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Ubiquitous signs of interactions in early-type galaxies with prolate rotation

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ABSTRACT

Context. A small fraction of early-type galaxies (ETGs) show prolate rotation; that is, they rotate around their long photometric axis. In simulations, certain configurations of galaxy mergers are known to produce this type of rotation.

Aims. We investigate the association of prolate rotation and signs of galaxy interactions among the observed galaxies.

Methods. We collected a sample of 19 nearby ETGs with distinct prolate rotation from the literature and inspected their ground-based deep optical images for interaction signs – 18 in archival images and 1 in a new image obtained with the Milanković telescope.

Results. Tidal tails, shells, disturbed asymmetric stellar halos, or ongoing interactions are present in all the 19 prolate rotators. Comparing this with the frequency of tidal disturbance among the general sample of ETGs of a roughly similar mass range and surface-brightness limit, we estimate that the chance probability of such an observation is only 0.00087. We also find a significant overabundance of prolate rotators that are hosting multiple stellar shells. The visible tidal features imply a relatively recent galaxy interaction. That agrees with the Illustris large-scale cosmological hydrodynamical simulation, where prolate rotators are predominantly formed in major mergers during the last 6 Gyr. In the appendix, we present the properties of an additional galaxy, NGC 7052, a prolate rotator for which no deep images are available, but for which an HST image revealed the presence of a prominent shell, which had not been reported before.

Key words. galaxies: evolution – galaxies: interactions – galaxies: peculiar – galaxies: kinematics and dynamics – galaxies: structure

1. Introduction

Spiral galaxies, as well as most early-type galaxies (ETGs) rotate around their minor axis. A fraction of ETGs show a significant misalignment between the photometric and kinematic axes. We say that a galaxy has prolate rotation when the misalignment is close to 90°; that is, the galaxy appears to be rotating more around the major morphological axis. This type of rotation is also often called “minor-axis rotation” since the gradient of the mean line-of-sight velocity is detected along the projected optical minor axis.

Minor-axis rotation was originally detected in one-dimensional (long-)slit spectroscopic data. Integral field spectroscopy (IFS), that is, two-dimensional observations, reveals more convincing cases of prolate rotation, and IFS surveys enable estimates of the frequency of this phenomenon. In the ATLAS^{3D} project (Cappellari et al. 2011), a complete volume and magnitude-limited sample of 260 ETGs, 3% of galaxies show prolate rotation (Krajnović et al. 2011). In the diameter-selected Calar Alto Legacy Integral Field Area (CALIFA; Sánchez et al. 2012) survey of around 600 ETGs, Tsatsi et al. (2017) find a volume-corrected fraction of prolate rotators of 9%.

Tsatsi et al. (2017) also notice that the fraction of prolate rotators is much higher among ETGs with stellar masses $M_* >$

$2 \times 10^{11} M_{\odot}$, around 27% for both CALIFA and ATLAS^{3D} surveys. The fraction is even higher for very massive ETGs. Krajnović et al. (2018) detect prolate-like rotation in about half of the sample of 25 MUSE Most Massive galaxies (M3G). However, these results are not confirmed by the MASSIVE survey of the 90 most massive ETGs within a distance of 108 Mpc (Ma et al. 2014). Ene et al. (2018) find that only 12% of the MASSIVE galaxies are prolate rotators. They also find that kinematic misalignment likely does not depend on stellar mass within the sample. Nevertheless, they find a dependence on the environment such that the misalignment is more frequent among galaxies in environments with higher galaxy densities.

On the other side of the galaxy-mass range, spectroscopic measurements of individual red-giant-branch stars reveal prolate rotation in two Local Group dwarfs: the M31 dwarf spheroidal (dSph) satellite Andromeda II (Ho et al. 2012; del Pino et al. 2017) and the transition-type dwarf Phoenix (Kacharov et al. 2017).

Kinematics and other observed properties of Andromeda II were reproduced in simulations of mergers of disk galaxies (Łokas et al. 2014; Ebrová & Łokas 2015; Fouquet et al. 2017). Generally, binary-merger simulations are known to be able to produce prolate rotation (e.g., Naab & Burkert 2003; Cox et al. 2006; Hoffman et al. 2010). Ebrová & Łokas (2015) show that

the amount of the prolate rotation in the merger remnants of disky progenitors decreases with the orbital angular momentum of the merger and increases with the disk inclination (with respect to the orbital plane). Similarly, [Tsatsi et al. \(2017\)](#) demonstrate the genesis of prolate rotation in simulations with the disk of one of the merger progenitors perpendicular to the merger orbital plane.

Prolate rotators have been also found in cosmological zoom simulations ([Naab et al. 2014](#)), the large-scale cosmological hydrodynamical simulation Illustris ([Ebrova & Lokas 2017; Li et al. 2018; Bassett & Foster 2019](#)), and the hydrodynamic cosmological Magneticum Pathfinder simulations ([Schulze et al. 2018, 2020](#)). [Schulze et al. \(2020\)](#) examine radial stellar spin profiles and find that they increase with the radius for all 14 prolate rotators in the Magneticum Pathfinder simulations. In these simulations, the merger history of galaxies with increasing profiles is dominated by gas-rich major merging. [Ebrova & Lokas \(2017\)](#) and [Li et al. \(2018\)](#) find that Illustris prolate rotators are formed in relatively recent, mostly major, and rather dry mergers. [Ebrova & Lokas \(2017\)](#) identify a few examples of other formation channels, but basically, all massive prolate rotators were created in major mergers (at least 1:5) during the last 6 Gyr of the Illustris simulation.

The angular momentum of prolate rotation comes mainly from the intrinsic rotation of one (usually the primary) or, sometimes, both merger progenitors ([Ebrova & Lokas 2015, 2017; Tsatsi et al. 2017; Li et al. 2018](#)). The term “prolate” refers to an ellipsoid that is rotationally symmetric around the major axis. The analyses of Illustris galaxies show that prolate rotators have prolate triaxial but never oblate shapes ([Ebrova & Lokas 2017; Li et al. 2018](#)), while oblate-like rotation occurs in the whole range of shapes ([Bassett & Foster 2019; Foster & Bassett 2020](#)).

Based on the Illustris galaxies, [Ebrova et al. \(2021\)](#) predict that the frequency of signs of the recent galaxy merger in host galaxies should be higher for prolate rotation than for kinematically distinct cores (KDCs). According to [Ebrova et al. \(2021\)](#), the KDCs in Illustris are also produced in mergers. The KDC and prolate rotation can even arise simultaneously during the same merger event. However, KDCs can more often have other origins, and if their origin is associated with mergers, the mergers can be minor or ancient.

This work aims to test the predicted association between mergers and prolate rotation among the observed galaxies. We compare a sample of prolate rotators with a reference sample of MATLAS galaxies. MATLAS (Mass Assembly of early Type galaxies with their fine Structures; [Duc et al. 2015; Bilek et al. 2020a](#)) is a deep imaging survey conducted at the 3.6 m Canada-France-Hawaii Telescope (CFHT) using the MegaCam imager. This survey consists of 177 nearby ETGs of ATLAS^{3D} located in environments with low to medium galaxy density; that is, it excludes Virgo Cluster members except for the galaxies at the outskirts of the cluster. The Next Generation Virgo Cluster Survey (NGVS; [Ferrarese et al. 2012](#)) is the complementary in-depth survey covering the entire Virgo Cluster area.

We construct a sample of 19 known observed prolate rotators in Sect. 2.1. In Sect. 2.3, we evaluate the presence of morphological signs of galaxy interaction in ground-based deep optical images and find the signs in all galaxies of our sample. In Sect. 3, we compare the findings with the MATLAS sample and show that the association of signs of galaxy interaction and prolate rotation in our sample is of a high statistical significance. Our work, like many other works, demonstrates the benefits of combining deep optical photometry with IFS for the understanding of the formation of galaxies.

2. Results

2.1. Sample selection

We compiled a sample of 19 nearby galaxies with prolate rotation. Our sample is based on the galaxies listed in [Tsatsi et al. \(2017\)](#), who attempted to gather all the prolate rotators and prolate-rotation candidates known at that time. Their list consists of prolate rotators from ATLAS^{3D}, CALIFA, and several additional galaxies drawn from the previously published literature. We completed the sample with newly published prolate rotators. We did not include the prolate-rotation candidates (i.e., cases where the prolate rotation is not convincingly detected) and galaxies known to have the prolate rotation only in the inner parts, which preferably could be qualified as a large-scale KDC. For a prolate rotator to be included in our sample, the available images of the galaxy need to be sufficiently deep so that we can compare the results with the findings of the MATLAS survey. Images from the DESI Legacy Imaging Surveys (hereafter the Legacy Surveys [Dey et al. 2019](#), see Sect. 2.3) and images of a similar or better surface-brightness limit are considered sufficient.

We selected all the galaxies from ATLAS^{3D} that have a misalignment between the photometric and kinematic axis that is greater than 45° within the error, according to the SAURON data analyses in [Krajnovic et al. \(2011\)](#); these consist of NGC 1222, NGC 4261, NGC 4365, NGC 4406 (M 86), NGC 5557, and NGC 5485. The latter is also a part of the CALIFA sample. We added NGC 4486 (M 87), which included in ATLAS^{3D}, but it does not exhibit convincing prolate rotation in the SAURON data, possibly because of the presence of a KDC. However, using the MUSE spectrograph, [Emsellem et al. \(2014\)](#) reveal NGC 4486 as a convincing prolate rotator.

From the CALIFA sample, we included all the galaxies listed in Table 1 in [Tsatsi et al. \(2017\)](#) except for UGC 10695, which is a possible candidate for prolate rotation, and NGC 6338, which exhibits prolate rotation only in the inner parts of the galaxy. The galaxies included in our sample from CALIFA are the following: NGC 647, NGC 810, NGC 2484, NGC 4874, NGC 5216 (Arp 104), NGC 6173, and PGC 021757 (LSBC F560–04).

Five other galaxies are listed as clear cases of prolate rotation in the introduction of [Tsatsi et al. \(2017\)](#). From those galaxies, we did not include NGC 5982 because the prolate rotation occurs only in the inner parts (see the velocity field from SAURON [Emsellem et al. 2004](#) and OASIS instrument [McDermid et al. 2006](#)). The galaxy instead qualifies as an oblate rotator with a KDC. NGC 7052 ([Wagner et al. 1988](#)) is not included in our sample either because the available images are not comparable with images in our comparison sample drawn from the MATLAS survey. However, we present this prolate rotator, with informative *Hubble* Space Telescope (HST) data, in Appendix A. The galaxies included in our sample from the [Tsatsi et al. \(2017\)](#) introduction are NGC 1052 ([Schechter & Gunn 1979; Davies & Illingworth 1986](#)), NGC 4589 ([Wagner et al. 1988; Moellenhoff & Bender 1989](#)), and PGC 018579 (AM 0609–331; [Moellenhoff & Marenbach 1986](#)).

The recently reported prolate rotators are NGC 7252 and galaxies in the MASSIVE survey. NGC 7252 is revealed as having a clear prolate-rotating component in the stellar velocity field by [Weaver et al. \(2018\)](#); we included this galaxy in our sample. The kinematic misalignment angle of MASSIVE galaxies is published in [Ene et al. \(2018\)](#). To select prolate rotators, we applied the above-mentioned criterion for misalignment. We only accounted for the uncertainties of the kinematic position angles because the errors of photometric position angles are not

Table 1. Sample of prolate rotators.

(1) Name	(2) Other names	(3) Survey	(4) Ψ (deg)	(5) D (Mpc)	(6) M_K (mag)	(7) $\log(M_{JAM})$
NGC 1222		A3D	73 ± 15 ^(a)	33.3 ^(f)	-22.71	10.50 ^(k)
NGC 4261		A3D	74 ± 3 ^(a)	30.8 ^(f)	-25.19	11.72 ^(k)
NGC 4365	VCC 731	A3D	76 ± 7 ^(a)	23.3 ^(f)	-25.20	11.53 ^(k)
NGC 4406	M 86	A3D	81 ± 13 ^(a)	16.8 ^(f)	-25.03	11.60 ^(k)
NGC 4486	M 87	A3D	46 ± 58 ^(a)	17.2 ^(f)	-25.37	11.73 ^(k)
NGC 5557		A3D, MAS	73 ± 6 ^(a)	38.8 ^(f)	-24.87	11.33 ^(k)
NGC 5485		A3D, CAL	80 ± 3 ^(b)	25.2 ^(f)	-23.61	11.06 ^(k)
NGC 0647		CAL	72 ± 3 ^(b)	184 ^(b)	-	(~11.57) ^(b)
NGC 0810		CAL	87 ± 2 ^(b)	110 ^(b)	-25.67	~11.7
NGC 2484		CAL	52 ± 4 ^(b)	192 ^(b)	-26.56	~12.1
NGC 4874		CAL, MAS	86 ± 5 ^(b)	102 ^(b)	-26.19	~12.0
NGC 5216	Arp 104	CAL	66 ± 5 ^(b)	42 ^(b)	-23.25	~10.7
NGC 6173		CAL	80 ± 2 ^(b)	126 ^(b)	-26.14	~11.9
PGC 021757	LSBC F560-04	CAL	57 ± 5 ^(b)	238 ^(b)	-26.79	~12.2
NGC 1052		-	~90 ^(c)	19.4 ^(g)	-24.00	~11.0
NGC 2783	UGC 04859	MAS	76 ± 11 ^(d)	85.8 ^(h)	-25.35	~11.6
NGC 4589		-	~45 ^(e)	22.0 ^(g)	-23.96	~11.0
NGC 7252	Arp 226	-	-	60.1 ⁽ⁱ⁾	-24.59	~11.3
PGC 018579	AM 0609-331	-	-	129 ^(j)	-24.48	~11.2

Notes. (1) The galaxy name in the NGC or PGC catalog; (2) An alternative galaxy name; (3) A3D, CAL, MAS – the galaxy is included in the ATLAS^{3D}, CALIFA, or MASSIVE survey, respectively; (4) Ψ , the misalignment angle between the kinematic and photometric axis, where available; (5) D , the distance of the galaxy; (6) M_K , total galaxy absolute magnitude (see Sect. 2.2); (7) $\log(M_{JAM})$, the dynamical mass of the galaxy – the ATLAS^{3D} value is adopted where possible, the rest are approximate estimates calculated from a M_K - $\log(M_{JAM})$ relation, except for NGC 0647, where the stellar mass estimate from Tsatsi et al. (2017) is listed instead (see Sect. 2.2). ^(a)ATLAS^{3D} (Krajnovic et al. 2011), ^(b)CALIFA (Tsatsi et al. 2017), ^(c)Davies & Illingworth (1986), ^(d)MASSIVE (Ene et al. 2018), ^(e)Moellenhoff & Bender (1989), ^(f)ATLAS^{3D} (Cappellari et al. 2011), ^(g)Tonry et al. (2001), ^(h)MASSIVE (Ma et al. 2014), ⁽ⁱ⁾Theureau et al. (2007), ^(j)Tully et al. (2013), ^(k)ATLAS^{3D} (Cappellari et al. 2013).

published in the paper. Ten MASSIVE galaxies satisfy the criterion. Two of these (NGC 4874 and NGC 5557) are already included in our sample. Three have Legacy Surveys images, but the images of NGC 2258 and NGC 2832 are spoiled with artifacts, so we cannot confidently confirm the presence of tidal structures in these galaxies. The remaining five do not have sufficiently deep images. The only additional prolate rotator from the MASSIVE survey included in our sample is NGC 2783.

Besides the prolate-rotation candidates, the galaxies with only inner prolate rotation, and prolate rotators without sufficient images, we did not include the two Local Group dwarfs with prolate rotation because they are far out of the range of galaxy masses of the reference sample. At the opposite end, the M3G survey targets the most massive galaxies in the densest galaxy environments at $z \approx 0.045$ (Krajnovic et al. 2018). Therefore, we did not include them either. The final sample of 19 prolate rotators is listed in Table 1.

2.2. Sample masses

In this paper, we compare the incidence of the morphological signs of galaxy interactions in these prolate rotators with the incidence in the MATLAS sample. Since the incidence shows a significant dependence on the host galaxy mass, it is important to have a general idea of the mass distribution of galaxies in our sample. The masses of the MATLAS galaxies are expressed as the dynamical mass, $\log(M_{JAM})$, obtained by Jeans anisotropic modeling (Cappellari 2008) within the half-light radius. The

values were derived in Cappellari et al. (2013) from the observed kinematic maps of the galaxies for the whole ATLAS^{3D} sample.

For the prolate rotators outside the ATLAS^{3D} sample, we derive approximate estimates from the total galaxy absolute magnitude, M_K (Col. (6) in Table 1). The value of M_K is computed following the ATLAS^{3D} sample in Cappellari et al. (2011). This is derived from the apparent magnitude K_T (the keyword `k_m_ext`) from the Two Micron All Sky Survey (2MASS) extended source catalog (XSC; Jarrett et al. 2000). Then M_K is calculated as $M_K = K_T - 5 \log_{10} D - 25 - A_B/11.8$, where D is the distance of the galaxy in megaparsecs (Col. (5) in Table 1). The A_B values for the correction for the foreground galactic extinction are adopted from Schlafly & Finkbeiner (2011).

There is a correlation between $\log(M_{JAM})$ and M_K . We fitted the available data of 258 ATLAS^{3D} galaxies with linear regression. The rms of residuals of the fit is 0.15. We used the fitted function to calculate approximate values of $\log(M_{JAM})$ for the rest of the sample (Col. (7) in Table 1). This calculation method was not possible for NGC 647 because the galaxy lacks the `k_m_ext` value in XSC. For this galaxy, we listed the stellar mass estimate from Tsatsi et al. (2017) instead.

We do not want to compare the exact mass distributions of the galaxies. For our purposes, (see Sect. 3.3) it is sufficient to have the general idea that almost all of our prolate rotators have $\log(M_{JAM})$, or its approximate equivalent, greater than 11 with the highest values around 12. Given the precision of our estimates, the maximum is roughly comparable with the MATLAS survey.

2.3. Ubiquitous interaction signs in the sample

In this section, we evaluate the presence of morphological signs of galaxy interactions in the prolate rotators in our sample. We then compare the frequency of the tidal disturbance in prolate rotators with the frequency reported for the MATLAS galaxies (Bílek et al. 2020a) in Sect. 3.3. The images of the prolate rotators that are evaluated in this section come from several sources, but in Sect. 3.1 we establish that all these images have surface-brightness limits similar or worse than the MATLAS images.

In compliance with the MATLAS classification, the signs of galaxy interaction are tidal features (tails, plumes, loops, streams, and stellar shells) and disturbed or asymmetric outer isophotes of the stellar halo. Tails or plumes usually come from a major merger. They are thick, elongated features directly attached to the body of the galaxy in question. Streams are usually thinner, sometimes detached, features typically created by stripping a lower-mass companion galaxy. Shells, also called ripples, are azimuthal arcs centered on the core of the host galaxy, usually with sharp outer edges.

For decades shell galaxies have been believed to result from close-to-radial minor mergers (e.g., Quinn 1984; Dupraz & Combes 1986; Hernquist & Quinn 1988; Ebrova et al. 2012). However, the view about their origin has recently shifted from minor mergers to intermediate-mass (Duc et al. 2015; Ebrova et al. 2020a) or even major mergers (Pop et al. 2018). Three morphological types of shell systems are recognized (Wilkinson et al. 1987, 1990, 2000; Prieur 1990). Type I (“cone” or “aligned”) systems are typically found in galaxies with a higher ellipticity. The shells are interleaved in radius on alternate sides of the galaxy; that is, the next outermost shell usually lies on the opposite side of the galaxy center. They are aligned well with the major photometric axis of the galaxy, mostly confined in a biconical structure. Shell separation increases with radius. Examples of such shells are NGC 810, 2484, 2783, 6173, and PGC 021757 (shown in Fig. 1). Type II (“randomly distributed arcs” or “all round”) have the position angles of the shells randomly distributed all around a somewhat circular galaxy. For example, NGC 5216 (Fig. 1) or the famous NGC 474 (not a prolate rotator). Type III (“irregular”) are shell systems with more complex structures or that have too few shells to be classified.

In the catalog of 137 shell galaxies Malin & Carter (1983), all three types occur in approximately the same fraction (Prieur 1990). Shell systems are appealing because they can be, in principle, used to constrain the time of the merger and the gravitational potential of the host galaxy (Quinn 1984; Dupraz & Combes 1986; Hernquist & Quinn 1987a,b; Merrifield & Kuijken 1998; Canalizo et al. 2007; Sanderson & Helmi 2013; Bílek et al. 2013, 2014, 2015; Ebrova et al. 2012, 2020a,b).

To inspect our sample, we used archival images from the MATLAS survey (Duc et al. 2015; Bílek et al. 2020a¹), the DESI Legacy Imaging Surveys (the Legacy Surveys; Dey et al. 2019²), the Sloan Digital Sky Survey (SDSS), the Burrell Schmidt Deep Virgo Survey (Mihos et al. 2017³), the Halos and Environments of Nearby Galaxies (HERON) survey (Rich et al. 2019), and an image from Wide Field Imager on the MPG/ESO 2.2 m telescope at the ESO La Silla Observatory. One of the galaxies (NGC 4589) was examined in images recently obtained

with the 1.4 m Milankovic telescope mounted at the Astronomical Station Vidojevica in Serbia. We describe the details of the observation in Appendix B. In several cases, we also show complementary images from the HST, but we never use these images as a source to evaluate the tidal disturbance of the galaxies in our sample.

Our findings are summarized below for each galaxy separately. We also added notes to individual galaxies about the presence of other features, such as KDCs and dust lanes, or other relevant information from the literature.

NGC 647

NGC 647 has clear interaction signs, most notably a distinct plume or loop stretching around 80'' to the north that is visible in the Legacy Surveys image (Fig. 1). The galaxy also displays a dust line in the center that is roughly allied with the minor photometric axis. Two close smaller galaxies (one 50'' to the north, the other 25'' to the southeast) are candidates for the surviving cores of the merging secondary galaxies.

NGC 810

NGC 810 is an excellent example of a rich Type I shell system with at least eight shells detected in the Legacy Surveys image (Fig. 1). The galaxy also possesses a prominent dust lane along the minor photometric axis. Around 10'' from the center, close to the dust line, there is a possible surviving core of the merging secondary galaxy.

NGC 1052

NGC 1052 (Fig. 2) is a dominant member of a galaxy group that became popular recently because it hosts NGC 1052-DF2 and NGC 1052-DF4, which are ultra-diffuse galaxies that are supposedly free of dark matter (van Dokkum et al. 2018, 2019).

The numerous signs of interactions in NGC 1052 are summarized in Muller et al. (2019a). Their deep optical image (Fig. 1 in Muller et al. 2019a) uncovers a 10' long stream pointing southeast, a loop in the southwest, and a shell-like structure in the northwest between NGC 1052 and NGC 1047. Moreover, an HI feature in the galaxy center seems to be associated with the optical tidal bridge leading to NGC 1047. The galaxy hosts a faint diffuse kiloparsec-scale dust lane situated roughly along the minor axis (Carter et al. 1983; Davies & Illingworth 1986). The star and gas kinematics are largely (about 66°) misaligned (Davies & Illingworth 1986). Finally, the modeling suggests a starburst in the center 1 Gyr ago due to a recent merger with a gas-rich galaxy (van Gorkom et al. 1986; Pierce et al. 2005).

NGC 1222

NGC 1222 (Fig. 3) has around six shells visible in the MATLAS image. The Type I shell system is somewhat atypical because it has more sharp shells on one (southern) side. There are additional asymmetric faint tidal features in the galaxy outskirts (both north and south). A significant amount of atomic hydrogen was detected in the galaxy and the gas and stellar kinematics are roughly aligned (Young et al. 2018). Abundant, irregularly shaped dust in the inner region tends to lie more along the minor photometric axis. In the MATLAS survey, NGC 1222 is classified as having shells, tails, disturbed outer isophotes, and prominent dust lanes (Bílek et al. 2020a).

¹ <https://obas-matlas.u-strasbg.fr>

² <https://www.legacysurvey.org>

³ <http://astroweb.case.edu/VirgoSurvey/>

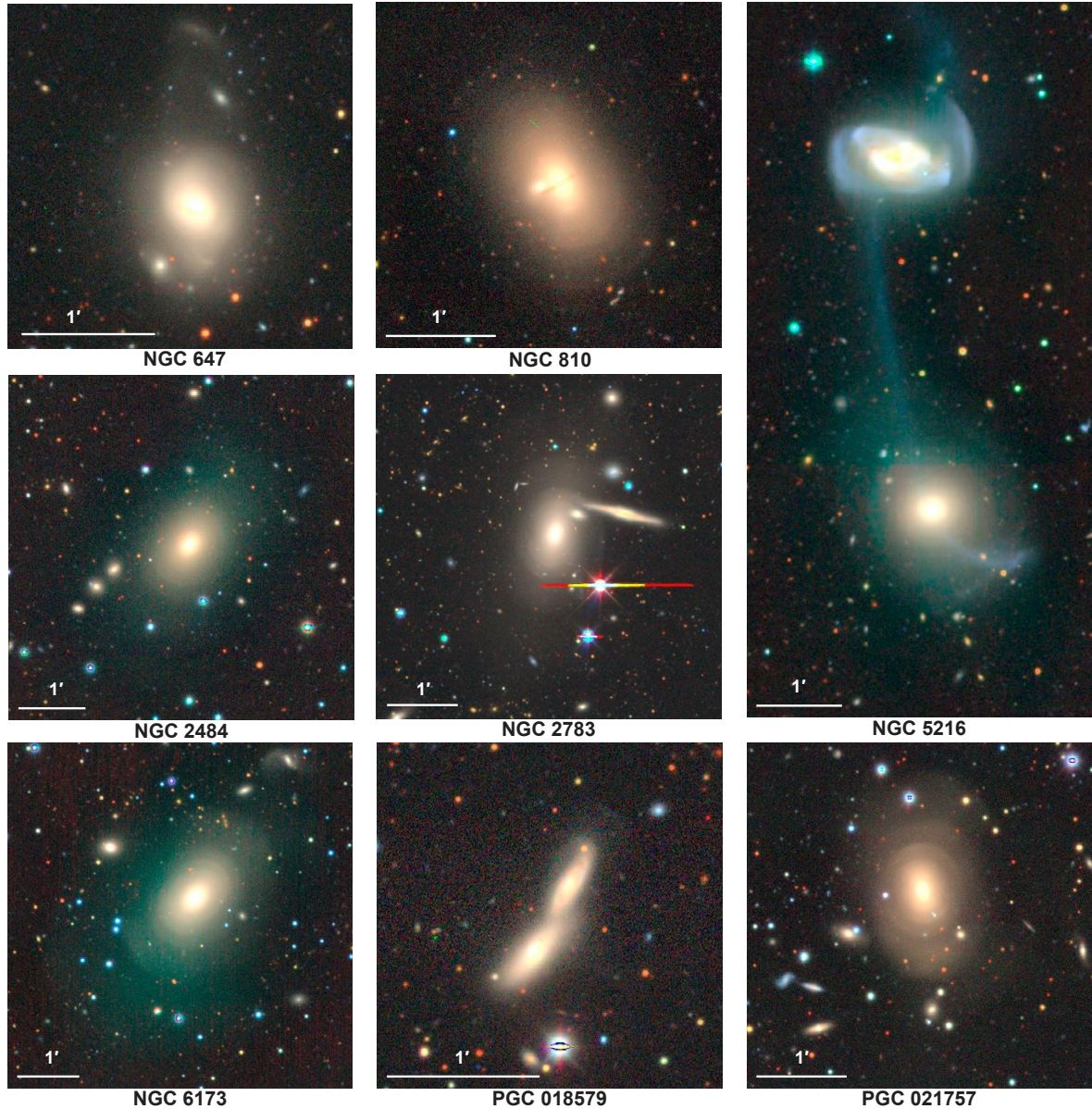


Fig. 1. Images of eight prolate rotators from our sample extracted from the Legacy Surveys. North is up, east is to the left.

NGC 2484

NGC 2484 is a BCG (brightest cluster galaxy) hosting a nice Type I shell system with at least four shells detectable in the Legacy Surveys image (Fig. 1).

NGC 2783

NGC 2783 is the brightest member of a small compact group of five galaxies, Hickson 37 (Rubin et al. 1991; Wiklind et al. 1995). This galaxy is another rich Type I shell system with at least six shells visible in the Legacy Surveys image (Fig. 1). The galaxy also contains a rapidly rotating disk of ionized gas (Calvani et al. 1989).

NGC 4261

NGC 4261 (Fig. 3) is a member of the Virgo cluster located in the outskirts of the cluster. The MATLAS image reveals a

narrow shell or umbrella feature stretching around 9' (29 kpc) to the north and a probable fainter, but wider, shell closer to the center (around 7', 22 kpc) on the other side of the galaxy. The galaxy also has dust lanes situated roughly along the major axis (Moellenhoff & Bender 1987; Mahabal et al. 1996) and a disk of cool dust and gas surrounding the nucleus (Jaffe et al. 1993). In the MATLAS survey, NGC 4261 is classified as having shells and disturbed outer isophotes (Bilek et al. 2020a).

NGC 4365 (VCC 731)

NGC 4365 (Fig. 4) is the dominant galaxy of the Virgo W' group, located ~6 Mpc behind the Virgo Cluster (Mei et al. 2007). The galaxy is long known to have a KDC (Bender 1988; Bender & Surma 1992; Bender et al. 1994; Forbes et al. 1995) and has also been extensively studied through the IFS (SAURON – Davies et al. 2001; Krajnovic et al. 2011 and MUSE – Nedelchev et al. 2019).

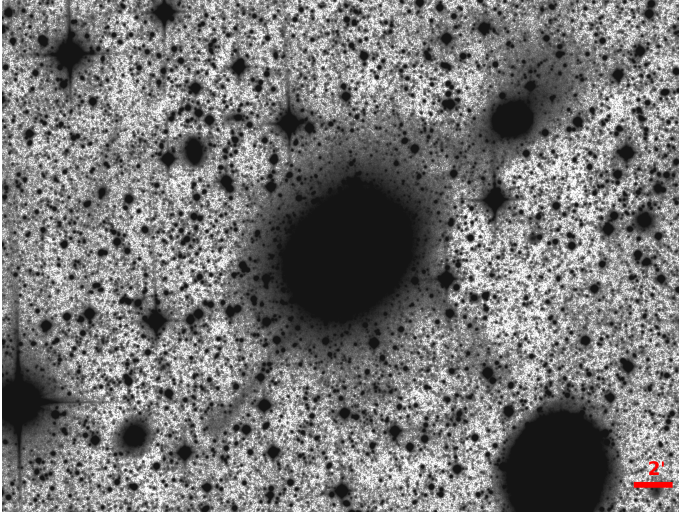


Fig. 2. Negative image of NGC 1052 from the HERON survey (Rich et al. 2019). The data are processed by Javier Román and Oliver Müller.

Several substantial tidal features have been described; Fig. 6 in Bogdán et al. (2012) and Fig. 9 in Mihos et al. (2017) show an asymmetric S plume; a NE loop around $26'$ (146 kpc) from the center; and most notably, a long SW Tail with a diffuse shell-like structure at its ending, around $40'$ (230 kpc) from the center. A companion galaxy, NGC 4342, sits in the middle of the tail. Blom et al. (2012a,b, 2014) studied globular clusters in the system. They find an overdensity of globular clusters in the tail. Their analysis of the colors and kinematics of the globular clusters suggests that they have been tidally stripped from NGC 4342. A similar conclusion is reached by Mihos et al. (2017), analyzing the colors and morphology of the diffuse stellar light of the tail. Moreover, NGC 4342 itself is an outlier on galaxy scaling relations in a way that is consistent with the galaxy being tidally stripped (Blom et al. 2014).

NGC 4406 (M 86)

M 86 is a massive elliptical galaxy in the Virgo cluster. This galaxy is long known to have a KDC (Bender 1988; Bender & Surma 1992; Bender et al. 1994) and has also been studied by IFS (Krajinović et al. 2011).

M 86 is a known shell galaxy (Forbes et al. 1994). A deep image reveals around five shells in the outskirts (see Fig. 5). The stellar halo hosts several other substructures such as several low-surface-brightness filaments, a tidal bridge, stream, and plumes (Mihos et al. 2005, 2017; Janowiecki et al. 2010). Some substructures cannot be safely assigned to M 86 since its halo is partially overlapped, in projection, with the halo of M 84, although the galaxies themselves may be well separated along the line of sight (Mei et al. 2007).

NGC 4486 (M 87)

M 87 is the central BCG of the Virgo cluster. This galaxy does not show convincing prolate rotation in the SAURON data (Krajinović et al. 2011). However, the MUSE spectrograph fully reveals the prolate character of the large-scale rotation and the presence of a KDC (Emsellem et al. 2014).

The extended stellar halo hosts a number of streams (often associated with satellite galaxies in the process of tidal stripping)

and signatures of more massive mergers, as summarized in Mihos et al. (2017). M 87 is long known to have asymmetric outer isophotes (Carter & Dixon 1978). A long ($38'$, 178 kpc) NW stream along the major photometric axis connects the stellar halo to the pair of galaxies NGC 4458 and NGC 4461 (Mihos et al. 2005; Janowiecki et al. 2010; Rudick et al. 2010). In the same direction but closer to the galaxy ($20'$, 90 kpc), there is a shell-like feature, the so-called “cap” or “crown”, which has been discussed frequently (Weil et al. 1997; Longobardi et al. 2015a,b). This feature may be connected to a kinematic substructure discovered in planetary nebulae by Longobardi et al. (2015a). There is also a kinematic substructure in globular clusters reported by Romanowsky et al. (2012). The kinematic substructures suggest a past merger event with a secondary galaxy of a mass of about $10^{10} M_{\odot}$. Besides the crown, there are hints of other diffuse shell-like structures in the direction of the major photometric axis, giving the galaxy an appearance of an almost fade-out Type I shell system, see Fig. 5.

NGC 4589

NGC 4589 is part of a small group. The galaxy also possesses a KDC (Forbes et al. 1995). It was not possible to assess the galaxy from the Legacy Surveys images as a result of the abundance of image artifacts. The left panel of Fig. 6 shows a new deep optical image of NGC 4589 obtained with the 1.4 m Milanković telescope. More details about these observations are available in Appendix B. All the features described below are visible without a model subtraction, but we show the residual image and emphasize the detected substructures.

We cut the original image to remove the noisy edges and smoothed it with a Gaussian function to bring out the faint structures. The right panel of Fig. 6 shows the smoothed residual image of NGC 4589.

Having cleared and masked the original image, we modeled the galaxy via the IRAF ELLIPSE routine⁴. The position angle and central coordinate parameters are set free during the ellipse fitting. We subtracted the model from the cleaned image of NGC 4589 to obtain the residual image. To reveal the faint structures, we smoothed this residual image with the same Gaussian function used for the original image. The cleaning process masks small and faint objects in the image. We did not take into account these masked regions during the ellipse fitting routine. After the ellipse fitting, we filled these masked regions with random pixel values drawn from a Gaussian distribution for cosmetic reasons. We determined the Gaussian distribution from a limited area surrounding the faint and small objects. However, the resulting mask seems like a disk-like artifact if the surrounding area contains a bright pixel.

There is a cirrus (a foreground dust cloud situated in our Galaxy) $7'$ to the west from the galaxy center (near the right side of the images in Fig. 6). This feature is at the border of a group of other cirri (outside the image), showing a typical morphology with filamentary substructures (Duc et al. 2015), similar to other cirri in the area, and all these structures are visible in the WISE 12-micron dust map. We do not consider this feature to be a sign of galaxy interaction.

On the east side, $3.6'$ from the center, there is a linear structure that is nearly perpendicular to the major photometric axis of the galaxy. It is denoted as a “stream” in the right panel of Fig. 6. This feature does not look like a cirrus; it is far from the group of

⁴ Image Reduction and Analysis Facility <http://ast.noao.edu/data/software>

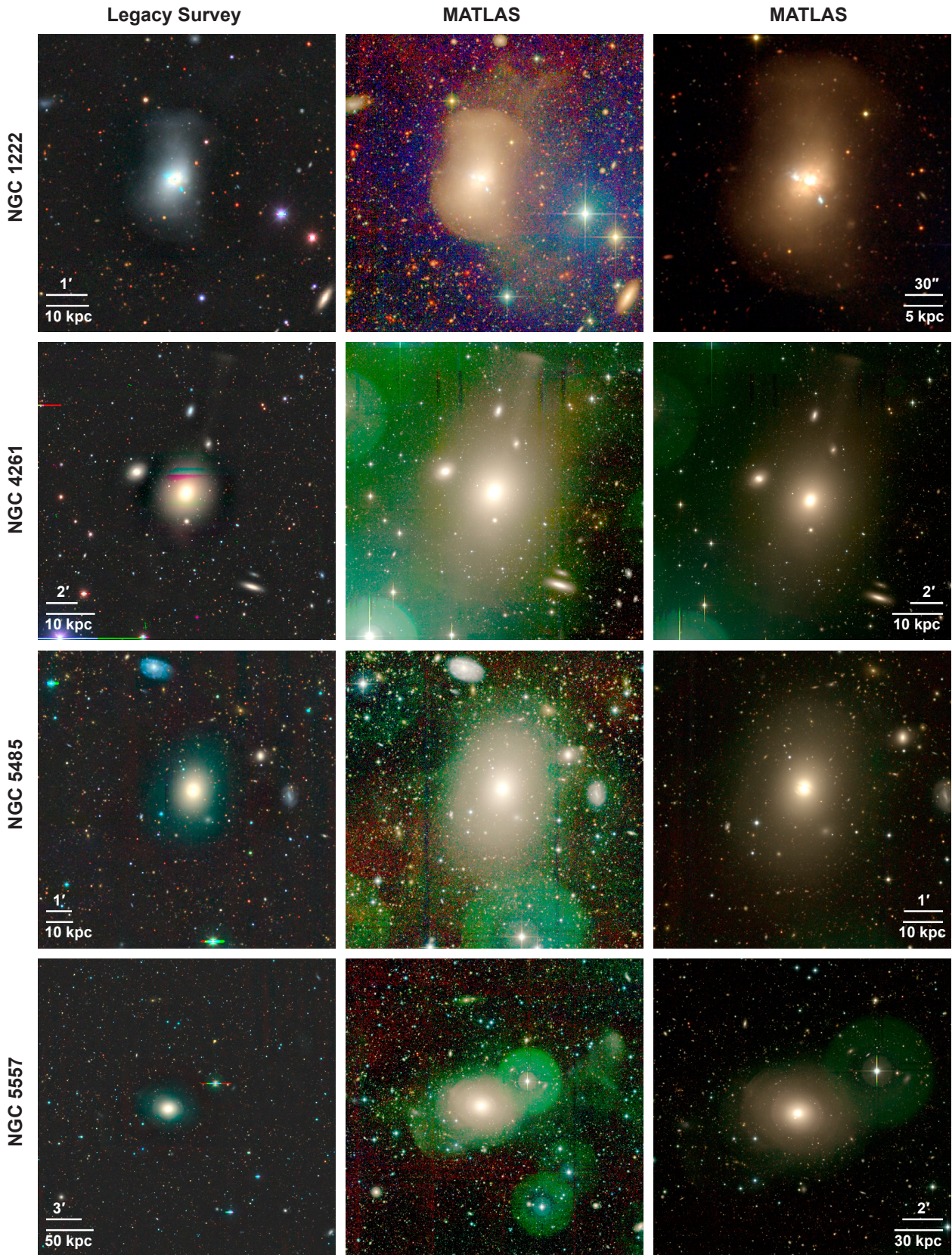


Fig. 3. Images of four prolate rotators from our sample. *Left column:* image extracted from the Legacy Surveys. *Middle column:* image from MATLAS showing the outer parts of the stellar halo with the same field of view as the image in the left column of the respective row. *Right column:* image from MATLAS showing more inner parts of the galaxy. North is up, east is to the left.

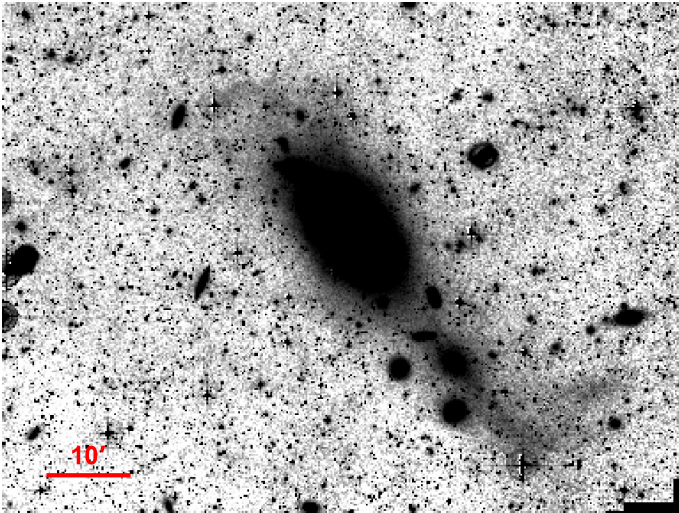


Fig. 4. Negative image of NGC 4365 from the Burrell Schmidt telescope. North is up, east is to the left. Image credit: The Burrell Schmidt Deep Virgo Survey, [Mihos et al. \(2017\)](#).

the cirri and shows no substructure. Moreover, unlike the cirrus in the west, this structure is not visible in the WISE 12-micron dust map, which is incorporated in the Legacy Survey viewer. At the extension of the stream in the Legacy Survey image, 11' to the southeast, there is a faint galaxy, probably a dwarf (assuming the same distance as NGC 4589), which is a possible progenitor of the stream.

The most notable feature in NGC 4589 is an elongated asymmetric excess of light roughly along the major photometric axis. We call it a “taper” (see the right panel of Fig. 6). It is about 8' long, thicker on the west side, and pierces through the stream on the east side. Such an irregular structure could be a tidal tail or a disk disrupted by a past galaxy interaction.

A companion galaxy NGC 4572, the northwest corner of Fig. 6, is tidally disturbed. The deep image reveals prominent tidal arms. [Buta et al. \(2015\)](#) consider NGC 4572 to be a strong candidate for a significantly warped disk with much extraplanar material or a strong tidal spiral. NGC 4589 is the only bigger galaxy in its surroundings. The radial-velocity difference of the galaxies, 230 km s^{-1} (SIMBAD, [Wenger et al. 2000](#)), is consistent with an association between these two galaxies.

The galaxy NGC 4589 has a strong dust lane parallel to the minor photometric axis ([Moellenhoff & Bender 1989](#); [Goudfrooij et al. 1994](#); [Wiklind et al. 1995](#); [Carollo et al. 1997](#)) that was also imaged by HST (see the inset in the right panel of Fig. 6). In studies concerning the dust morphology and kinematics of stars and gas, several authors concluded that this galaxy is a merger remnant ([Moellenhoff & Bender 1989](#); [Ravindranath et al. 2001](#); [Hakobyan et al. 2008](#)).

NGC 4874

NGC 4874 has weak but clear prolate rotation. It is one of two dominant members of the Coma cluster (Abell 1656) and is considered a BCG (e.g., [Liuzzo et al. 2010](#)).

The stellar halo of the galaxy is highly asymmetrical and is lopsided toward the northeast direction. This asymmetry is not apparent in the Legacy Surveys image, the middle panel of Fig. 7, owing to several artifacts and the local background subtraction. Fortunately, the lopsided halo becomes evident in the SDSS image (left panel of Fig. 7). The galaxy also

possesses faint shells that are barely visible in the Legacy Surveys image, but they are present when looking at the residuals available in the Legacy Surveys viewer (right panel of Fig. 7).

NGC 5216 (Arp 104)

NGC 5216 is a Type II shell galaxy with at least four distinct shells visible in the Legacy Surveys image (Fig. 1). There is an ongoing mass transfer from a bluer companion galaxy – a thin blue tail stretches across the whole body of NGC 5216 and extends about 3' north, connecting to the strongly disturbed NGC 5218. The shells of NGC 5216 can originate from a previous interaction with the companion galaxy NGC 5218 or another past merger event.

NGC 5485

In the MATLAS image (Fig. 3) NGC 5485 has a disturbed asymmetrical stellar halo with a stream or tail pointing toward a possible faint shell in the southeast. A deep color image of NGC 5485 shows a ring-like dust structure in the central region oriented along the minor photometric axis (Fig. D.49 in [Yıldız et al. 2020](#)). The inclination makes the dust structure look like an eyebrow. In the MATLAS survey, NGC 5485 is classified as having streams, disturbed outer isophotes, prominent dust lanes, and an unsure detection of shells ([Bílek et al. 2020a](#)).

NGC 5557

NGC 5557 (Fig. 3) is another rich shell galaxy with around nine shells visible in the MATLAS image. There are more tidal features of irregular shapes found up to about 13' (160 kpc) from the center (see also [Duc et al. 2011](#)). In the MATLAS survey, NGC 5557 is classified as having shells, tails, and disturbed outer isophotes ([Bílek et al. 2020a](#)).

NGC 6173

NGC 6173 is a BCG in Abell 2197 ([Postman & Lauer 1995](#)) with an outstanding Type I shell system. Around nine shells are visible in the Legacy Surveys image (Fig. 1).

NGC 7252 (Arp 226)

NGC 7252 (Fig. 8) is a famous merger-remnant galaxy, also known by the nickname “atoms for peace”. The galaxy is equipped with two long tails, several loops, and many (more than ten) shells. The HST image also reveals a dusty disk in the inner parts.

The VLT-VIMOS integral-field spectrograph observations uncover complex stellar kinematics with a clear prolate-rotating component, while the gas shows precise oblate rotation in the inner parts and prolate rotation in the outer parts ([Weaver et al. 2018](#)). A major merger of two disk galaxies is a widely accepted scenario for the origin of NGC 7252 ([Schweizer 1982, 1983](#); [Borne & Richstone 1982, 1991](#); [Mihos et al. 1993](#); [Hibbard & Mihos 1995](#)). Combining information from the ongoing and past star formation and the gas and stellar morphology and kinematics with the results from theoretical studies, [Weaver et al. \(2018\)](#) derive a probable time of the final coalescence of the merger to be within the last 200 Myr.

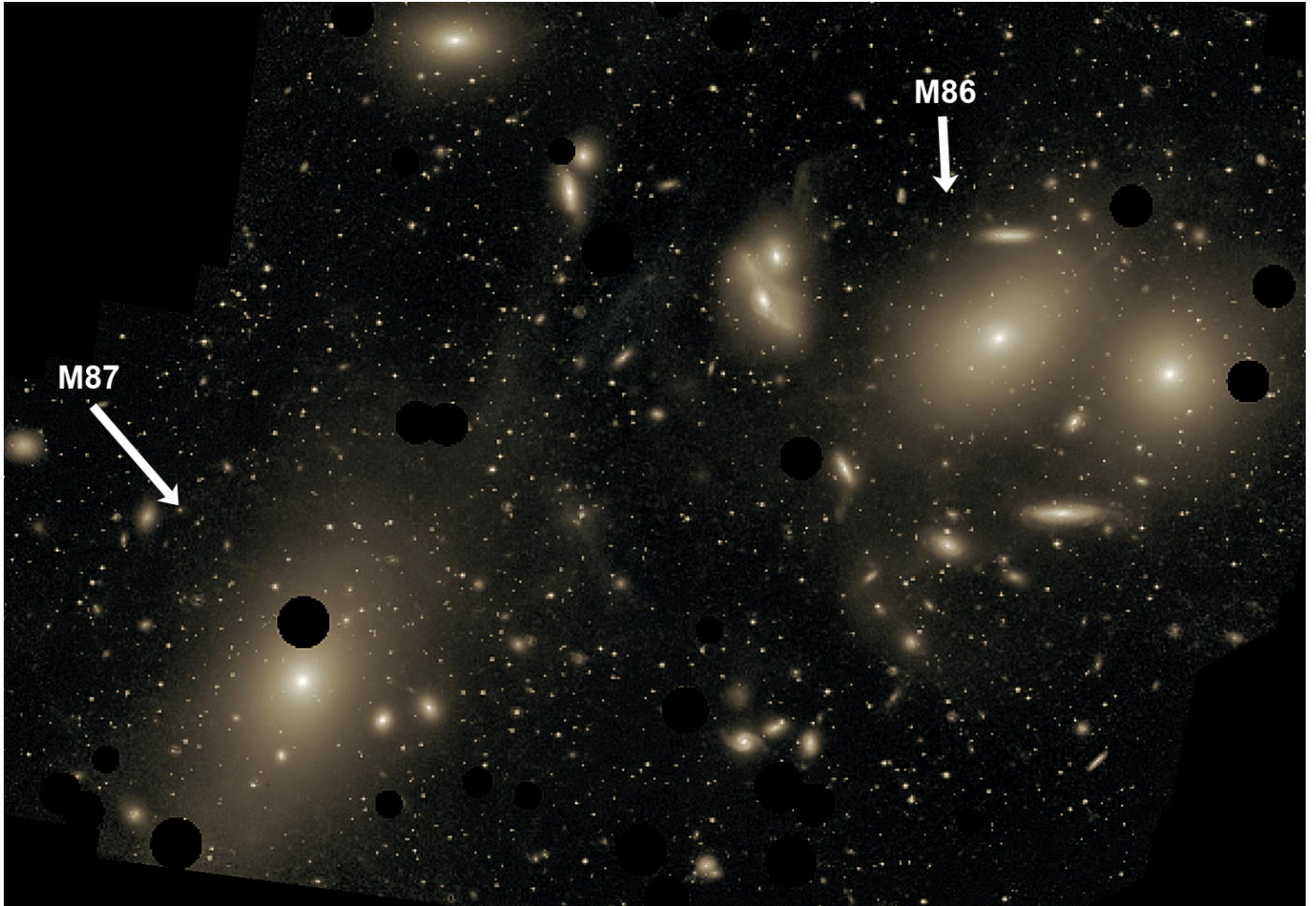


Fig. 5. Images of two prolate rotators from our sample. The deep image of the Virgo Cluster was obtained by Chris Mihos and his colleagues using the Burrell Schmidt telescope. The two prolate rotators from our sample (M86 and M87) are the two biggest galaxies in the image. The dark spots indicate where bright foreground stars were removed from the image. North is up, east is to the left. Image credit: Chris Mihos (Case Western Reserve University) and ESO.

PGC 018579 (AM0609–331, ESO 364–IG 042)

As seen in the Legacy Surveys image (Fig. 1) PGC 018579 is a galaxy in an interaction, which creates a contact pair with 2MASXJ06110577–3318037. In the north, there is a hint of a faint shell around the companion.

PGC 021757 (LSBC F560–04)

PGC 021757 is a BCG with an exemplary Type I shell system. In the Legacy Surveys image (Fig. 1) at least nine shells are visible.

3. Discussion

We detected, often multiple, signs of interaction in all 19 prolate rotators in our sample. In this section, we compare the significance of the detection with the rate of interaction signs in the MATLAS sample.

3.1. Detectability in MATLAS

Only four of our prolate rotators are also in MATLAS. These four galaxies were also classified as tidally disturbed under the MATLAS classification (Bılek et al. 2020a).

Most of the galaxies in our sample have images in the Legacy Surveys. We can safely say that those interaction signs detected in Legacy Surveys images would be detected if the galaxy was a part of the MATLAS sample (see Fig. 3). The MATLAS images have a deeper surface-brightness limit, and the survey was optimized for detecting extended low-surface-brightness structures. This is paramount in discovering the signs of past galaxy interactions. Without optimization, many signs of interaction can escape detection.

In some cases, especially for galaxies with larger angular sizes, the Legacy Surveys images can show the shape of the outer halo worse than the SDSS images (see NGC 4874, Fig. 3), even though the Legacy Surveys generally have a better surface-brightness limit than SDSS. This discrepancy is due to the artifacts at the borders of individual images in the Legacy Surveys and the local background subtraction that often suppresses the outer halo of the galaxies.

Five other prolate rotators in our sample do not have sufficiently good images in the Legacy Surveys. The three prolate rotators located in the Virgo cluster were examined using the Burrell Schmidt Deep Virgo Survey images. As stated in Mihos et al. (2017), the surface-brightness limit of these images is 29.5 (28.5) mag arcsec^{−2} in the *B* (*V*) band, which is comparable with MATLAS. For NGC 1052, we took advantage of the

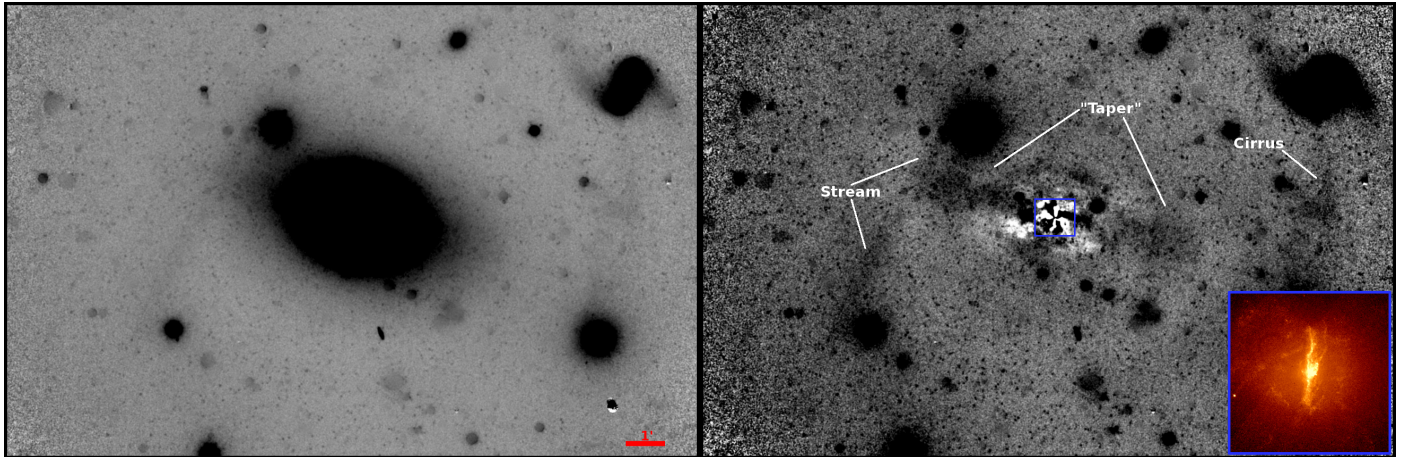


Fig. 6. Negative images of NGC 4589. *Left*: deep optical image of the galaxy by a 1.4 m Milanković telescope; *right*: residual image of the galaxy in the left panel. Both panels have the same field of view. The image in the *left panel* has been cleaned (see the text for the details) and the small disk-like shapes are remnants of this cleaning process. The inset, an HST color image obtained using the $F814W-F435W$ filters, shows a closer view of the central region indicated by a blue box in the *right panel*. The dust filaments, especially that perpendicular to the major axis, are apparent in the HST data. North is up, east is to the left.



Fig. 7. Images of NGC 4874, one of the prolate rotators from our sample. *Left*: SDSS image; *middle*: Legacy Surveys image; *right*: Legacy Surveys residual image. All panels have the same field of view. North is up, east is to the left.



Fig. 8. Images of NGC 7252, one of the prolate rotators from our sample. *Left*: image taken by the Wide Field Imager on the MPG/ESO 2.2 m telescope at the ESO La Silla Observatory in Chile with a total exposure time of more than four hours (image credit: ESO). *Right*: HST/WFC3 image of the inner parts of the galaxy processed by Judy Schmidt to emphasize fine structures (image credit: NASA & ESA; acknowledgement: Judy Schmidt). North is up, east is to the left.

published image from the HERON survey with a similar surface-brightness limit of $28.5 \text{ mag arcsec}^{-2}$ in the r band (Muller et al. 2019a). NGC 4589 is assessed in the image obtained with the Milankovic telescope (for more details, see Appendix B). From our experience, substructures in galaxies in the images from this telescope in L band, taken with a comparable exposure time as the NGC 4589 image, have similar visibility as in MATLAS (Vudragovic et al. 2021, see also Muller et al. 2019b; Bilek et al. 2020b).

NGC 7252 is not included in the Legacy Surveys at all. The image presented in the left panel of Fig. 8 was taken by the Wide Field Imager on the MPG/ESO 2.2 m telescope at the ESO La Silla Observatory. The photometric depth of this image is comparable with Legacy Survey images.

For two prolate rotators from our sample (NGC 4589 and NGC 4874), we also show the residual images (i.e., images after the model subtraction) to emphasize the detected substructures or reveal additional substructures. However, all the galaxies have signs of tidal disturbance that is visible without the model subtraction. In summary, all 19 prolate rotators in our sample have signs of galaxy interaction found in the images (without the model subtraction) that are shallower or have a similar depth compared with the MATLAS images. We can confidently conclude that all 19 prolate rotators would be classified as tidally disturbed if they were a part of the MATLAS survey.

3.2. Environment density

The deep imaging of the complete volume and magnitude-limited ATLAS^{3D} sample was divided into two groups: (1) the NGVS covering the full Virgo Cluster area (Ferrarese et al. 2012), and (2) the MATLAS sample covering the rest of the ATLAS^{3D} galaxies (Duc et al. 2015, see also Duc et al. 2013; Duc 2020). Thus, the MATLAS sample consists of galaxies only from environments with a relatively low galaxy density, while some of our prolate rotators reside in clusters.

Generally, the tidal structures are less abundant among the cluster galaxies (Tal et al. 2009). Especially shells, which occur in most of our prolate rotators, are known to occur significantly more in environments with low galaxy density (Malin & Carter 1983; Reduzzi et al. 1996; Colbert et al. 2001). On the other hand, the preliminary results of NGVS show no significant difference in the frequency of tidal disturbance found in the NGVS and MATLAS galaxies (Duc, priv. comm.). In summary, by neglecting the effect of the environment, we do not artificially increase the significance of our results, rather the opposite.

3.3. Statistical significance of the results

If the probability that a randomly chosen galaxy exhibits interaction signs is p , then the probability to find k such galaxies in a sample of N galaxies follows the binomial distribution:

$$P(k|p) = \binom{N}{k} p^k (1-p)^{N-k}. \quad (1)$$

By the Bayes theorem and the law of total probability, the posterior probability density function of p given the observation of k such galaxies in the sample is written as

$$P(p|k) = \frac{P(k|p)P(p)}{P(k)} = \frac{P(k|p)P(p)}{\int_0^1 P(k|p)P(p)dp}, \quad (2)$$

where $P(k)$ is the prior probability of observing k such galaxies in the sample, and $P(p)$ is the prior probability density function of p , which we assume to be constant. The probability of finding l such galaxies by chance in another sample of M galaxies can be found by the following application of the law of total probability:

$$\begin{aligned} P(l) &= \int_0^1 \binom{M}{l} p^l (1-p)^{M-l} P(p|k) dp \\ &= \frac{N+1}{M+N+1} \frac{\binom{N}{k} \binom{M}{l}}{\binom{M+N}{k+l}}, \end{aligned} \quad (3)$$

and the probability to find at least l such galaxies is $P(\geq l) = \sum_{l'=l}^M P(l')$.

We take MATLAS as our reference sample. The frequency of tidal features is known to increase with the host galaxy mass (e.g., Atkinson et al. 2013; Bilek et al. 2020a). The MATLAS sample consists of ETGs with $9.5 < \log(M_{\text{JAM}}) < 11.8$. For galaxies with $\log(M_{\text{JAM}}) > 11$, the incidence of shells and streams increases about 1.7 times. All but two galaxies in our sample of prolate rotators have the dynamical mass (or its approximate estimate; see Sect. 2.2 and Col. (7) in Table 1) $\log(M_{\text{JAM}}) > 11$. Thus, we are going to compare the frequency of interaction signs with the frequency among the 35 ETGs with $\log(M_{\text{JAM}}) > 11$ in MATLAS (the entry ‘‘Any tidal disturbance’’ in Table 7 in Bilek et al. 2020a). Out of the 35 ETGs, 22 are classified as tidally disturbed (including seven uncertain detections). This means we have $N = 35$ and $k = 22$ for the reference sample and $l = M = 19$ for our sample of prolate rotators, leading to the probability of the observation equal to 0.00087. This proves the strong connection between the prolate rotation and the morphological signs of the galaxy interactions.

3.4. Overabundance of shells

In this section, we perform the same analysis as we did in Sect. 3.3 for the signs of any tidal disturbance, but restricted only to shells. The presence of multiple shells in the galaxy is most likely an indication of a significant merger undergone by the host galaxy. We count only galaxies in which multiple (at least three) shells are visible. We did not include galaxies with an insufficient number of shells or an unclear detection of them (e.g., NGC 647, 1052, 4261, 4486, 5485). We also did not count NGC 4874, which has multiple shells visible only in the residual image, and residual images were not part of the MATLAS classification procedure. Ten prolate rotators satisfy our criteria: NGC 810, 1222, 2484, 2783, 4406, 5216, 5557, 6173, 7252, and PGC 021757.

The reference sample is again the 35 MATLAS ETGs with $\log(M_{\text{JAM}}) > 11$. Among these, there are eight ETGs classified as having or likely having shells, including all three of our prolate rotators that are in MATLAS in that mass bin. The fourth prolate rotator, NGC 1222, is also classified as having shells, but it has $\log(M_{\text{JAM}}) < 11$. From these eight ETGs, five (including one of our prolate rotators) satisfy our criteria: NGC 680, 3613, 3613, 4382, 5557. That means we have $N = 35$ and $k = 5$ for the reference sample; $M = 19$ and $l = 10$ for our sample of prolate rotators, leading to the chance probability of the observation equal to 0.0033. The significance of the connection between multiple shells and prolate rotation is thus lower than for tidal disturbances in general but still very high.

3.5. Interpretation

The fact that a tidal feature is visible in a galaxy means that the related galaxy interaction (presumably merger) happened relatively recently, within the last few gigayears. The overabundance of the interaction signs in prolate rotators has several possible explanations:

(1) Prolate rotation is created in mergers, but generally, the rotation is not stable over a long time. Therefore, we only see prolate rotators formed in recent mergers.

(2) Prolate rotation is created in mergers, and it is stable over a long time, but ancient mergers are not suitable for the production of prolate rotation. In such a case, we would, again, observe only prolate rotators formed in recent mergers. Ancient mergers are typically considerably more gas-rich, even compared to recent wet mergers. This condition can, in principle, lead to a quick renewal of oblate rotation after the merger. This outline is similar to the evolution of ETGs in Illustris reported by [Penoyre et al. \(2017\)](#), where slow rotators are created during the last 8 Gyr of the simulation by the combination of mergers and the inability to regain spin. This scenario requires the lifetime of tidal features to be, in most cases, comparable or longer than the epoch in which the mergers are sufficiently gas poor. If the lifetime of tidal features were significantly shorter than the epoch, we would expect at least some of the prolate rotators to exhibit no signs of interactions.

(3) Prolate rotation can be (in some or all cases) formed a long time ago, but preferentially in environments with frequent galaxy interactions. In such a scenario, the hosts can contain signs of galaxy interaction that are not directly related to the origin of the prolate rotation. Prolate rotation could have been created either in mergers (the merger can be ancient in this scenario) or by another mechanism that has to occur preferentially in environments with frequent galaxy interactions. In this case, prolate rotation has to be able to survive through the event that created the tidal features that are currently observed in prolate rotators. Support for this scenario comes from the fact that some of the prolate rotators are currently clearly experiencing galaxy interactions (PGC 018579 and NGC 5216) or are likely part of ongoing interactions while having signs of past, possibly unrelated, interactions (M 86, M 87, NGC 1052, NGC 4365, NGC 4589, NGC 4874, and NGC 6173).

We note that two or all three scenarios, or some of their aspects, can take place simultaneously in the Universe. The first two points are consistent with the large-scale cosmological hydrodynamical simulation Illustris, where prolate rotators are mostly created in major mergers within the last 6 Gyr of the simulation ([Ebrova & Łokas 2017](#)). Such mergers are expected to produce tidal features that should be, in the majority of cases, visible in deep imaging surveys such as MATLAS. However, even in this scenario, some of the interaction signs observed in prolate rotators may not be related to the origin of the prolate rotation.

4. Conclusions

We collected a sample of 19 nearby ETGs with convincing prolate rotation from ATLAS^{3D}, CALIFA, and the literature. We inspected their deep optical images for signs of galaxy interactions – 18 in the archival images and one in an image newly obtained with Milankovic telescope. We found tidal tails, shells, or asymmetric/disturbed stellar halos in all 19 prolate rotators. We compared this with the tidal disturbance frequency among the galaxies with a similar mass range drawn from the MATLAS

sample – a volume-limited general sample of nearby ETGs. We verified that the MATLAS survey has a similar or better surface-brightness limit than the images of the prolate rotators. We found that the chance probability of observing 19 out of 19 ETGs with interaction signs is only 0.00087.

There is also a strong but less significant connection between the prolate rotation and the presence of multiple shells in the host galaxy, with the chance probability of the observation equal to 0.0033. Our results agree with the Illustris large-scale cosmological hydrodynamical simulation, where prolate rotators are predominantly formed in major mergers during the last 6 Gyr of the simulation.

In addition, we report a discovery of a shell in the HST archival images of NGC 7052. The galaxy is a known prolate rotator, but it could not be included in our sample because the available images do not qualify as comparable with MATLAS images.

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Appendix A: Shell in NGC 7052

NGC 7052, Fig. A.1, is an isolated field galaxy with no nearby companion. It is a known prolate rotator (Wagner et al. 1988) that is not a part of our sample. The galaxy was observed with HST, but generally, HST probes galaxies at different scales than CFHT MegaCam. Thus the HST images do not qualify as comparable with MATLAS and we cannot include NGC 7052 in the sample, but we inspected the images anyway.

We used the HST/WFC3 *F110W* archival data obtained on Jun 14, 2016 (exposure time 2496 s; PI: John Blakeslee). We found a previously unreported shell in the northeast direction, about 42'' from the center along the major photometric axis. The galaxy also shows strong outer boxy isophotes (Lauer 1985; Bender et al. 1988; Gonzalez-Serrano et al. 1993; de Juan et al. 1994; Verdoes Kleijn et al. 1999) indicating a possible presence of more unresolved outer shells. Additionally, there is a large central dust disk with a diameter of 1 kpc (4.0'') oriented along the optical major axis (Nieto et al. 1990; de Juan et al. 1996).

To improve the visibility of the shell, we modeled the galaxy using the same method as for NGC 4589. However, IRAF's 1D ellipse fitting algorithm cannot overcome the boxy outer regions and results in an X-shaped residual. Therefore, we used the GALFIT program (Peng et al. 2010) with two Sersic and one

exponential component. As a result, the GALFIT finds the boxy outer shape's presence; the parameter C0 is approximately 0.24. The GALFIT cannot model the center since there is an intense dust lane. Therefore, we used a mixed model: Having matched the scales of the models, we replaced the inner regions of the GALFIT model with that of the IRAF model. To remove the sharp transition, we smoothed the mixed model with a Gaussian function. The right panel of Fig. A.1 shows the residual image obtained by using the mixed model.

Such a shell should be detectable in the MATLAS survey. The shell in NGC 7052 is located 42'' from the center and it is visible even without any special image processing. In Bilek et al. (2016), a famous shell galaxy NGC 3923 was analyzed using HST and MegaCam images. MegaCam is the same instrument that was used for the MATLAS survey and the images of NGC 3923 have a similar depth and observation strategy as MATLAS. Even the innermost (11'' from the center) shells of NGC 3923 and all the shells that are visible without a special image processing, are detected in both HST and MegaCam images. However, the HST images probe a different range of galactocentric distances, thus the HST images cannot be used as a source for the systematic search for tidal disturbance when compared with the MATLAS results.

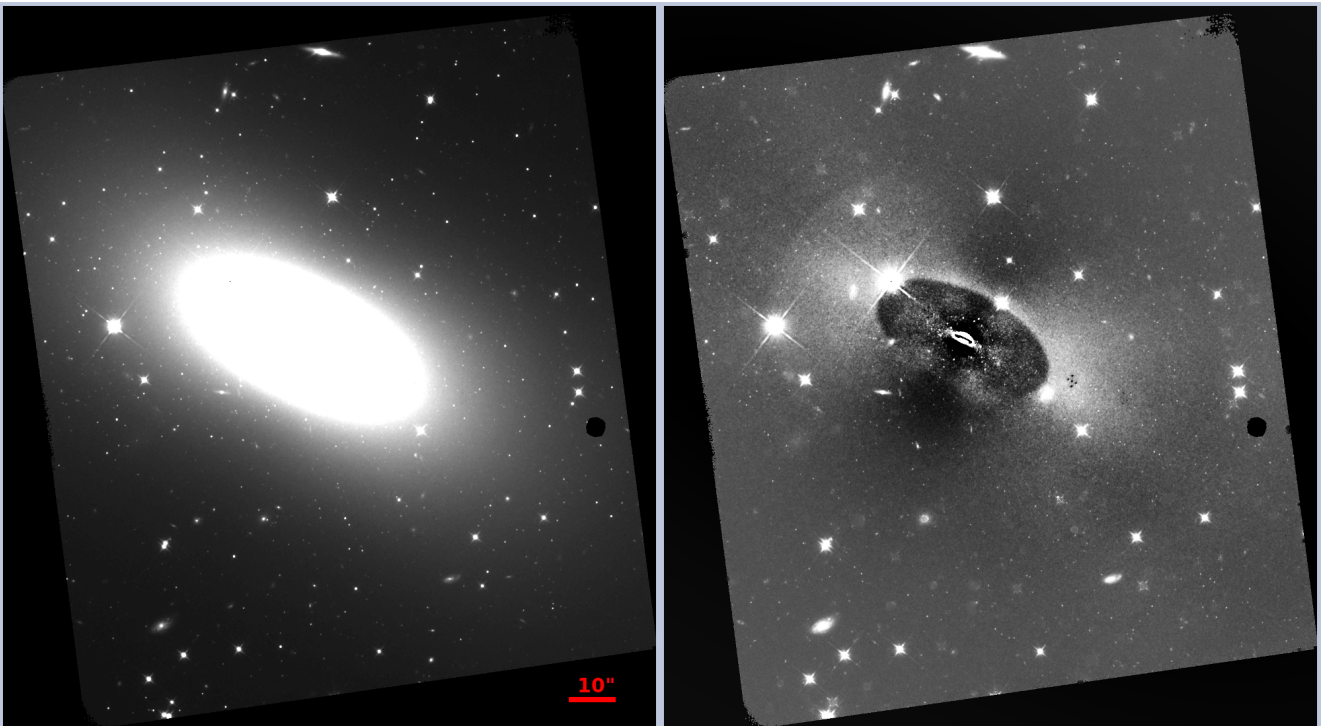


Fig. A.1. Images of NGC 7052, a prolate rotator that is not part of our sample. *Left*: original HST image; *right*: residual image of the one on the left. The image in the *right panel* has been obtained by combining two different models, IRAF's 1D ellipse for inner parts and GALFIT for outer parts, see Appendix A for more details. Both panels have the same field of view. North is up, east is to the left. The newly discovered shell, especially clearly visible in the residual image, is situated about 42'' in the northeast direction.

Appendix B: NGC 4589 observations

NGC 4589 was observed on 15/09/2020 with the 1.4 m Milanković telescope equipped with an Andor IKONL CCD camera mounted at the Astronomical Station Vidojevica (Serbia). Total of 205 frames, each exposed for 100 s in the L -band, was taken with the dithering of 500 pixels ($195''$), summing up to the 5.7 h integrated on-source exposure time. The field-of-view with the focal reducer of 13.3×13.3 was enlarged by random dithering to the 23.8×23.9 in the final co-add image.

Raw images were reduced using the pipeline for the Milanković telescope (Müller et al. 2019b) optimized for the detection of low-surface-brightness features. This pipeline creates the sky flat using largely dithered images. However,

dithering of 500 pixels was not large enough to ensure flatness of the background in the final co-add image. So, the sky flat was created median combining images from which the galaxy was removed. Prior to the reduction, galaxy was modeled and subtracted from all raw images with the Galfit code (Peng et al. 2010), where, in addition to other objects, the central part of the galaxy was masked to enable Galfit to better model the outer parts of the galaxy surface brightness profile. This intervention substantially improved the final co-add in terms of the flatness of the background. The final co-add image was created using SWarp software (Bertin 2010) median combining all calibrated frames for which WCS solution was obtained using Astrometry software (Lang et al. 2010).