large-scale galaxy

disks, it is perhaps not surprising to find that the Sérsic index is ≈ 0.4 , i.e. less than 1 (the value associated with an exponential disk). Allen et al. (2006, their Figure 14) reveal that this is in fact a common result for disks. The outer part of the galaxy, or rather that hosting the inner disk, is found to be well described with an $n = 1$ Sérsic model. While the model parameters are given in the caption to Figure 2, the galaxy's major-axis half-light radius is around $10''$, where the surface brightness is $i' = 21.64$, $r' = 21.97$ and $g' = 22.64$ mag arcsec $^{-2}$ (obtained from additional Suprime-Cam images).

The task ELLIPSE approximates the isophotes using a Fourier series such that

$$I(\theta) = I_0 + \sum_{n=1}^{\infty} (A_n \cos n\theta + B_n \sin n\theta), \quad (1)$$

where θ is the azimuthal angle and I_0 is the average intensity over the ellipse. Within the output of ELLIPSE, the A_4 coefficient to the $\cos 4\theta$ Fourier component is normalised by the semi-major axis length a to give A_4/a , which is used for quantifying the isophotal deviation from an ellipse and is positive (negative) when the isophotes are discy (boxy). The intensity-weighted mean value across a galaxy, typically measured from 2 seeing radii to 1.5 half-light radii, is denoted by a_4/a (see Carter 1978, 1987; Bender et al. 1988; Hao et al. 2006). For reference, typical (non-dwarf) 'boxy' galaxies have $-0.02 < a_4/a < -0.00$, with extreme values reaching as low as -0.04 (e.g. Hao et al. 2006). The inner disk in LEDA 074886 has a peak ellipticity of 0.65 and isophotes with A_4/a peaking at $+0.022$ at $3.5''$ (Figure 2). Beyond where the edge of the inner disk has influence (> 7.5 – $12''$), the A_4/a term becomes increasingly negative (boxy), reaching a value of -0.05 by $30''$ and -0.08 by $52''$ at which point the galaxy light appears to truncate rapidly.

We additionally have Echelle Spectrograph and Imager (ESI; Sheinis et al. 2000) spectra obtained with the Keck Telescope. As detailed in Forbes et al. (2011), this has revealed solid body rotation indicating the presence of a central stellar disk (or bar) which reaches a rotation velocity of 33 ± 10 km s $^{-1}$ by a radius of ~ 5 arcseconds (Figure 3b). This inner most component is evident in Figure 3a, in which we have adjusted the contrast levels to display this embedded feature.

3. RELATIVE RARITY

In this section we attempt to at least qualify how rare the rectangular shape of the emerald cut galaxy is. While common wisdom holds that the Universe tends not to build square-looking galaxies, there have not been many large quantitative studies on the boxiness of galaxy isophotes. Jiang et al. (2011, their Figure 11) did however present single, galaxy average, indices for 111 galaxies, while Liu et al. (2008, their Figure 10) presented single values for 85 brightest cluster galaxies (BCGs) plus 244 non-BCG early-type galaxies. In general, a_4/a was observed to be confined to > -0.02 . Possibly the largest study to date looking at the distribution of a_4/a parameters is Hao et al.'s (2006) analysis of 847 luminous early-type galaxies, in which the bulk have $a_4/a > -0.01$, with just 2.2% of the sample having $-0.02 < a_4/a < -0.01$. However, due to radial changes, i.e. gradients, in the boxiness of isophotes, a single boxy parameter such as a_4/a can be somewhat limited, and will miss identifying ex-

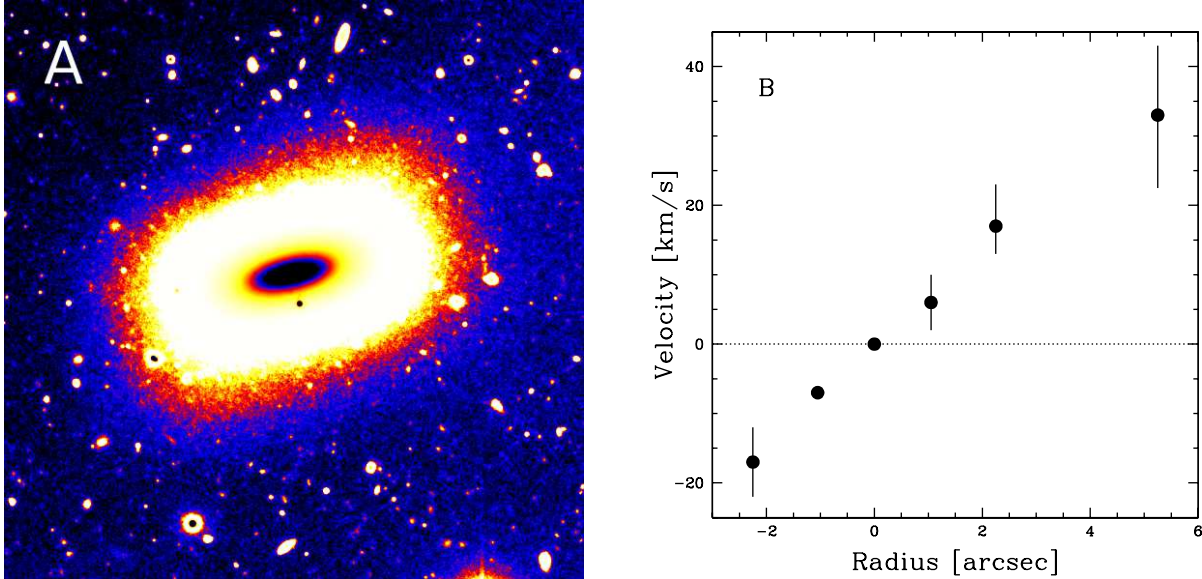


FIG. 3.— Panel A: False-color image of LEDA 074886, taken with Suprime-Cam at the Subaru Telescope. The central contrast has been adjusted to reveal the inner disk/bar-like component. For reference, the major-axis of the boxy outer red annulus spans 3.2–3.8 kpc, while the outer-edge of the outer-most blue annulus has a major-axis of 5.2 kpc. Panel B: Central rotation curve, taken with ESI at the Keck Telescope, from a slit placed across the disk of the galaxy; no data is available beyond ~ 3 arcseconds (300 pc) in the SE (bottom left) direction. Profile adapted from Forbes et al. (2011, their Figure 6).

tremely boxy galaxies if only their outer isophotes are boxy, as is the case with LEDA 074886.

Deep photometry of NGC 3628 reveals an edge-on disk galaxy with outer isophotes displaying a rectangular-shaped thick disk, see also NGC 4370 (=VCC 758) and NGC 4638 (=VCC 1938). From Ferrarese et al.’s sample of 100 early-type Virgo cluster galaxies, NGC 4638 has the most boxy isophotes, with $a_4/a \sim -0.04$. Although whether these three examples of disk galaxies, rather than of galaxies with embedded disks, can evolve into something like LEDA 074886, or vice-versa, is unclear.

The boxiness of our emerald cut galaxy’s outer isophotes may be better appreciated by comparing them with data from 475 early-type Virgo cluster galaxies taken from Janz & Lisker (2008). In Figure 4 we show the location of LEDA 074886’s outer isophotes in the ellipticity–(a_4/a) diagram and the absolute magnitude–(a_4/a) diagram. The values for the Virgo cluster galaxies are roughly the median values from 1.41 to 2.82 R_e , rather than the average value within 1.5 R_e . These values, not published before, have come from the ELLIPSE fits generated in Janz & Lisker (2008). The depth of their Virgo cluster galaxy images prevents an analysis further out than this. In future work we hope to acquire deeper images of the more boxy Virgo galaxies, and determine how their A_4/a profiles behave with increasing radius. It should be noted that the flaring observed at fainter magnitudes in Figure 4 is in part due to the increased measurement errors arising from the reduced signal-to-noise in those galaxy images. In passing it is also noted that the magnitude–(a_4/a) diagram’s branch of ‘disky’ galaxies at $-20 > M_r > -22$ is populated by lenticular galaxies, while the brighter galaxies tend to be boxy (see also, for example, Davies et al. 1983; Carter 1987; Bender et al. 1989; Pasquali, van den Bosch & Rix 2007).

Due to the limited nature of the above comparison, we additionally asked ourselves what are the squarish

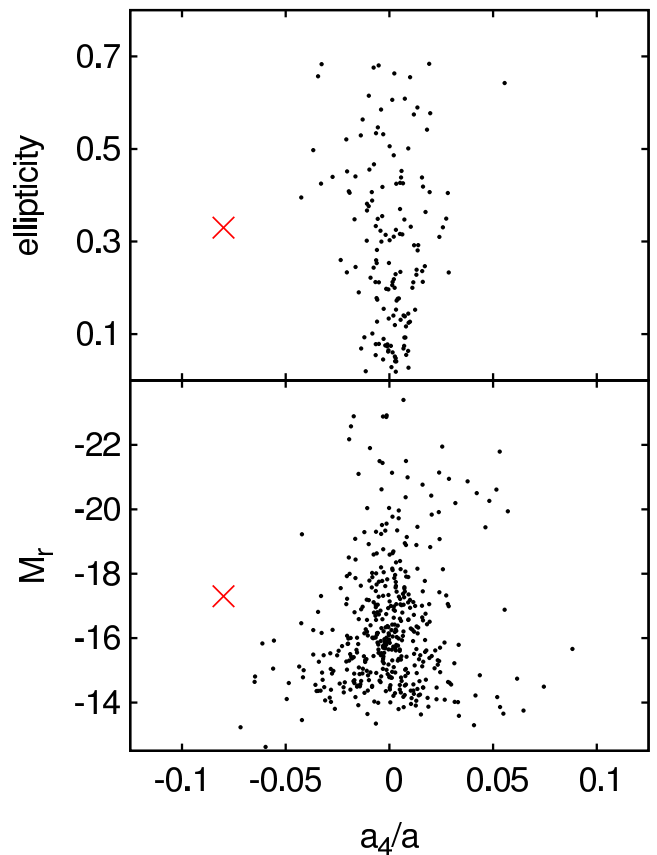


FIG. 4.— The rare nature of LEDA 074886’s rectangular-shape can be seen by contrasting its location, denoted by the cross, with that of Virgo cluster early-type galaxies in the ellipticity–(a_4/a) and magnitude–(a_4/a) diagram. The 475 Virgo cluster galaxies (lower panel) are described in Janz & Lisker 2008. For comparison with similarly bright galaxies, the upper panel shows the 166 Virgo cluster galaxies with $-19 < M_r < -16$ mag. Note: The R -band magnitude for LEDA 074886 (-17.3 mag) has been used here, along with its ellipticity and A_4/a values at $52''$.

galaxies that we know of. Basically, after an extensive literature search, we concluded that there are very few square-looking galaxies known in the universe. So few in fact that it is possible, and we thought that it may be helpful and interesting, to list and contrast them with LEDA 074886. Doing so further highlights the unique nature of this galaxy.

1. The spiral galaxy **SDSS J074018.17+282756.3** has a rather squarish-looking spiral-armed interior, but is quite distinct in form to LEDA 074886 which has no apparent spiral arms and a boxy exterior.
2. A more well known galaxy with a squarish appearance, when looking at the expanding shell of young (<100 Myr) blue stars, is the Local dwarf irregular galaxy **Sextans A** (e.g. van Dyk et al. 1998). However this galaxy is also very different to LEDA 074886, having a much lower mass and density, and no central disk.
3. The blue compact dwarf galaxy **VCC 1699** (e.g. Noeske et al. 2003, their Figure 12) is another rectangular looking galaxy ($a_4/a = -0.04$), although possessing a central comet-like feature with a head-tail structure rather than a rotating disk.
4. The presence of an inner disk in LEDA 074886 suggests that it is not a boxy elliptical galaxy built solely from a dissipationless major merger (e.g. Naab, Burkert & Hernquist 1999), as is thought to be the situation with the diskless, boxy galaxy **NGC 5322** (Bender, Doebereiner, & Möllenhoff 1988). The somewhat rectangular-looking lenticular galaxy **NGC 4270** (=VCC 375) has what appear to be outer shells and it may be another example of a dissipationless merger (e.g. Eliche-Moral et al. 2006; González-García et al. 2009) with warped, boxy outer isophotes (Gamaleldin 1995), but it too has no inner disk.
5. The rectangular / bow-tie shaped galaxy **NGC 4488** (=VCC 1318) also has no inner disk; it additionally has two arms coming off diagonally opposite ‘corners’ of the main galaxy, suggestive of a gravitational tidal disturbance or interaction.
6. The (15 degree) misalignment of the inner disk in LEDA 074886 with the outer rectangle may rule out the possibility that this is a polar ring galaxy like the square-looking **UGC 5119** (Yakovleva & Karataeva 2004).
7. The galaxy with the closest match to LEDA 074886’s appearance is not a dwarf galaxy but the somewhat forgotten **IC 3370** (Schweizer & Ford 1984). It is a relatively luminous ($M_B = -20.5$ mag, Galactic extinction corrected) $R^{1/4}$ early-type galaxy with a half-light radius $R_e = 4$ kpc.

4. DISCUSSION

Efforts to explain the presence of some dwarf spheroidal galaxies within galaxy clusters, from non-primordial origins, have invoked ‘galaxy harassment’

(Moore et al. 1996, 1998, 1999) of disk galaxies. Through this process, close encounters can result in pure disk galaxies developing a strong stellar bar (e.g. Noguchi 1988; Gerin, Combes, & Athanassoula 1990) which remains intact while the remaining outer disk is eventually stripped away by multiple high-speed encounters with other galaxies. Candidates include VCC: 794, 1392, 1400, 1460, 1501, and 1567. When seen face-on, these ‘naked-bars’ can appear rather rectangular (Mastropietro et al. 2005), although slightly more elongated than LEDA 074886. A beautiful example of a real ‘naked bar’ can be seen in Penny et al. (2012, in preparation). However naked bars, when rectangular in appearance, will have their rotation in the plane-of-the-sky, where as LEDA 074886 displays a prominent central “edge-on” disk rotating perpendicular to the plane-of-the-sky.

A dwarf galaxy’s gas can be removed as it ploughs through the hot halo of a massive galaxy, preventing any new star formation. The external tidal perturbation, strongest during the galaxy’s pericenter passages around the massive galaxy, can also trigger a disk instability which generates a bar-like component while also kinematically heating many stars out of the disk plane. The morphological transformation as the disk, and then bar, puff out and partially evaporate, both lowers the average stellar density and can result in the galaxy looking somewhat rectangular (Mayer et al. 2007; Lokas et al. 2010). However this process does not appear to match the morphology of LEDA 074886 with its well-defined embedded disk and outer rectangular morphology. Although cosmological gas inflow, infall events, and secular evolution can create cold embedded disks, this alone would not explain the boxy nature of LEDA 074886’s outer isophotes.

LEDA 074886 at least *resembles* a rotating, vertically-heated disk, i.e. a short cylinder seen side-on, akin to the boxy giant galaxy IC 3370, and if its disk is precessing then it may explain the misalignment with the outer symmetry. Unfortunately LEDA 074886 is too faint for us to acquire dynamical information regarding the rotational state beyond the inner major-axis. As such we are unable to confirm cylindrical rotation, as previously shown for IC 3370, in which the line-of-sight velocity appears constant along lines running parallel to the central rotation axis.

Jarvis (1987a,b) has suggested that IC 3370 may actually be a merger remnant. Like LEDA 074886, it also has an inner disk, but rotating at a speedy ~ 100 km s $^{-1}$. While IC 3370 displays a 25 degree twist, the position angle of LEDA 074886 twists from ~ 100 to ~ 115 degrees when going from the inner disk to the outer regions.

The model by May, van Albada, & Norman (1985) to form peanut/box-shaped bulges supports a scenario in which a cylindrical torque (possibly from a flyby passage of NGC 1407) may have transformed a dwarf elliptical galaxy into a cylindrically-rotating box-shaped galaxy. However the presence of an inner disk in LEDA 074886 suggests that more may be going on than this.

The collision of a disk galaxy with a spheroid-shaped galaxy, or of two appropriately aligned disk galaxies with major-axes possibly pointing towards the corners of the box (Binney & Petrou 1985), may be a better option. Such (near) edge-on mergers, coupled with the right viewing angle, may explain why LEDA 074886 appears

to be so rare. Nonetheless, we advocate the exploration of inner disks, and strong negative A_4/a gradients, in other boxy galaxies such as those plotted in Figure 4 as it may yield new insight into the development of galaxies. The simulations by Naab et al. (2006) which used inclined mergers of 30 degrees generated boxy galaxies. LEDA 074886 may have formed from disks that merged in a plane, coupled with gas that dissipated to form the new inner disk. This dissipation in the plane would preferentially adiabatically contract the long axis of the new galaxy.

Building on the work of Jesseit et al. (2005) and Naab et al. (2006), Hoffman et al. (2010) have revealed how major, i.e. equal mass, mergers of disk galaxies can, in the presence of 15%–20% gas, generate early-type slowly rotating galaxies with kinematically distinct cores. They additionally showed how doubling this gas fraction results in galaxies with sharp embedded disks on the $\sim 1 R_e$ scale, but which resemble dissipationless mergers, i.e. boxy, at large radii not affected by gaseous star formation (see their Section 3.4). Such a hybrid model with star formation in the inner regions of what is effectively a ‘dry’ merger event at larger radii, may be a plausible explanation for LEDA 074886, and IC 3370.

Given LEDA 074886’s velocity dispersion of 23 km s^{-1} (Forbes et al. 2011), one has $v_{\text{rot}}/\sigma \sim 1.4$. Hoffman et al. (2010) report that the inner disks which form in their gas rich 1:1 disk galaxy merger remnants have v/σ up to ~ 1 , but they note that larger gas fractions (Robertson et al. 2006) can produce faster rotating disks.

If the above scenario is correct, then one would expect the inner disk to be made of younger stars than the surrounding galaxy. Face-on examples of inner disks — not to be confused with the ~ 10 – 100 pc nuclear disks — which are embedded in a spheroidal-shaped galaxy may be found in NGC 2320 ($M_B = -21.7$ mag, Young et al. 2009, see their Figure 5) and in IC 3094 (VCC 213, $M_r = -17.5$ mag) — as seen in the Sloan Digital Sky Survey (SDSS; York et al. 2000) repository². While the nucleus of LEDA 074886 is already exceedingly blue (see Figure 2), one may additionally expect there to be dust reddening of the inner disk light. Assuming that the disk-dominated region of the galaxy is at least as metal-rich as the outer parts, then the flat colour profile (rather than an increasingly red color as one heads into the galaxy centre) across the disk region may be due to a younger mean age for the disk. This may therefore be similar to the situation inferred for the disky elliptical galaxy NGC 821 which reveals a luminosity-weighted age of ~ 4

Gyrs for the disk and ~ 12 Gyrs for the outer spheroidal stars (Proctor et al. 2005). This suggests a recent (few Gyrs) dissipative gas event that led to the formation of new disk stars.

Martig et al. (2009) discussed how red elliptical galaxies containing gas disks, like NGC 2320 mentioned in the preceding paragraph, may turn into blue elliptical galaxies under certain conditions. Driver et al. (2007) have shown that these are relatively rare objects, making up just 1.5% of the galaxy population brighter than $M_B = -17$ mag, while Lee et al. (2008) report a value of 4% using SDSS DR4 data. It is hard not to speculate on the connections between elliptical galaxies with blue cores (e.g. Im et al. 2001; Ann 2010) and the presence of inner disks, and it would be of interest to take a closer look at the blue spheroids found by Driver et al. (2007). If such galaxies have inner disks which are dynamically heated and effectively evaporated by the outer spheroid, and if these disk stars fade to produce a normal red elliptical galaxy, then one may wonder how many local red elliptical galaxies are descendants of such high- z blue elliptical galaxies (e.g. Shioya & Yamada 2002) formed from hybrid wet/dry merger events (e.g. Carpineti et al. 2012) not involving a galaxy-wide star burst.

5. ACKNOWLEDGMENT

We are grateful to Nicola Pastorello for his assistance and input. AWG is supported by Australian Research Council funding (DP110103509 and FT110100263). TL is supported within the framework of the Excellence Initiative by the German Research Foundation (DFG) through the Heidelberg Graduate School of Fundamental Physics (grant number GSC 129/1). JJ acknowledges the support of the Gottlieb Daimler and Karl Benz Foundation and the Academy of Finland. AWG, DAF and LRS acknowledge financial support from the Access to Major Research Facilities Programme which is a component of the International Science Linkages Programme established under the Australian Government’s innovation statement, Backing Australia’s Ability. Based in part on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan, awarded via Gemini Telescope time swap program GN-2006B-C-18, and at the W.M. Keck Observatory, which is operated by the California Institute of Technology, the University of California and the National Aeronautics and Space Administration.

² www.sdss.org

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