LED 074886: A REMARKABLE RECTANGULAR-LOOKING GALAXY

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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 $2 R_e,_{\text{disk}} = 12'' = 1.2$ kpc) for which Forbes et al. reported $v_{\text{rot}}/\sigma \approx 1.4$. 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.

Key words: 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 ($R = 0.33^\circ 40^\prime 43^\prime 2, \delta = -18^\circ 38^\prime 43^\prime 1; J2000$) resides within the hot gas halo of the massive, spherical galaxy NGC 1407 (E0), with a projected separation of $\sim 50$ 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 et al. 2006).

2. DATA AND ANALYSIS

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'' $\approx 101$ pc.

We discovered the unusual shape of LEDA 074886 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 center 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 modeled 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 modeling 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 S´ersic model. As revealed by Forbes et al. (2011), the galaxy possesses an embedded, edge-on stellar disk extending to $\sim 12''$. We therefore modeled 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" to 27", the extrapolated fit provides a good description to at least $\sim 45''$ where $\mu_{i'} = 28$ mag arcsec$^{-2}$ (see Figure 2).

Figure 2 also reveals that the inner disk component is well described with a S´ersic $R^{1/n}$ 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 S´ersic index is $\approx 0.4$, 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 $n = 1$ S´ersic 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

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

where $\theta$ 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 normalized 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 disky (boxy). The intensity-weighted mean value across a galaxy, typically measured from 2 seeing radii to 1.5 half-light radii, is denoted by $a_k/a$ (see Carter 1978, 1987; Bender et al. 1988; Hao et al. 2006). For reference, typical (non-dwarf) “boxy” galaxies have $−0.02 < a_k/a < −0.00$, 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 Echellette 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 $33 \pm 10 \text{ km s}^{-1}$ by a radius of $≈5 \text{ arcsec}$ (Figure 3(b)). This innermost component is evident in Figure 3(a), 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, $a_k/a$ was observed to be confined to $>−0.02$. Possibly the largest study to date looking at the distribution of $a_k/a$ parameters is Hao et al.’s (2006) analysis of 847 luminous early-type galaxies, in which the bulk have $a_k/a > −0.01$, with just $2.2\%$ of the sample having $−0.02 < a_k/a < −0.01$. However, due to radial changes, i.e., gradients, in the boxiness of isophotes, a single boxy parameter such as $a_k/a$ can be somewhat limited, and will miss identifying extremely 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 (2006) sample of 100 early-type Virgo cluster galaxies, NGC 4638 has the most boxy isophotes, with $a_k/a \sim −0.04$. 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–($a_k/a$) diagram and the absolute magnitude–($a_k/a$) 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 $a_k/a$ 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 ratio in those galaxy images. In passing it is also noted that the magnitude–($a_k/a$) diagram’s branch of “disky” galaxies at $−20 > M_ > −22$ 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 et al. 2007).
Figure 3. (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 annulus spans 3.2–3.8 kpc, while the outer-edge of the outermost blue annulus has a major-axis of 5.2 kpc. (b) Central rotation curve, taken with ESI at the Keck telescope, from a slit placed across the disk of the galaxy; no data are available beyond ∼3 arcsec (300 pc) in the SE (bottom left) direction. Profile adapted from Forbes et al. (2011, their Figure 6).

Figure 4. 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–(a4/a) and magnitude–(a4/a) diagrams. 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 A4/a values at 52″.

Due to the limited nature of the above comparison, we additionally asked ourselves what are the squarish 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 from 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 (a4/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 et al. 1999), as is thought to be the situation with the diskless, boxy galaxy NGC 5322 (Bender et al. 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 also 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 deg) 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 et al. 1990) that 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 S. J. 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; Łokas 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, 1987b) 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 $\sim 100$ km s$^{-1}$. While IC 3370 displays a 25 deg twist, the position angle of LEDA 074886 twists from $\sim 100$ to $\sim 115$ deg when going from the inner disk to the outer regions.

The model by May et al. (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 toward the corners of the box (Binney & Petrou 1985), may be a better option. LEDA 074886 would then be another example of a dwarf–dwarf galaxy merger (e.g., Martínez-Delgado et al. 2012). 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 $A_d/a$ 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 deg 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 kinematically distinct cores. 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, IC 3370, and possibly also NGC 3377 (e.g., Peletier et al. 1990).

Given LEDA 074886’s velocity dispersion of 23 km s$^{-1}$ (Forbes et al. 2011), one has $v_{rot}/\sigma \sim 1.4$. Hoffman et al. (2010) report that the inner disks which form in their gas rich 1:1 disk galaxy merger remnants have $v/\sigma$ up to $\sim 1$, 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 $\sim 10$–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, $M_B = −17.5$ mag)—as seen in the Sloan Digital Sky Survey (SDSS; York et al. 2000) repository.5 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 color profile (rather than an increasingly red color as one heads into the galaxy center) 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 diskly elliptical galaxy NGC 821 which reveals a luminosity-weighted age of $\sim 4$ Gyr for the disk and $\sim 12$ Gyr for the outer spheroid stars (Proctor et al. 2005). This suggests a recent (few Gyr) dissipative gas event that led to the formation of new disk stars.

5 www.sdss.org
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 DR-4 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.

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