

The Halos and Environments of Nearby Galaxies (HERON) survey

IV. Complexity in the boxy galaxies NGC 720 and NGC 2768

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ABSTRACT

The shapes of galaxies, their outer regions in particular, are important guideposts to their formation and evolution. In this work, we report on the discovery of strongly box-shaped morphologies of the otherwise well-studied elliptical and lenticular galaxies NGC 720 and NGC 2768 from deep imaging. The boxiness is strongly manifested in the parameter shape A_4/a of -0.04 in both objects, and significant center shifts of the isophotes of $\sim 2\text{--}4$ kpc are also seen. One reason for such asymmetries commonly stated in the literature is a merger origin, although the number of such cases is still sparse, and the exact properties of the individual boxy objects are highly diverse. Indeed, for NGC 2768, we identify a progenitor candidate (dubbed “Pelops”) in the residual images, which appears to be a dwarf satellite that is currently merging with NGC 2768. At its absolute magnitude of M_r of -12.2 mag, the corresponding Sersic radius of 2.4 kpc is more extended than those of typical dwarf galaxies from the literature. However, systematically larger radii are known to occur in systems that are in tidal disruption. This finding is bolstered by the presence of a tentative tidal stream feature on archival GALEX data. Finally, further structures in the fascinating host galaxy include rich dust lanes and a vestigial X-shaped bulge component.

Key words. galaxies: formation – galaxies: halos – galaxies: individual: NGC 720, NGC 2768 – galaxies: interactions – galaxies: elliptical and lenticular, cD – galaxies: structure

1. Introduction

The morphology of a galaxy holds important clues about its formation and evolutionary processes, be it in the spiral versus elliptical dichotomy, as prominently illustrated in the Hubble tuning fork and its extensions (Hubble 1926; de Vaucouleurs 1959), or via including irregular objects that are often the result of past or ongoing tidal interactions or mergers (Arp 1966; Tal et al. 2009). One particular case is represented by galaxies with isophotes that significantly deviate from smooth ellipses¹. The most extreme deviations can tend toward a “disky” ($A_4/a > 0$) or a “boxy” ($A_4/a < 0$) shape. Graham et al. (2012) report on a rectangular dwarf galaxy (LEDA 074886; $M_R = -17.3$ mag) with a very high negative boxiness parameter ranging from $A_4/a = -0.05$ to -0.08 between 3 and 5 kpc, which they dubbed the “Emerald Cut Galaxy” (hereafter, ECG). One possible reason for the boxiness of ECG discussed in their work is the edge-on merger of two spiral galaxies. However, Graham et al. (2012) emphasized

that there are only a few highly boxy examples known in the literature, yet their shapes are diverse, and accordingly, pinning down one single formation channel is unrealistic. This picture has hardly changed in the literature over the past decade.

In this work, we report on the discovery of boxy morphologies in the halos of two otherwise well-studied galaxies in the Local Volume, NGC 720 (E5) and 2768 (E6/S0), each with stellar masses of a few $\times 10^{11} M_\odot$ (Rembold et al. 2005; Forbes et al. 2012; Pastorello et al. 2014). Rich et al. (2019) lists their halo shape as “boxy” and “round”, respectively, purely based on visual inspection. Prompted by previous shallower works that did not detect any peculiarities in these objects, this begs the question of whether their boxiness is an intrinsic property of the individual galaxy or if it might represent the general presence of disks or other substructures (e.g., Pasquali et al. 2007). To investigate this question, we employed new deep imaging from the Halos and Environments of Nearby Galaxies (HERON) survey (Rich et al. 2019), bolstered by archival data from the Sloan Digital Sky Survey (SDSS), and the Galaxy Evolution Explorer (GALEX; Bianchi & GALEX Team 2000; Morrissey et al. 2007) to investigate the shapes of those two particularly boxy galaxies. This paper is organized as follows: In Sect. 2, we describe the images that are the basis of our study. Sect. 3 is dedicated to the structural analysis of the two galaxies. Finally, we discuss our findings in terms of the formation histories of each object in Sect. 4.

¹ Commonly quantified in terms of the fourth-order Fourier parameter in an isophote analysis, the nomenclature of these parameters differs among the literature. Here, we follow the internal naming of our used IRAF ellipse task, which denotes the isophote-intensity weighted fourth moment (B_4/a) as A_4/a (e.g., Bender & Moellenhoff 1987; Jedrzejewski 1987; Bender et al. 1988, 1989) and the third moment (B_3/a) as A_3/a .

2. Observations: Centurion 28 imaging

Out of the sample of 119 HERON galaxies, the two objects of this study were chosen by eye based on their optical appearance and indications of boxiness. In the following, we briefly introduce the two datasets employed in our structural analysis.

The images used in this work were taken as part of the HERON survey, and details of their reduction are given in Rich et al. (2019) alongside a general characterization of the galaxies, for instance in terms of their halo sizes. Imaging for the two targets was acquired in October and November 2011 with the 28-inch Centurion (C28) telescope at the Polaris Observatory Association in Lockwood Valley, California (Rich et al. 2012, 2019; Brosch et al. 2015; Koch et al. 2017). The pixel scale of the detector is $0.82'' \text{ pixel}^{-1}$, which for NGC 720 has been resampled by a factor of two in either dimension. This corresponds to 218 and 88 pc per pixel at the adopted distances of NGC 720 and 2768, respectively².

The fields around the galaxies were exposed for 13×300 s (NGC 720) and 3×300 s (NGC 2768) using a broadband Astrodon Luminance filter, which has a bandwidth from 4000 to 7000 Å and thus effectively acts as a wide Sloan *r*-filter. As a result, the images reach surface brightnesses of 29.9 and 28.9 mag sq. arcsec⁻¹ for NGC 720 and NGC 2768, respectively. The seeing conditions of the observations were rather low, at 6.4'' for NGC 720 and 3.5'' for NGC 2768. Figure 1 shows the full C28 images for each galaxy.

The fundamental coordinate system was attached to the images using the public service³ (Lang et al. 2010), which builds on blind pattern matching. Finally, we obtained the photometric calibration by performing aperture photometry of stellar sources within the images using SExtractor (Bertin & Arnouts 1996) and cross-matching the results to the *r*-band photometry of the 14th data release of the Sloan Digital Sky Survey (SDSS DR14; Abolfathi et al. 2018).

3. Analysis

We performed an isophotal analysis of both galaxies using IRAF's "ellipse" task (as was also done by Graham et al. 2012), which fits basic ellipse parameters to the flux with the option to include higher order parameters where our chief focus lies on A_4/a . To prepare the images, stellar sources were masked within IRAF, and we used a 2σ -clipping within ellipse to interpolate over any possible residual flux. The resulting radial profiles of the key shape parameters are shown in Figs. 2 and 4 for each galaxy down to 3σ above the sky. In the following, we discuss the implications of their boxiness and potential formation scenarios. For the case of the surface brightness profile, the magnitudes have been corrected for extinction by $A_r = 0.036$ mag for NGC 720 and $A_r = 0.103$ mag for NGC 2768 (Schlafly & Finkbeiner 2011).

3.1. NGC 720

In the first series of HERON papers, Rich et al. (2019) traced NGC 720 down to a surface brightness of 29.9 mag arcsec⁻² and stated a halo diameter at a flat-rate 28.0 mag arcsec⁻² based on ocular inspection. The respective halo "size" thus extends to

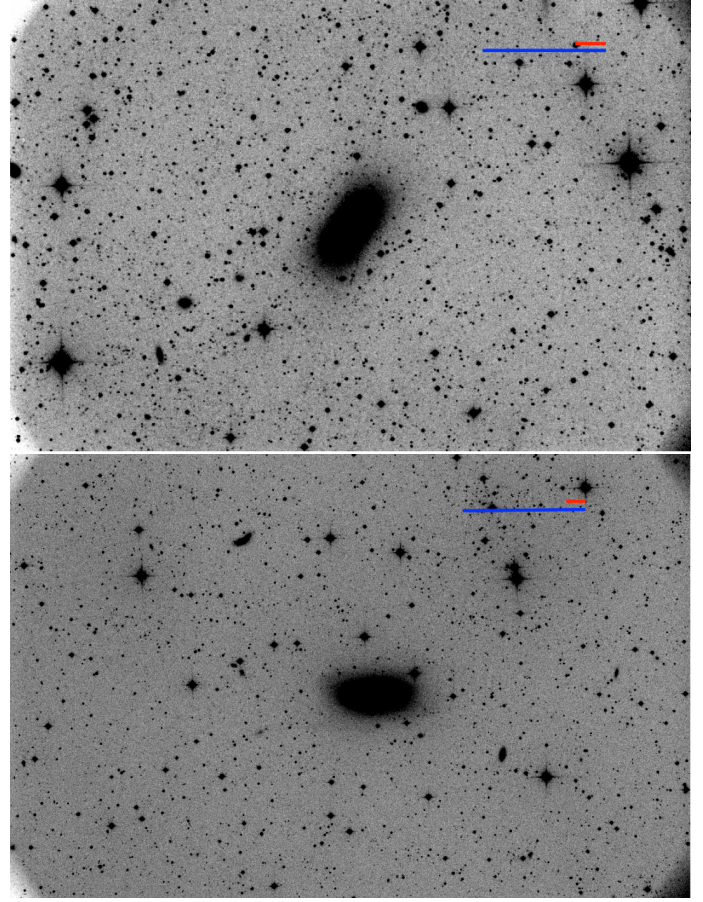


Fig. 1. Full C28 images of NGC 720 (top panel) and NGC 2768 (bottom panel) on a linear stretch. North is up, east is to the left. We also indicate scale bars of 10' (blue line) and 20 kpc (red line) at the adopted distance to the galaxies.

23 times its half-light radius (at 6.7 kpc), and the profile sampled in this work reaches to about 10 half-light radii. We note, however, that our profiles are truncated at a surface brightness of 3σ above the background. NGC 720 has been classified as an E5 galaxy with a total mass of $3.29 \times 10^{11} M_{\odot}$ (Rembold et al. 2005) and only little rotation. Also our ellipticity profile (middle left of Fig. 2) meanders around the corresponding value of $\epsilon \sim 0.4$ –0.6.

Of main interest for our work is the intensity-weighted mean boxiness/diskiness parameter A_4/a . This is typically measured from two seeing radii to 1.5 half-light radii (e.g., Carter 1978, 1987; Bender et al. 1989; Hao et al. 2006; Graham et al. 2012). To guide the eye, galaxies that are labeled "boxy" (excluding dwarfs) have parameters ranging from -0.02 to around zero, with values reported as low as -0.04 (e.g., Hao et al. 2006). The boxiness parameters around -0.04 are effectively rare in the literature. In terms of this parameter, the ECG stands out in having very low values of -0.05 down to -0.08 between 3 and 5 kpc (Graham et al. 2012). The boxy nature of NGC 720 had already been noted by Rich et al. (2019) "by eye" and is now quantitatively confirmed (bottom-left panel of Fig. 2), reaching an A_4/a of -0.04 in its outskirts, which uniquely classifies this galaxy as boxy, albeit to a lesser extent than the ECG.

Moreover, we found a strongly varying center position for NGC 720 throughout the annuli, varying by 10–20 px (~ 2 –4 kpc at the adopted distance). This is likely due to the same event that caused the boxiness of the isophotes, which we conjecture

² The distances were taken as 27.38 Mpc and 22.15 Mpc to NGC 720 and NGC 2768, respectively (see Rich et al. 2019 and references therein).

³ <https://nova.astrometry.net/>

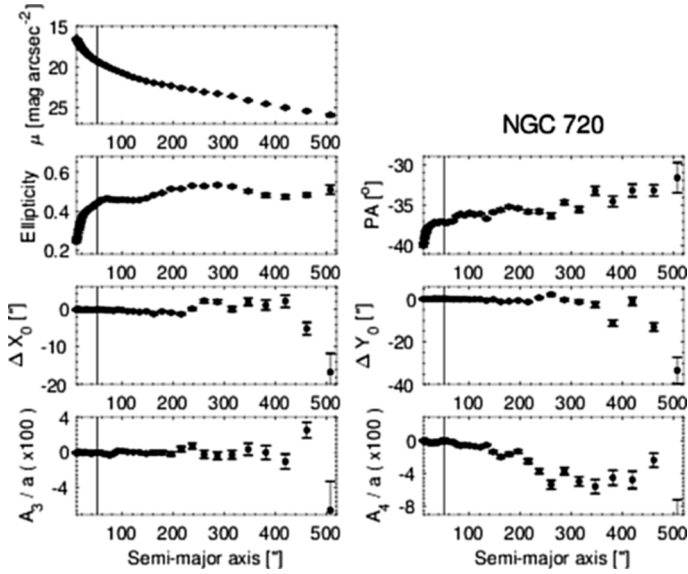


Fig. 2. Photometric and morphological parameters of NGC 720 from ellipse shown as a function of semi-major axis distance. The half-light radius is indicated.

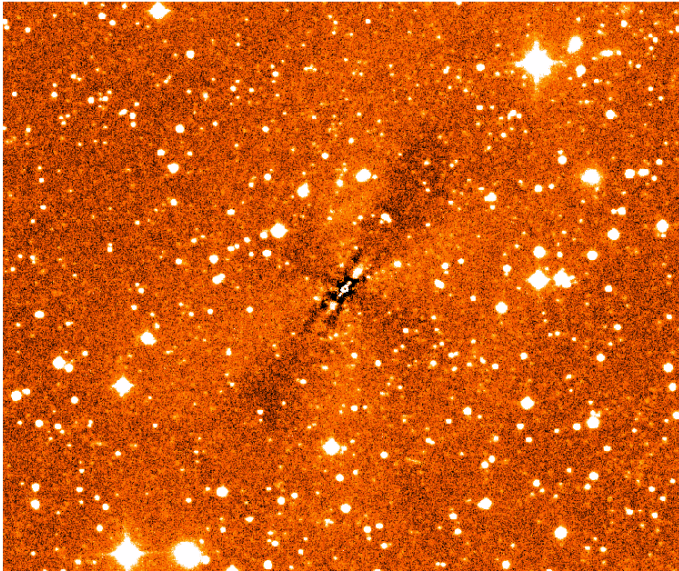


Fig. 3. Model subtracted image of NGC 720 covering $25' \times 20'$. North is up, East is toward the left.

to be a merger (see also Sect. 3.2.2). The residual image (Fig. 3) displays further butterfly-shaped features, which are a common feature if the disk component is not properly modeled and removed, thus revealing complexities in the disk such as dust lanes.

3.2. NGC 2768

This galaxy has been traced down to $28.9 \text{ mag arcsec}^{-2}$ by Rich et al. (2019), and its diameter at the $28 \text{ mag arcsec}^{-2}$ level is reported as 96 kpc, corresponding to ~ 13 effective radii (the latter being 7.6 kpc). In turn, the data we scrutinize cover approximately six half-light radii (above 3σ of the sky) before the background hampered a further meaningful analysis. NGC 2768 already appears boxy to the eye (Fig. 1), which is bolstered by the shape profiles in Fig. 4 (bottom-right panel). The low values

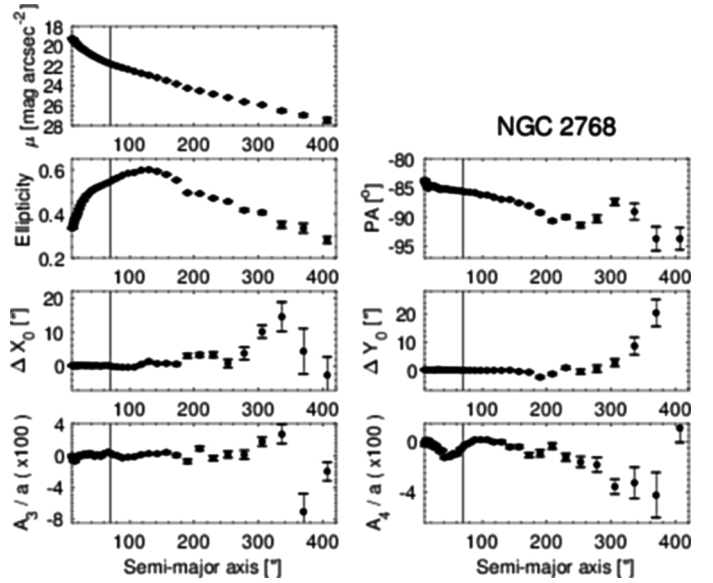


Fig. 4. Same as Fig. 2 but for NGC 2768.

of A_4/a of -0.04 in its outer regions render it a clear contender to be a boxy galaxy. Its nature as a purported lenticular to elliptical (E5) galaxy is also sustained by our derived ellipticity profile (middle-left panel of Fig. 4).

Just as for NGC 720, we found a significant center shift across the full isophotes, amounting to as much as 20 px in the x - and y -direction, which corresponds to ~ 1.8 kpc at the used pixel scale and adopted distance to the target galaxy. In fact, the most pronounced shifts for both galaxies appear after 200–300 arcsec.

A hint of the peculiarity in this galaxy was already found by Pulsoni et al. (2018), who measured the kinematics of planetary nebulae out to $5 R_e$, resulting in a non-point-symmetric distribution. They found this object to be a fast rotator out to large radii, and they quantified its asymmetry with similar parameters to ours (viz., c_4 and s_4 , accounting for sine and cosine projections). Pulsoni et al. (2018) judged these asymmetries as “likely real”, as they have also already been seen in the deep optical images of Duc et al. (2015).

3.2.1. A disk in NGC 2768

A prominent dust lane, visible as black stripes on the model-subtracted image of NGC 2768 (Fig. 5), had already been noted by Kim (1989), and a hint of it can also be seen in our original C28 image (Fig. 1) when using a proper stretch. Moreover, we note the possible presence of a vestigial X-shaped bulge structure that is also known to exist in the Milky Way (McWilliam & Zoccali 2010).

An identical isophotal analysis on the HST data as on our C28 imaging revealed the exact same features. Finally, we note that we also investigated archival SDSS images in the r -band, which confirm the presence of the dust.

3.2.2. The progenitor that built NGC 2768

Figure 6 is the result of masking not only the stars before running ellipse but also the dust features mentioned in Sect. 3.2.1. This model-subtracted image clearly shows the presence of a large plume toward the west of NGC 2768’s center, which we consider to be the ongoing merger that caused the strong distortions of NGC 2768’s isophotes and which we henceforth call

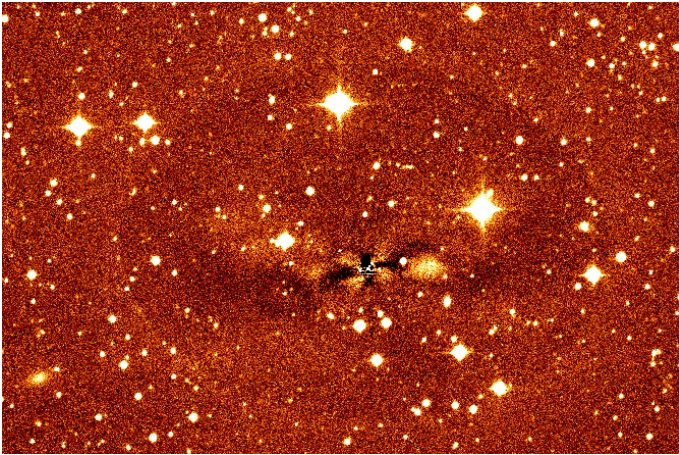


Fig. 5. Model subtracted image of NGC 2768, covering $20' \times 13'$.

“Pelops”⁴. Using GALFIT (Peng et al. 2002), we fitted a Sersic profile to the model-subtracted image. The result of this fit is shown in Fig. 6, and its basic parameters are summarized in Table 1. GALFIT explicitly accounts for the point spread function (PSF) of the images in its fitting so that the stated radii are the ones obtained after deconvolution with the PSF profile. Similarly, this is considered (internally within GALFIT) for the error analysis.

Assuming this blob feature (Casey et al. 2023) to be at the same distance as NGC 2768, we determined its absolute magnitude as $M_r = -12.2 \pm 0.12$ mag. The best-fit Sersic index was determined as 0.37 ± 0.02 , which is rather small and typical of disrupting galaxies and indicates that a simple Sersic modeling is no longer adequate. Furthermore, we determined an axis ratio of 0.55 ± 0.01 and the position angle of Pelops, $88.4^\circ \pm 1.09^\circ$.

To find further evidence of the reality of the merging galaxy, we consulted archival data from the Galaxy Evolution Explorer (GALEX; Bianchi & GALEX Team 2000; Morrissey et al. 2007), which targeted the surroundings of NGC 2768 in the context of the NGA campaign (Gil de Paz et al. 2007) in February 2005. While no detection can be made in the far-UV image, the 182-s exposure in the near-UV clearly depicts the host galaxy (Fig. 7). Furthermore, we note the presence of a vestigial stream and possibly an extension into a further arc to the south of the host galaxy. These are indicated to guide the by eye in the bottom panel of Fig. 7. A natural suspicion is that the structure we see could be a reflection. However, according to the GALEX documentation⁵, ghosts chiefly appear at $30''$ to $60''$ above and below the bright source along the y -direction on the detector. In our case, the arcs appear at a much larger separation of $140''$ with an even larger extent and a shape that does not resemble such ghostly donut shapes. Therefore, we deem it unlikely that the purported stream is an artifact.

3.2.3. Properties of Pelops from SDSS images

The same feature also stands out in identically model-subtracted SDSS images in the g , r , and i bands, confirming that we most likely observed a real feature, although it is fainter in the u

⁴ Son of Tantalos. According to Greek mythology, Pelops was “tidally disrupted” (rather, chopped to pieces) and served for the gods to feast on.

⁵ http://www.galex.caltech.edu/wiki/Public:Documentation/Chapter_8#Ghosts

and z bands. The (lack of) depth of the SDSS prevented us from obtaining any meaningful structural or photometric parameters from GALFIT. However, we performed aperture photometry by simply adding the calibrated flux on each image within one effective radius for both the merger candidate and the host galaxy. The magnitudes were dereddened using the dust maps of Schlafly & Finkbeiner (2011) and the extinction law of Cardelli et al. (1989). We find it is worth noting that both the $g-r$ and $r-i$ colors of both objects are in very good agreement and within the (Poisson) errors.

Based on our photometry, we consulted the E-MILES simple stellar population (SSP) models (Vazdekis et al. 2016), which we computed for an LMC-like metallicity and with the universal initial mass function of Kroupa (2001) for 53 ages between 0.03 Gyr and 14 Gyr. For each age, we varied the intrinsic reddening, A_V , between zero and two in steps of 0.05. Next, we computed the reduced χ^2_ν between the predicted SSP colors and the ones measured from the SDSS images. This resulted in a best-fit age of $6.5^{+5.5}_{-3.8}$ Gyr and an intrinsic reddening of 0.15 ± 0.15 mag. The according mass-to-light (M/L) ratio in the r -band was found to be $1.9^{+1.0}_{-0.9}$ in solar units, which is rather on the low side for a typical dwarf galaxy (e.g., Koch 2009). This would imply, adopting the satellite’s absolute magnitude, a total mass of $\sim 10^7 M_\odot$.

3.2.4. Pelops in context

The surface brightness at the effective radius is fully in agreement with those of dwarf galaxies in various environments (Fig. 8, middle panel). However, at its absolute magnitude, this merging candidate appears too large by a factor of a few, when compared to typical galaxies of similar magnitude. Its corresponding half-light radius is 2.4 ± 0.3 kpc, and an investigation of systematically more extended objects is often used to confirm the presence and absence of tidal disruptions (Koch et al. 2017). Indeed, the contender within NGC 2768 lies within ± 1.5 mag of the strongly disrupted NGC 4449B (Rich et al. 2012) and HCC-087 (Koch et al. 2012) at similarly large radii. We note, however, that the shown literature sample is given in the Johnson-Cousins R -band (and in parts transformed from Sloan g and i band magnitudes; Byun et al. 2020), whereas our value is in Sloan- r and converted from our luminance measurement, so a slight offset in magnitude may be inherent. We further note that we adopted a single Sersic profile, which does not account for tidal features, while other galaxies in the literature may employ other types of profiles, adding to the discrepancy. Two data points in the bottom panel of Fig. 8 are worth mentioning. Firstly, the Local Group dwarf spheroidal And XIX, which is at $M_R = -9.74$ and $R_h = 1.7$ kpc (McConnachie 2012), stands out in the radius-magnitude diagram. Moreover, this ultra-diffuse object is a result of tidal interactions with its host galaxy, M31 (Collins et al. 2020). Secondly, Antlia 2 has been named “an enormous Galactic dwarf satellite”, (Torrealba et al. 2019) and its properties are also indicative of a strong tidal evolution. We therefore concluded that the overdensity is, by effective and absolute magnitude, a common dwarf galaxy in the process of tidal interactions with the host, NGC 2768.

To place the merging galaxy in context, we compared its absolute magnitude with the Local Group dwarf sample (McConnachie 2012). Albeit given in the V -band, the satellite to NGC 2768 appears similar to Andromeda II, which, intriguingly, might be the remnant of a merger itself (Amorisco et al. 2014). Our candidate has a luminosity of $\sim 5 \times 10^6 L_\odot$. Adopting the M/L-ratio determined above, this results in a mass of the dwarf



Fig. 6. Left panel: Pelops-centered image of $1.5' \times 1.3'$ (thus encompassing ~ 4 half-light radii). Middle panel: Best-fit ($\chi^2/\nu = 0.96$) GALFIT model. Right panel: Residual image.

Table 1. Parameters of the NGC 2768 merger candidate, Pelops.

Parameter	Value	Method ^(a)
α	09:11:24.6	G, C28
δ	+60:02:18.2	G, C28
M_R	-12.2 ± 0.2	G, C28
μ_e	22.96 ± 0.01	G, C28
r_e	2.4 ± 0.3 kpc	G, C28
n	0.37 ± 0.02	G, C28
e	0.55 ± 0.01	G, C28
PA	$88.4^\circ \pm 1.1^\circ$	G, C28
u_0	19.19 ± 0.26	A, SDSS
g_0	17.93 ± 0.14	A, SDSS
r_0	17.00 ± 0.09	A, SDSS
i_0	16.65 ± 0.08	A, SDSS
z_0	16.50 ± 0.07	A, SDSS
$(g-r)_0$	0.93 ± 0.17	D
$(r-i)_0$	0.35 ± 0.12	D

Notes. ^(a)G, C28: GALFIT values from our C28 images. A, SDSS: Aperture photometry within r_e on the SDSS residual images. D: Derived.

candidate on the order of $10^7 M_\odot$. If the NGC 2768 merger and And II were of similar type and the present object had the same mass-to-light ratio as And II (~ 20 Côté et al. 1999), this would yield a mass ten times larger, $\sim 10^8 M_\odot$. This is similar to the host galaxy’s (disk plus bulge) mass of $\sim 10^{11} M_\odot$ (Forbes et al. 2012). No matter which M/L is used, we face a minor merger that is still seemingly capable of deforming the structure of the galaxy and inducing many of its morphological and dynamical properties.

4. Discussion

Upon visual inspection of the rich HERON dataset, we detected unusually boxy isophotes of two otherwise well-studied galaxies. Such objects are hitherto rare, and in one case, we could even identify a merger candidate, which we believe has caused the isophotal distortions.

Graham et al. (2012) suggested an edge-on merger of two disk galaxies as the origin of the ECG, one of the most rectangular galaxies known. In their scenario, initial gas was driven inwards and formed an inner disk, while larger radii experienced a dissipationless merger. The “boxiness” parameters of the two well-known objects measured in our study are not as extreme as

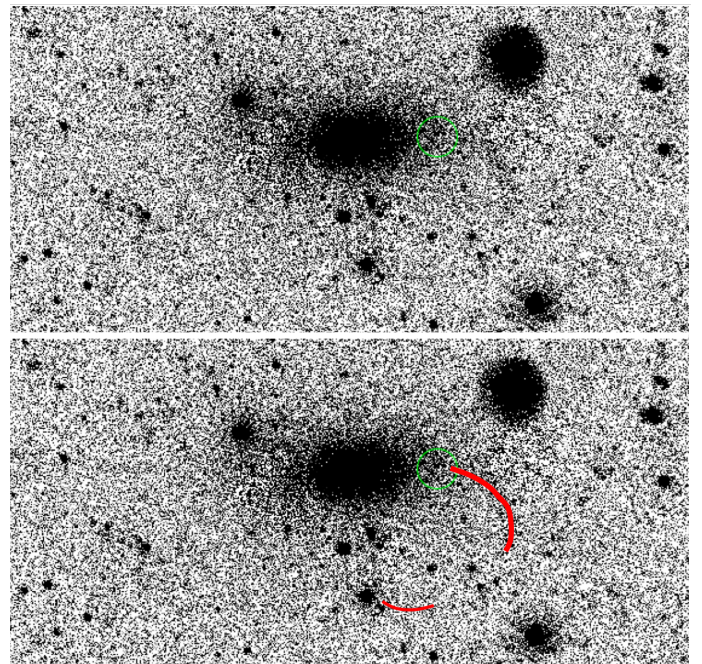


Fig. 7. GALEX NUV image of NGC 2768. The location of the Pelops overdensity identified in Fig. 6 is indicated with a green circle. The purported stream is highlighted by the red lines in the bottom panel. The image covers $14' \times 7'$.

for the ECG (A_4/a of -0.08 versus our -0.04). While no remnant could be identified for NGC 720, a merger origin of its morphology is bolstered by Rembold et al. (2005), who identified this galaxy as an unequal-mass merger remnant based on its kinematics from longslit spectroscopy.

NGC 2768 has been classified as an E5 galaxy (Pastorello et al. 2014) but has also been named E6/S0 (Zanatta et al. 2018; Rich et al. 2019). Early on, it was already found that its gas has different kinematics from the stars in the inner regions (Fried & Illingworth 1994), hinting at a dynamically special history. Similarly, Forbes et al. (2012) performed a bulge-disk decomposition based on various photometric and kinematic tracers (planetary nebulae, stars, and globular clusters) and found that the disk of NGC 2768 rotates rapidly, with its velocity dispersion decreasing with radius. In contrast, the bulge turned out to be pressure supported with only a slow rotation. As the resulting ratio of the disk’s rotational velocity to its velocity dispersion resembles that of a spiral galaxy,

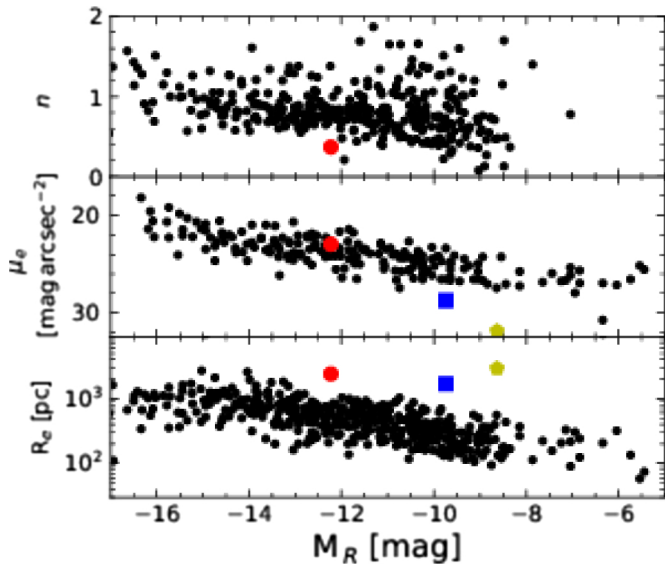


Fig. 8. Location of Pelops (red point) on the magnitude-radius plot (bottom panel) and in relation to the surface brightness at the effective radius (middle panel) and the Sersic-index (top panel). Data from dwarf galaxies in various groups and clusters are shown as black points (Chiboucas et al. 2009; Müller et al. 2015; McConnachie 2012; Muñoz et al. 2015; Park et al. 2017; Byun et al. 2020). Indicated in blue and green are the dwarf spheroidals And XIX and Antlia 2, which are the most extended objects in the Local Group.

Forbes et al. (2012) concluded that NGC 2768 is a transformed late-type galaxy. Similarly, Zanatta et al. (2018), also using globular clusters and planetary nebulae as tracers, noted that NGC 2768’s red (i.e., old) globular cluster system displays rotation, which is most pronounced at inner radii ($R < 1$ kpc), indicating that mergers seem to have played an important role in its history. Overall, lenticular galaxies can evolve from spiral galaxies via various processes that remove most of their gas and erase spiral structures (e.g., Byrd & Valtonen 1990; Bournaud et al. 2005; Zanatta et al. 2018). Interestingly, the ECG also shows a disk-bar-like structure in its very center, where a solid body rotation indicates the presence of a central disk (Forbes et al. 2011; Graham et al. 2012).

An obvious question of interest is how frequent galaxies with such strongly boxy morphologies appear in the (local) Universe. Several similar contenders have been reported in the literature (see Graham et al. 2012 and references therein), although none of them display such boxiness as the ECG. For instance, Bidaran et al. (2020) found boxy isophotes in the Virgo cluster dE galaxy VCC 0608, which also has a severe misalignment between the photometric and kinematic position angles, indicative of a past merger. As Graham et al. (2012) discussed, all boxy galaxies have very individually different properties. In this work, different galaxy types are covered, and head-tail structures and warps have also been identified. As a result, it remains difficult to uniquely identify one tailor-made mechanism to produce boxy isophotes.

Hao et al. (2006) reported that in their sample of nearby early-type galaxies (elliptical and lenticular) from the SDSS, only 19 out of 847 galaxies are boxy (i.e., 2.2%), with $-0.02 < A_4/a < -0.01$, while the remaining 97.8% show disk-like isophotes (i.e., $A_4/a > -0.01$). This fraction is in agreement with the number of boxy early-type galaxies in the Virgo Cluster Catalog (VCC; Binggeli et al. 1985), as identified in Graham et al. (2012) and Bidaran et al. (2020), which adds up to roughly 3%

of the VCC’s population. This highlights that boxy galaxies are still a rare species that await further detections and require more in-depth investigations.

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