THE NEXT GENERATION VIRGO CLUSTER SURVEY. XII. STELLAR POPULATIONS AND KINEMATICS OF COMPACT, LOW-MASS EARLY-TYPE GALAXIES FROM GEMINI GMOS-IFU SPECTROSCOPY

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ABSTRACT

We present Gemini Multi Object Spectrograph integral-field unit (GMOS-IFU) data of eight compact, low-mass early-type galaxies (ETGs) in the Virgo cluster. We analyze their stellar kinematics and stellar population and present two-dimensional maps of these properties covering the central 5″ × 7″ region. We find a large variety of kinematics, from nonrotating to highly rotating objects, often associated with underlying disky isophotes revealed by deep images from the Next Generation Virgo Cluster Survey. In half of our objects, we find a centrally concentrated younger and more metal-rich stellar population. We analyze the specific stellar angular momentum through the $\lambda_R$ parameter and find six fast rotators and two slow rotators, one having a thin counterrotating disk. We compare the local galaxy density and stellar populations of our objects with those of 39 more extended low-mass Virgo ETGs from the SMAKCED survey and 260 massive ($M > 10^{10} M_\odot$) ETGs from the ATLAS$^3D$ sample. The compact low-mass ETGs in our sample are located in high-density regions, often close to a massive galaxy, and have, on average, older and more metal-rich stellar populations than less compact low-mass galaxies. We find that the stellar population parameters follow lines of constant velocity dispersion in the mass–size plane, smoothly extending the comparable trends found for massive ETGs. Our study supports a scenario where low-mass compact ETGs have experienced long-lived interactions with their environment, including ram-pressure stripping and gravitational tidal forces, that may be responsible for their compact nature.

Key words: galaxies: clusters: individual (Virgo) – galaxies: dwarf – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: kinematics and dynamics – galaxies: stellar content

1. INTRODUCTION

Bright galaxies are known to obey well-defined sets of scaling relations linking their structural, kinematic, and stellar population properties. During the past decade, a new generation of observational surveys based on optical integral-field unit (IFU) spectroscopy—and supplemented with spectroscopic and imaging data covering a wide wavelength range—has greatly improved our understanding of these high-luminosity galaxies. Notable examples of such surveys include SAURON (de Zeeuw et al. 2002), ATLAS$^3D$ (Cappellari et al. 2011), and CALIFA (Sánchez et al. 2012).

The ATLAS$^3D$ survey, which carefully examined the structure, kinematics, gas content, and stellar populations of 260 early-type galaxies (ETGs) using the SAURON instrument on the 4.2 m William Herschel Telescope, has provided many new insights into the formation and evolution of galaxies belonging to this broad class. Employing a $K_s$-band magnitude selection, complete down to $M_K < -21.5$ for morphologically-l ETGs within 42 Mpc, ATLAS$^3D$ thoroughly sampled the ETG population down to a stellar mass of $M_\star \sim 6 \times 10^8 M_\odot$. As it happens, this limit coincides roughly with the well-known inflection point in the mass–size and mass–surface brightness relations that are sometimes taken to separate the ETGs into high- and low-mass classes (see, e.g., Figure 16 of Ferrarese et al. 2012). The low-mass ETGs themselves appear to subdivide into separate branches, diffuse and compact (see, e.g., Figure 2 of Dabringhausen et al. 2008), suggesting different origins. Based on their simulations, diffuse low-mass ETGs are thought to be formed mainly through tidal interactions in a weak field, whereas compact low-mass galaxies would be the low-mass counterparts of massive ETGs. It is difficult from imaging alone to assess the extent to which low-mass ETGs have properties similar to high-mass ETGs and whether or not they have experienced similar formation and evolutionary processes (e.g., hierarchical merging, violent relaxation, cold gas accretion, tidal stirring or stripping, and ram-pressure stripping). Whereas strong evidence, both from observations (Huxor et al. 2011; Seth et al. 2014) and simulations (Okazaki & Taniguchi 2000; Metz & Kroupa 2007), exists on the importance of tidal stripping in the formation of low-mass ETGs, the respective roles of mergers and gas accretion are not clear yet, although the latter...
is prominent for more massive ETGs. In clusters, ram-pressure stripping may also be an efficient driver for the transformation of late-type star-forming galaxies into low-mass ETGs (Boselli et al. 2009; Vollmer et al. 2009; Fumagalli et al. 2014).

There have been several recent attempts to provide an initial characterization of the kinematics and stellar populations of low-mass ETGs using long-slit or IFU spectroscopy (e.g., Michielsen et al. 2008; Chilingarian 2009; Koleva et al. 2011b; Paudel et al. 2011; Rys et al. 2014; Toloba et al. 2014c). These studies have focused almost entirely on low-mass ETGs that have generally been classified as dE or dSO types (i.e., comparatively diffuse objects of both the nucleated and nonnucleated varieties). These are obvious first targets because such morphological classes make up the great majority of low-mass ETGs.

A general finding from these studies is that low-mass ETGs show a surprising variety of kinematic structures, features that are remarkably similar to what has been observed in the more massive ETGs. The low-mass ETGs are also found to exhibit a wide range in age and metallicity. Thus, in terms of their stellar content, kinematics, and structural parameters, they seem to bridge the gap between the faintest ETGs (such as the “dwarf spheroidals” found in the Local Group) and the massive ETGs studied by ATLAS3D. Still, the number of low-mass ETGs that have been examined using high-quality spectroscopy remains small, and existing samples include almost none of the compact (i.e., high surface brightness) ETGs that appear to form a second branch in the photometric scaling relations. Although such systems are known to be very rare (see, e.g., Bender et al. 1992), a full understanding of ETGs will remain elusive until the nature of these objects can be understood with the benefit of high-quality (and preferably two-dimensional) spectroscopy.

In this paper, we carry out a spectroscopic survey of low-mass, compact ETGs in the Virgo cluster using IFU spectroscopy acquired with the 8.1 m Gemini North Telescope. Our target galaxies have been selected from both the pioneering photographic survey of Binggeli et al. (1985) and from our own Next Generation Virgo Cluster Survey (NGVS; Ferrarese et al. 2012). The NGVS is a large (~900 hr) program carried out with the 3.6 m Canada–France–Hawaii Telescope (CFHT) between 2008 and 2013. The survey used the MegaCam instrument to perform panoramic imaging of the Virgo cluster, from its core to virial radius, in the $\mu^* giz$ filters (a total area of $\approx100 \text{ deg}^2$). For a subset of the survey area, $r$- and $K$-band imaging is also available (see, e.g., Muñoz et al. 2014). The point-source completeness limit for the survey is roughly $g \approx 25.9$ mag (10σ), with a corresponding surface-brightness limit of $I_{25} \approx 29$ mag arcsec$^{-2}$ (2σ above sky level). The NGVS image quality is also excellent, with a median $i$-band seeing of FWHM $\approx 0.54^\prime$. A key deliverable from the NGVS will be an updated catalog of confirmed and probable Virgo cluster members, including a complete census of the low-mass compact ETGs that are the focus of this paper.

Other papers in the NGVS series related to the general topics considered here include studies of the globular cluster populations in Virgo (Durrell et al. 2014), the dynamical properties of star clusters, ultracompact dwarfs (UCDs), and galaxies in the cluster core (Zhu et al. 2014; Zhang et al. 2015), a census of UCDs in Virgo’s three main subclusters and an examination of tidal stripping as a possible origin for at least some UCDs (C. Liu et al. 2015, in preparation), and investigations into ongoing tidal interactions of galaxies within the cluster environment (Arrigoni Battaia et al. 2012; Paudel et al. 2013).

This paper is organized as follows. We describe our sample selection and data reduction procedures in Section 2, and we discuss our kinematical and stellar population analysis in Section 3. Our results are presented in Section 4 and discussed in Section 5, wherein we examine possible formation scenarios for low-mass ETGs in cluster environments. We summarize our findings in Section 6.

2. DATA
2.1. Sample Selection

The Virgo cluster is the galaxy cluster nearest to the Milky Way, containing nearly 2,000 cataloged members (Binggeli et al. 1985). The majority of these are classified as low-luminosity ETGs, thus making them a very significant morphological group by number and an important sample for understanding galaxy evolution in dense environments. We selected our targets from Binggeli et al. (1985), as well as from the NGVS.

We first identified Virgo ETGs (Binggeli et al. 1985) with $M_B < -18.0$ and then selected compact, high-surface-brightness objects that were objectively defined as lying more than 1σ above the ridgeline in the magnitude–surface brightness diagram shown in Figure 1 of Ferrarese et al. (2012). This approach is motivated by the fact that more massive galaxies ($M_\text{stellar} \geq 10^9 M_\odot$) generally follow this relation within a 1σ limit, whereas some low-mass ETGs lie well above the relation, a region where tidally stripped galaxies may reside (e.g., King 1962; Faber 1973; Keenan & Innanen 1975). Recently, Toloba et al. (2014b, 2014c), as well as Rys et al. (2013), have suggested that most low-mass ETGs (i.e., systems with lower surface brightness than the objects targeted in this study) are the remains of galaxies that have been strongly transformed by ram-pressure stripping and gravitational harassment after falling into the cluster. Rys et al. (2014) also found that their stellar mass has contracted relative to their progenitors (assumed to be late-type). Therefore, our CFHT/Gemini survey—which targets some of the most compact (i.e., highest surface brightness) Virgo ETGs with $i \geq 12$—should provide new insights into the formation of these extreme objects.

We obtained Gemini data for 8 of the 19 galaxies that comprised our parent low-mass, compact ETG sample in the Virgo cluster, with bad weather conditions precluding observations of the remaining galaxies. Despite the fact that our actual sample is not complete, it should nevertheless be representative and allows us to probe a size–mass regime that has not yet been surveyed with the benefit of integral field spectroscopy (IFS) data. The galaxies in our sample have surface brightnesses in the range $17 \lesssim I_{25} \lesssim 20$ mag arcsec$^{-2}$ and effective radii of $2'' \lesssim R_e \lesssim 9''$, which corresponds to 165–740 pc at their intrinsic distances of, respectively, 16.3 Mpc (Jordán et al. 2007) and 16.7 Mpc (Blakeslee et al. 2009). The properties of our sample galaxies are summarized in Table 1.

Although this was not a criterion for the selection, most of our objects are nucleated, or possibly nucleated, galaxies, as shown in the ACSVCS survey (Côté et al. 2004, 2006). They span a wide range in projected cluster-centric distance, from the center of the cluster close to M87 (NGC 4486), out to Virgo’s
outskirts (see Figure 1). Three of them (VCC 1178, VCC 1192, and VCC 1199) have projected distances from M49 (NGC 4472, the brightest galaxy of the Virgo cluster) of less than 50 kpc, while another (VCC 1627) is located close to the massive ETG M89 (NGC 4552). A fifth galaxy, VCC 1297, is a companion of the central massive ETG M87 (NGC 4486). Redshift-independent distance estimates from surface brightness fluctuations (Mei et al. 2007; Blakeslee et al. 2009) and globular cluster luminosity functions (Jordán et al. 2007; Villegas et al. 2010) show that the projected distances are representative of the intrinsic positions of the galaxies in the cluster, with the exception of VCC 1627, which is located at the front side of the cluster at a distance of 15.6 Mpc. VCC 0032 has no redshift-independent distance, so we assume a mean Virgo distance of 16.5 Mpc. A more thorough discussion of the environment of our sample galaxies and its possible influence on their structure, kinematic properties, and stellar populations is presented in Section 5.

2.2. Observations

Our observations were carried out at the 8.1 m Gemini North Observatory, using the IFU of the Gemini Multi Object Spectrograph (GMOS, Hook et al. 2004), with a combination of one- and two-slit modes due to configuration availability. The observations were taken in service mode between 2012 March and 2013 July under the programs GN-2012A-Q-81, GN-2013A-Q-76, and GN-2013A-Q-108. Table 2 provides details on the instrumental setup and exposure times.

We used the GMOS-IFU (Allington-Smith et al. 2002) primarily in its two-slit mode, giving a 7′ × 5′ field of view (FOV) with 1,000 hexagonal fibers of 0.2′′ projected diameter. Five hundred similar additional fibers, covering an area of

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Table 1

| Galaxy | Other ID | R.A.(J2000) | Decl.(J2000) | Distance (Mpc) | d(M87) (Mpc) | d(M49) (Mpc) | m_i (mag) | μ_i (mag arcsec⁻²) | R_e (arcsec) | ϵ |
|--------|----------|-------------|-------------|----------------|------------|-------------|-----------|----------------|-------------|---|
| VCC 0032 | IC 0767 | 12:11:02.73 | +12:06:14.4 | 16.5 | 1.394 | 1.777 | 13.12 | 18.85 | 5.60 | 0.18 |
| VCC 1178 | NGC 4464 | 12:29:21.29 | +08:09:23.8 | 15.8 | 1.172 | 0.052 | 11.90 | 17.91 | 6.34 | 0.30 |
| VCC 1199 | NGC 4467 | 12:29:30.25 | +07:59:34.3 | 16.3 | 1.255 | 0.019 | 13.54 | 19.10 | 5.17 | 0.35 |
| VCC 1297 | NGC 4486b | 12:30:31.97 | +12:29:24.6 | 16.3 | 0.035 | 1.278 | 12.62 | 16.72 | 2.64 | 0.09 |
| VCC 1440 | IC 0798 | 12:32:33.41 | +15:24:55.4 | 16.1 | 0.858 | 2.092 | 13.58 | 20.10 | 8.06 | 0.01 |
| VCC 1475 | NGC 4515 | 12:33:04.97 | +16:15:55.9 | 16.7 | 1.140 | 2.420 | 12.01 | 18.81 | 9.13 | 0.35 |
| VCC 1627 | … | 12:35:37.25 | +12:22:55.4 | 15.6 | 0.319 | 1.255 | 13.89 | 18.74 | 3.71 | 0.10 |

Note. (1) Galaxy name from the catalog of Binggeli et al. (1985), (2) alternative galaxy name in the NGC or IC catalogs, (3) J2000 coordinates (NED), (4) redshift-independent distance when available (Mei et al. 2007; Jordán et al. 2007; Blakeslee et al. 2009) or mean Virgo distance, (5)–(7) projected distances in Mpc from M87 (NGC 4486) and M49 (NGC 4472), respectively, (8) apparent magnitude and surface brightness measured from NGVS i-band images, (9) ellipticity derived as a moment of the surface brightness of the NGVS i-band images, at R_e/2, except for two targets, VCC 1440 and VCC 1475, that we only cover up to R_e/3 with our GMOS-IFU observations.

Table 2

| Galaxy | PA_{sky} (deg) | PA_{inst} (deg) | Run ID | T_{exp} (seconds) |
|--------|----------------|----------------|--------|------------------|
| VCC 0032 | 76.0 | 164 | 1 | 4 x 1800 |
| VCC 1178 | 5.2 | 295 | 2 | 4 x 900 |
| VCC 1192 | 30.8 | 265 | 2 | 6 x 1800 |
| VCC 1199 | 30.8 | 302 | 2 | 6 x 1800 |
| VCC 1297 | 71.1 | 1 | 3 | 8 x 2100 |
| VCC 1440 | 81.9 | 35 | 2 | 6 x 1800 |
| VCC 1475 | −5.8 | 83 | 1 | 4 x 1800 |
| VCC 1627 | −81.4 | 170 | 3 | 5 x 1800 |

Note. (1) Galaxy name from the Binggeli et al. (1985) catalog, (2)–(3) position angle of the galaxy major axis on the sky and GMOS instrument in the northeast frame, (4) Run: 1 = GN-2012A-Q-81; 2 = GN-2013A-Q-76 (two-slit mode); 3 = GN-2013A-Q-76 (one-slit mode), (5) total on-source exposure time in seconds.
5′ × 3′5 and pointing ~1 arcmin away from the science field, are used to estimate the sky background level. Each slit covers half of the FOV and disperses over the corresponding half of the detectors. To avoid spectral overlap on the detectors between the spectra from the two slits, different filters can be set in front of the gratings. We opted for the B600-G5307 grating combined with a g′ filter, giving a clean wavelength range of 3980–5480 Å. This spectral range provides extensive coverage of strong stellar absorption lines (e.g., the Hβ, Fe, and Mg b triplet) for measuring the kinematics as well as the population parameters of age and metallicity. The instrumental spectral resolution is 1688 at FWHM of 2.7 Å at 4610 Å.

Typical exposure times for our campaign were 4 × 1800 s and 6 × 1800 s, for example, 2 and 3 hr, respectively (see Table 2), to reach a S/N of 20 or better with spatial binning while keeping enough spatial resolution. One exception is VCC 1178, for which an exposure time of 4 × 900 s was considered sufficient. Due to scheduling constraints on the GMOS-IFU configuration, two targets (VCC 1297 and VCC 1627) were observed in GMOS-IFU one-slit mode. This mode covers only half of the FOV of the two-slit mode, i.e., 5′ × 3′5, and as a consequence the time of integration had to be doubled to cover the original FOV (see Figure 2 for an illustration of the coverage of our targets). All other parameters are similar to the two-slit mode except for an extended wavelength coverage, e.g., 4200–7200 Å. For consistency, however, we considered only the overlapping wavelength range between the one-slit and two-slit mode data in our analysis (i.e., 4200–5480 Å).

The GMOS focal plane consists of a mosaic of three 2k × 4k e2v DD detectors with gaps equivalent to approximately 37 unbinned pixels each (~20 Å). To avoid losing spectral information, we used a spectral dithering technique by shifting the central wavelength of the grating by 50 Å for half of the exposures, using two central wavelength settings: 4800 and 4850 Å. Variations in the point-spread function between exposures, however, complicate the optimal combination of the spectral dithers, so instead we simply excluded the spectral gaps when performing our analysis.

2.3. Data Reduction

We used the official Gemini IRAF package v1.11.1, released in 2012 March, to reduce all of our data, i.e., perform bias subtraction, flat-fielding and illumination correction, wavelength calibration, cosmic-ray rejection, and sky subtraction. The final cubes (formed from a combination of individual exposures) were created using the XSAURON software (Bacon et al. 2001), developed by the Centre de Recherche Astrophysique de Lyon. We developed a dedicated PYRAF script to automate the end-to-end data reduction, ensuring a homogeneous treatment of the reduction procedure across all targets.

Raw frames (e.g., science, flat lamp, and twilight exposures) were overscan and bias subtracted using the task gprep. The arcs were only overscan subtracted as they were taken in fast-read mode. The dark current of GMOS e2v DD CCDs is typically less than one electron per hour and was thus ignored.

The flat lamps within the Gemini calibration unit, GCAL, were used to derive the flat-field response map for each associated science exposure. We used the task gresponse to derive the maps from the flats, and we used one twilight per observation run (see Table 2) to correct for illumination. The science spectra were extracted using the aperture mask derived from their associated flat lamp (taken immediately before or after the exposure) and corrected for flat-fielding and illumination using the task gextract. As explained in the Section 2.2, in two-slit mode each slit disperses over one half of the detector mosaic, and a filter (g′ in this case) was used to avoid overlap between the spectra coming from each slit. However, the blue end of the spectra coming from the left side of the FOV can still overlap with the red end of the spectra coming from the right side of the field. Thus, the spectra were shortened by 10% (~12 Å) in the overlapping area to eliminate any contamination from one slit on the other.

We checked the quality of the flat fielding by applying our procedure on twilight exposures, which should provide a homogeneously illuminated field. We found a residual uncertainty of about 1% between spectra from the same slit, but a systematic offset of 10%–20% between the two slits. This issue is known to arise from errors in the normalization from the Gemini IRAF flat-fielding recipe itself and not from the data. We chose not to correct for this offset because our analysis does not require accurate absolute flux calibration, and the spectral shape is not significantly affected. However, the isophotes derived from the integrated flux in the data cubes show some residual asymmetry as a result of this effect (see Figure 5), and so they should be viewed with caution.

We derived the wavelength solution based on the GCAL arc-lamp exposures using the task gswavelength with a fourth-order Chebyshev polynomial. Due to charge transfer efficiency issues that can systematically affect the relative centroid of strong and weak lines, as well as introduce effects related to the readout direction of the detector, we fitted only the 20 brightest lines available in the CuAr arc lamps. We carefully checked that those lines sample the whole wavelength range appropriately. Unfortunately, no bright lines are available redward of 5187 Å when using a central wavelength of 4800 Å, which reduced the accuracy of our wavelength solution beyond that wavelength for that configuration. We therefore excluded the wavelength range 5180–5480 Å for the kinematic analysis. Unfortunately, the Mg b triplet lines were consequently excluded from the fit for the majority of our galaxy sample, but the S/N of our spectra is sufficiently high to still allow us to reach the low velocity dispersion levels required (see Section 3.1 and Figure 3 for details). We obtained typical formal rms errors in the wavelength calibration of 0.1 and 0.08 Å for the 4800 and 4850 Å central wavelength settings, respectively.

Finally, we ran the task gscreej on each exposure to reject cosmic rays and cleaned the remaining bright cosmic impacts via another cosmic-ray rejection algorithm implemented within XSAURON. The sky contribution in the science spectra was subtracted by running the task gisky using the median of all dedicated sky fibers.
VCC 1297 is set by the boundary of the models used, i.e., 12.5 Gyr.

The ellipse fit was performed by median sampling of the image in elliptical annuli with the semimajor axis incremented by 10% at each iteration. During the procedure, all parameters (center, ellipticity, position angle) were allowed to vary. The models used to obtain the residual images shown in the lower panels do not include higher-order moments and therefore only highlight deviations of the isophotes from pure ellipses. The green rectangle on each image indicates the GMOS-IFU FOV for the relevant mode (approximately 5″ × 7″ for two-slit mode observations and 5″ × 6″ for the mosaicked one-slit mode observations). All images are oriented to show north up and east to the left. The effective radius of each galaxy is indicated at the bottom right of its residual image to give an idea of the relative coverage of our observations.

Figure 2. Composite giz-color images from the NGVS survey (top row) and NGVS i-band residual images obtained by subtraction of a model computed with ELLIPSE. The ellipse fit was performed by median sampling of the image in elliptical annuli with the semimajor axis incremented by 10% at each iteration. During the procedure, all parameters (center, ellipticity, position angle) were allowed to vary. The models used to obtain the residual images shown in the lower panels do not include higher-order moments and therefore only highlight deviations of the isophotes from pure ellipses. The green rectangle on each image indicates the GMOS-IFU FOV for the relevant mode (approximately 5″ × 7″ for two-slit mode observations and 5″ × 6″ for the mosaicked one-slit mode observations). All images are oriented to show north up and east to the left. The effective radius of each galaxy is indicated at the bottom right of its residual image to give an idea of the relative coverage of our observations.

3. ANALYSIS

3.1. Merging and Binning

We used the software XSAURON to reconstruct the final cubes starting from the individual reduced exposures described in Section 2.3. All individual exposures were first truncated to a common wavelength range (4200−5400 Å) and spatially aligned using isophote contours. The exposures were then merged by interpolating each one onto a common 0′/2 × 0′/2 grid and then taking the optimally weighted sum of the exposures at each pixel.

To increase the S/N of our data, we used the adaptive spatial binning software developed by Cappellari & Copin (2003), based on a Voronoi tessellation. The formal error spectra are not fully propagated through the reduction process by the Gemini IRAF package. Therefore, as a first approximation, we assumed that the noise in a given spaxel was directly proportional to the square root of its integrated flux (i.e., Poissonian). We performed a spectral fit of the central unbinned spectrum (see Section 3.2 for a description of the spectral fitting method used) to get a good estimate of the noise from the fit residuals, which we used to renormalize our Poissonian noise estimate before applying the Voronoi binning. We tested that this renormalization did not depend on which region of the galaxy was used to compute the fit, and we found no dependence.

ETGs in the luminosity range of our program galaxies have typical velocity dispersions of ∼30 km s−1, which is well below our instrument dispersion of 75 km s−1. We used Monte Carlo simulations with model spectra adapted to match the spectral properties (wavelength range, resolution, pixel size) of the GMOS-IFU observations. Figure 3 shows that, at velocity dispersions of 30−40 km s−1, binning our data to a S/N threshold of 25 was sufficient to recover low velocity dispersions with errors of ∼11 km s−1 for both the mean velocity V and velocity dispersion σ. This was considered an acceptable compromise between the kinematic errors and degree of spatial binning. During the binning process, we rejected all spectra with an S/N lower than 3 so as to avoid creating very large poor-quality bins. The adaptive spatial binning on average delivers the target S/N in each spectrum within a standard deviation of 8%. From our simulations, this small spread in S/N corresponds to a variation of only
Figure 5. Maps of mean radial velocity, $V$, velocity dispersion, $\sigma$, and stellar population parameters (age and metallicity $[Z/H]$) for our eight low-mass ETGs in the Virgo cluster. The box in each subpanel indicates the values corresponding to the extreme colors of the color bar on the right. The dark contours in each panel represent the isophotometric contours of the specific target computed from the integrated reconstructed cube.
1–2 km s\(^{-1}\) in the errors of velocity and velocity dispersion and similarly small relative errors on the line strengths.

3.2. Kinematics Extraction

To measure the stellar kinematic properties of our objects (mean radial velocity, \(V\), and velocity dispersion, \(\sigma\)), we fitted the data using the penalized pixel-fitting method (pPXF) from Cappellari & Emsellem (2004) as implemented in XSAURON. We used an empirical library of 89 stars taken from the MILES library (Sanchez-Blazquez et al. 2006; Falcón-Barroso et al. 2011) that covers the spectral range of 3525–7500 Å at a spectral resolution of 2.3 Å FWHM (\(\sigma \sim 60\) km s\(^{-1}\) at 5000 Å), similar to (but lower than) the GMOS-IFU spectral resolution. We selected these stars in such a way to cover uniformly the parameter space \((T_{\text{eff}}, \log(g), [\text{Fe/H}])\) expected for dwarf galaxies. For each individual target, we first fitted the spaxel having the highest S/N to obtain the combination of stars that best reproduces the galaxy spectrum. We then used this single best-fit template for all spaxels to minimize the impact of template variations within the FOV. We fitted the spectrum over the range 4200–5180 Å, excluding the redder wavelengths for the reasons mentioned in Section 2.3.

We performed the same kinematic extraction on the twilights obtained during the different runs (observed with the same setup and reduced in the same way as the science exposures) to check the quality of our wavelength calibration. Ideally, the twilight illuminates the full GMOS-IFU FOV, and one can expect to obtain the same radial velocity and velocity dispersion on each of the 1,000 science fibers. Any variations from one fiber to another will represent the uncertainties of our measurements due to, e.g., systematic instrumental signatures or reduction processes. In two-slit mode, we measured a small radial velocity systematic offset of \(-5\) km s\(^{-1}\) between the two slits of the GMOS-IFU instrument (i.e., the two sides of the field) and variations of a few kilometers per second within a single slit (for both one-slit and two-slit modes). Both measurements are within the wavelength calibration error (rms \(~0.1\) Å, i.e., \(\Delta V \sim 7\) km s\(^{-1}\)) and kinematic errors due to noise as estimated in Figure 3.

We measured on the final binned maps (see Section 4.1 and Figure 5) the standard deviation of the radial velocity \(V\) and velocity dispersion \(\sigma\) over a 10 × 10 spaxel area where the binning was strong (i.e., at the edge of the GMOS-IFU FOV). We performed these measurements on objects having relatively flat \(V\) or \(\sigma\) profiles (e.g., VCC 0032, VCC 1440, VCC 1627), so these quantities represent the global true uncertainties on the kinematics. The typical standard deviations found are of 10 km s\(^{-1}\) for \(V\) and 15 km s\(^{-1}\) for \(\sigma\), which are similar to the values estimated from our simulations.

3.3. Age and Metallicity Measurements

To study the stellar populations in our galaxies, we apply spectral fitting to derive values of age and metallicity using the MIUSCAT models (Vazdekis et al. 2012) that provide single-age, single-metallicity stellar population models based on the MILES and CaT (Cenarro et al. 2001) libraries. We used a subset of 203 models covering an age range of 0.5–12.5 Gyr, a metallicity range of \(-2.32\) to \(+0.22\) dex, and computed using a unimodal IMF with a slope of 1.3, equivalent to a Salpeter (1955) IMF. The model spectra were retrieved from the MIUSCAT website, sampled at 2.5 Å FWHM resolution (similar to GMOS-IFU data) and covering the wavelength range 3464–5550 Å. As with the kinematics extraction, we used pPXF software to fit the galaxy spectra over the wavelength range of 4200–5400 Å, excluding the H\(\beta\) and [O\(\text{ii}\)] lines to avoid being contaminated by any possible emission from ionized gas.

3.3.1. Regularized Spectral Fits

As our primary approach, we used regularization of our spectral fits such that the best distribution of templates found to fit the data is also the smoothest in the parameter space (in this case, age and metallicity). In other words, we impose the condition that the star-formation history is the smoothest possible. The age and metallicity values are then derived by taking the mean age and metallicity of the selected templates, weighted by their mass contribution to the combined template. This is equivalent to the spectral fitting approach used by McDermid et al. (2015) for the ATLAS3D survey.

We performed this analysis on each spaxel of our galaxy cubes, spatially binned to an S/N of 35. This S/N value was chosen to preserve spatial information on each target while still providing robust measurements and acceptable errors. Two targets, VCC 1199 and VCC 1627, were kept with an S/N of 25 because the data are of lower quality, and we opted to retain the smaller bin size. For each individual target, we used the spaxel with the highest S/N to derive the degree of regularization to use for all of the spaxels. In this way, we keep the degree of regularization constant over the full FOV. The maps of the mass-weighted age and metallicity are shown in Figure 5 and discussed in Section 4.

To estimate the errors made on the mass-weighted age and metallicity, we performed the same exercise on the stellar population binned maps as with the kinematic maps and found typical standard deviations of 0.4 Gyr in age and 0.05 dex in metallicity. However, it is important to notice that these measurements are mostly formal uncertainties that mostly depend on systematics and the spectral library used. The exact impact of the library used for the measurements is beyond the scope of this paper.

3.3.2. Best Single SSP Fit

In order to compare the stellar population properties of our sample galaxies with others in the literature (Koleva et al. 2011b; Ryš et al. 2014; Toloba et al. 2014b, 2014c), we also carried out a single stellar population (SSP) analysis similar to the spectroscopic indices method (Michielsen et al. 2007; Koleva et al. 2011a). This method, which is well studied and described in Koleva et al. (2008), consists of selecting the single SSP model that, in terms of \(\chi^2\), best fits the data, taking the age and metallicity of this model as the measured value. To reduce the limitations of discreteness in the grid of model age and metallicity values, we interpolated the \(\chi^2\) surface within the parameter space \(\log(\text{age})–[\text{Z/H}]\). We used this interpolation to determine the position of the \(\chi^2\) minimum and the \(\Delta \chi^2\) error surface.

We performed this analysis for each of our targets on the single spectrum obtained by spatially stacking spectra within an ellipse equivalent in area to a circular aperture of \(R_e/2\), except for two targets, VCC 1440 and VCC 1475, that we only cover up to \(R_e/3\). Effective ellipses have been derived using moments
of the surface brightness of our galaxies in the NGVS i-band images. The corresponding ellipticities are given in Table 1.

We compared our results with published values for VCC 0032 and VCC 1192 (Sánchez-Blázquez et al. 2006), VCC 1178 and VCC 1475 (Koleva et al. 2011b), and VCC 1297 (Spolaor et al. 2010b) by simulating their long-slit data and performing the analysis on the same apertures. Our findings are in good agreement with these previous studies, as illustrated in Figure 4. The errors on our measurements are taken to be where the marginalized $\chi^2$ surface of the fit shows a difference of one with respect to the minimum value, corresponding to the 68% confidence limits.

4. RESULTS

Several IFU-based studies of low-mass ETGs, spanning a broad range of properties, have been published in recent years (Prugniel et al. 2005; Chilingarian 2009; Ryš et al. 2013). As discussed in Section 2.1, our study focuses on the most compact low-mass ETGs, thereby probing a largely unexplored regime in size ($165 \lesssim R_e \lesssim 740$ pc) and surface brightness ($\mu_e \lesssim 20$ mag arcsec$^{-2}$). From an observational perspective, such objects are challenging targets due to their small sizes; as a result, only a few have had their basic kinematic and stellar population properties characterized. The spatial resolution and sensitivity of the GMOS-IFU have allowed us to obtain resolved two-dimensional spectroscopy of the central parts of eight of these compact objects in the Virgo cluster. The kinematics, age, and metallicity maps for this sample are presented in Figure 5. We also provide some further details pertaining to two noteworthy objects (VCC 1297 and VCC 1475).

4.1. Kinematics

Six of the eight galaxies in our sample show significant stellar rotation. The exceptions, VCC 0032 and VCC 1440, have mean stellar rotation velocities consistent with zero within the entire GMOS-IFU FOV, i.e., up to about half the effective radius for VCC 0032 and a third of the effective radius for VCC 1440. Interestingly, these two galaxies happen to reside in the outskirts of the cluster (see Figure 1). Typical mean radial velocity amplitudes for the other six objects are between 15 and 30 km s$^{-1}$, which is similar to other low-mass, but more diffuse, ETGs (Toloba et al. 2011; Ryš et al. 2013). Two galaxies, namely VCC 1178 and VCC 1297, show significantly larger stellar velocities (90 and 68 km s$^{-1}$, respectively). Our GMOS-IFU data also confirm and highlight the presence of a counterrotating core in VCC 1475. This feature was first noted by Koleva et al. (2011b) using long-slit data and later reanalyzed by Toloba et al. (2014a) (see Section 4.3.2 for more details).

The galaxies in our sample have typical stellar velocity dispersions of 20–60 km s$^{-1}$, again similar to what has been observed for other low-mass ETGs. Half of the sample has fairly flat stellar dispersion profiles (VCC 0032, VCC 1192, VCC 1440, and VCC 1627). However, the remaining four galaxies show significant central dispersion peaks, rising to values of 60 km s$^{-1}$ (VCC 1199), 70 km s$^{-1}$ (VCC 1475), 155 km s$^{-1}$ (VCC 1178), and 235 km s$^{-1}$ (VCC 1297). The last three objects also show significant organized rotation, as well as disky isophotes in the photometry of the same central regions (visible in Figure 2).

Figure 2 shows the composite giz images from the NGVS survey as well as the i-band residual images of our target galaxies, obtained by subtracting from the original image the best ellipse fit at each radius (from the center and incremented by 10% at each iteration). The center, ellipticity, and position angle of the fit were allowed to vary, but the models used to obtain the residual images do not include higher-order moments and therefore only highlight deviations of the isophotes from pure ellipses. Three galaxies (VCC 1199, VCC 1440, and VCC 1627) show little structure in their residual images, but typical “X-shaped” residuals of disky isophotes are apparent in the other five (VCC 0032, VCC 1178, VCC 1192, VCC 1297, and VCC 1475). This is confirmed by the cosine fourth-order moment in the Fourier expansion of the intensity (Jedrzejewski 1987), which is positive out to several tens of arcseconds for VCC 0032, VCC 1778, VCC 1297, and VCC 1475 and out to a few arcseconds for VCC 1192. This is in agreement with the potential high degree of substructure present in low-mass ETGs (e.g., Lisker et al. 2007; Turner et al. 2012). Note that the lack of structure in the residual images can also be due to projection effects, at least for VCC 1440, which is a round object ($c \approx 0.13$) that does not show much rotation and therefore could be an intrinsically flattened object seen close to face-on.

A significant fraction of the sample of dwarfs observed by Chilingarian (2009) exhibited central drops in velocity dispersion (see also Ryš et al. 2013). In our sample, only VCC 1475 shows such a decreasing velocity dispersion profile with decreasing radius. This feature is certainly linked with the presence of the two counterrotating components, which induce two peaks in the velocity dispersion map along the major axis, rather than a decrease in the center (see Section 4.3.2).

Although our small sample is not a complete census of the compact low-mass ETGs in the Virgo cluster, it is quite striking that we observe such a variety of kinematic signatures. Indeed, the apparent diversity is remarkably similar to what is observed in more massive ETGs, from nonrotating to highly rotating systems, and in the existence of large-scale, kinematically decoupled components.

Further details regarding the dynamical support of the galaxies in our sample are provided in Section 5 via the specific stellar angular momentum parameter, $\lambda_R$, defined in Emsellem et al. (2007).

4.2. Stellar Populations

Mapping the stellar population parameters of age and metallicity, along with kinematic substructure, can provide interesting constraints on the formation and assembly history of galaxies. Here we present our results on the mass-weighted age and metallicity distributions of the central regions of our objects, obtained as described in Section 3.3.1. Our SSP-equivalent age and metallicity estimates are presented in Table 3 and discussed in more detail in Section 5.3.

On average, our objects comprise old to very old stars, with mass-weighted mean ages of 6–11.5 Gyr. The age variation within one galaxy spans a relatively large range from 0–3.5 Gyr between the center of the galaxy and the maximum radius covered by GMOS-IFU FOV, i.e., about half of the effective radius. Indeed, four galaxies do not show any age gradient (VCC 1192, VCC 1199, VCC 1440, and VCC 1627), whereas the four others show a negative variation of 0.5 Gyr (VCC 1178), 1 Gyr (VCC 1475), 1.5 Gyr (VCC 1297), and
3.5 Gyr (VCC 0032) going toward the center (i.e., younger in the core). Younger central stellar populations in low-mass ETGs were previously noted by others (Michielsen et al. 2008; Chilingarian 2009; Paudel et al. 2011; Ryś et al. 2013) and are interestingly present in both nonrotating (e.g., VCC 0032) and rotating (e.g., VCC 1297) objects. In terms of metallicity, the results of the regularized full spectral fitting show a wide range in behavior among our objects, from fairly flat profiles (e.g., VCC 1178, VCC 1192, VCC 1199, and VCC 1440) to positive gradients with decreasing radius (e.g., VCC 0032, VCC 1297, VCC 1475, and VCC 1627). All of our objects have solar to subsolar stellar populations with metallicity, \([Z/H]\), ranging from −0.8 to +0.2 dex, with a typical variation of, at most, 0.2 dex between the center of the galaxy and the edge of the GMOS-IFU FOV. In most cases, the central regions, which are composed of more metal-rich stars, correspond to younger stellar populations (see Figure 5), in agreement with Michielsen et al. (2008) and studies of more extended dwarf galaxies in the Virgo cluster. However, VCC 1297 has an even more interesting stellar population structure that is discussed below.

### 4.3. Specific Cases

#### 4.3.1. VCC 1297: A Central Black Hole

VCC 1297 (NGC 4486b) is a compact, low-mass ETG that lies very close to the center of the Virgo cluster, just 35 kpc from M87 in projected distance. This M87 companion galaxy has been well studied and is thought to have a central black hole of \(6 \times 10^8 M_\odot\) (Kormendy & Bender 1997). It has been reported to show a double nucleus with a separation of 0″15 (Lauer et al. 1996), but this feature was not evident in imaging from the ACSVCS (Côté et al. 2006; Ferrarese et al. 2006).

Our observations cover the galaxy up to its effective radius of 2″3. Despite its fairly round isophotes (e = 0.088), a thin, fast-rotating disk-like structure is observed in the central 3″ × 1″ region that corresponds to the location of the disky isophotes revealed by the NGVS residuals image (see Figure 2 and also Ferrarese et al. 2006). Its stellar radial velocity peaks at 68 km s\(^{-1}\) at ~1″ along the major axis, in agreement with Kormendy & Bender (1997) to within the uncertainties. The GMOS-IFU data also reveal that the galaxy rotates much more slowly (~20 km s\(^{-1}\) at ~1″ away from the major axis, similar to its rotation at larger radii (\(r \sim 4″\)) along its major axis. The velocity dispersion is about 150 km s\(^{-1}\) within one effective radius but peaks, after a steep inward rise, at 235 km s\(^{-1}\) within the central 1″ × 1″. This strong peak in velocity dispersion leads to a Sérsic-dependent dynamical mass of \(1.1 \times 10^{10} M_\odot\) (see Section 5.1 for details), implying that the black hole contributes more than 5% of the dynamical mass. This puts it significantly above the fundamental relation of black hole—host galaxy masses (Ferrarese et al. 2006).

Very interestingly, the increase of velocity dispersion at the galaxy center coincides with a drop in age. The stars in the central regions are found to be 1.2 Gyr younger than the main body of the galaxy (i.e., 9.3 versus 10.5 Gyr). At the same time, the metallicity map shows a 0.1 dex enhancement along the fast-rotating disk-like structure compared to the main body (0.0 versus −0.1 dex). A gradient within the disk is also visible, with the nucleus being less metal-rich than its outer part. These observations suggest that an episode of star formation happened at the center of this galaxy after its formation, possibly triggered by an external gas accretion that would also explain the metallicity gradient within the disk (i.e., more metal-poor in the center).

#### 4.3.2. VCC 1475: A 2σ Galaxy

VCC 1475 (NGC 4515) is a low-mass ETG containing a kinematically decoupled core (KDC) that was first identified by Koleva et al. (2011b) using long-slit data and later reanalyzed by Toloba et al. (2014a). This galaxy is located in the outskirts of the cluster, about 1.1 Mpc in projected distance from M87 (i.e., 0.7 the subcluster A virial radius). It has a mildly flattened
shape ($e \sim 0.2$) within its effective radius of 9.3″ but becomes increasingly flattened ($e \sim 0.42$) within its central 2″ × 2″, resulting in an ellipticity of 0.35 within the GMOS-IFU FOV. The isophotes in that region are disky, as emphasized in the residual image presented in Figure 2. Our two-dimensional data cover the full KDC and reveal a true counterrotating disk (aligned with the major axis) that has a minimal size of ∼5″ (∼400 pc) in diameter. The two stellar counterrotating components have mean velocity amplitudes of 8 km s$^{-1}$ (inner component) and 16 km s$^{-1}$ (outer component, within the GMOS-IFU FOV). The stellar velocity dispersion map shows two off-center peaks along the major axis, making VCC 1475 a bona fide 2σ galaxy (Krajnović et al. 2011). The amplitudes of the peaks are of order 100 km s$^{-1}$ and correspond to the apparent transition regions between the two counterrotating disks. The velocity dispersion drops to 70 km s$^{-1}$ in the nucleus. We thus confirm the discovery of a KDC in VCC 1475 by Koleva et al. (2011b), but we clearly reveal its counterrotating and 2σ nature with our GMOS-IFU data. Figure 6 presents a magnified view of the kinematic maps for VCC 1475, as well as a comparison of the rotation curve of Koleva et al. (2011b) with that extracted from our GMOS-IFU data. Like VCC 1297, this 2σ galaxy has a stellar population that is 1 Gyr younger in its core region than in the external region covered by our observations (9.5 versus 10.5 Gyr). This outward increase in age is accompanied by a decline in metallicity going from the central to outer regions (∼0.1 versus ∼0.5 dex, respectively). These differences in stellar populations seem to spatially match the two kinematically distinct components and are very similar to the behavior seen in VCC 0032, both in terms of age and metallicity gradients. The kinematically distinct inner component in VCC 1475, coupled to its younger stellar populations, strongly suggests that a dissipative accretion event has occurred in this galaxy, followed by an episode of star formation.

5. DISCUSSION

In Sections 3 and 4, we have analyzed two-dimensional spectroscopic data for eight compact dwarf ellipticals in the Virgo cluster obtained with the GMOS-IFU instrument. In this section, we discuss our findings in the context of possible ETG evolution scenarios.

5.1. Mass, Size, and Local Galaxy Density

A key goal of our study is to understand whether the compactness of our program objects is related in any way to a specific physical evolutionary process. Many previous investigations have emphasized the importance of harassment (Moore et al. 1998; Boselli et al. 2008), strangulation (Smith et al. 2012), ram-pressure and tidal stripping (Gnedin 2003; Mayer et al. 2006; Lisker et al. 2013; Toloba et al. 2014c), and, more generally, interactions with the underlying galaxy population or intergalactic medium in the evolution of low-mass galaxies (Boselli et al. 2014). In that spirit, we first turn our attention to the relationship between the basic properties of our targets and the galactic density in the regions in which they reside.

In Figure 7, we use the unique coverage and depth of the NGVS data set to examine this relationship for Virgo galaxies using a mass–size diagram (effective radius, $R_e$, versus dynamical mass, $M$). We compute masses for our objects using the virial theorem

$$M = 0.7 \beta (n_0 \sigma_b^2 R / G),$$

Figure 6. Radial stellar velocity, $V$, and velocity dispersion, $\sigma$, maps for VCC 1475 from GMOS-IFU data (top row). The $x$ and $y$ axes are both in arcseconds. The black dotted lines indicate the region of the galaxy observed with a long slit by Koleva et al. (2011b). The bottom panels show comparisons of the Koleva et al. (2011b) $V$ and $\sigma$ profiles with comparable long-slit data simulated from our GMOS-IFU observations. The error bars are computed using the light weighted standard deviation of the points considered within the simulated slit. Koleva et al. (2011b) error bars are typically 0.7 km s$^{-1}$ and are smaller than the marker points.
where $\beta(n)$ depends on the Sérsic index, i.e., the radial profile of the surface brightness, following Equation (20) of Cappellari et al. 2006; see Bertin et al. 2002. Here, $\sigma_R$ denotes the stellar velocity dispersion within an aperture of radius $R$, and $G$ is the gravitational constant. We used the Sérsic indices measured from the $i$-band NGVS images and derived the velocity dispersion within the largest ellipse covered by our observations to estimate $\sigma_R$ using Equation (1) of Cappellari et al. 2006. For an aperture of one effective radius, this mass is representative of the enclosed dynamical mass (Cappellari et al. 2006, 2013a). Our derived masses are presented in Table 3.

We then combined our sample with 39 (on average) more extended objects from Toloba et al. (2014b) observed with the long-slit part of the SMAKCED survey and representative of the low-mass ETGs of the Virgo cluster within the magnitude range $-19.0 < M_r < -16.0$. Dynamical masses from these objects were derived by Toloba et al. (2014b) in a way similar to ours, using the Sérsic-dependent virial estimate. We also compared the NGVS effective radius values with those of Toloba et al. (2014b) for the objects in common and found a very good agreement. Therefore, we can be confident in the relative position of our sample compared to the Toloba et al. (2014b) sample in the mass–size diagram. We also extended the analysis to significantly higher masses using 56 Virgo ETGs observed as part of the ATLAS3D project. The sizes and masses for the ATLAS3D sample come from Cappellari et al. (2013a, 2013b). The masses were derived via anisotropic Jeans dynamical modeling and were shown to give good agreement with Sérsic-dependent virial mass estimates (Cappellari et al. 2013a). As expected, Figure 7 (panel (a)) shows that our sample contains low-mass ETGs that are more compact than those targeted in Toloba et al. (2014b). Indeed, for the same dynamical mass ($10^{9}$–$10^{10} M_\odot$), our galaxies have effective radii that are nearly an order of magnitude smaller than their extended counterparts: thus, our study probes a new parameter space for low-mass ETGs. Clearly, it will be of interest in future IFU surveys to target galaxies in this underrepresented part of parameter space. Note that the prominent gap in mass between Toloba et al. (2014b) and ATLAS3D ETGs in Figure 7 is purely due to sample selection effects. Two objects from our sample, namely VCC 1178 and VCC 1297, are of particular interest as they overlap in mass with the low-mass range of the ATLAS3D objects (see also Figure 10) but are located within the “zone of exclusion” (ZOE) defined by Cappellari et al. 2013b). Both objects have an absolute $K$-band magnitude ($M_K = -21.4$ and $-20.8$, respectively) that is fainter than the ATLAS3D sample selection definition ($M_K < -21.5$). At face value, this implies an

Figure 7. Location of Virgo galaxies from our GMOS-IFU sample, those of Toloba et al. (2014b) observed with a long slit, and of Cappellari et al. (2013b) from the ATLAS3D survey, in the mass–size $(M - R_e)$ plane, with color-coded symbols representing a proxy of the local galaxy density. The (a) and (c) (left) panels use the luminosity of the brightest galaxy among the 15 closest neighbors of the target galaxy, normalized by its luminosity, $L_{\text{max}} / L_r$; the (b) and (d) (right) panels use the $\Sigma_{15}$ parameter, defined as the number of galaxies per square degree within a region that includes the 15 neighbors closest to the target galaxy. The bottom panels show a LOESS version of the original data set presented in the top panels using a regularization factor of 0.3. The gap between the low- and high-mass ETGs is due to sample selection effects.
unusually high mass-to-light ratio for these objects, but detailed modeling would be required to determine the cause of this, which is outside the scope of this paper.

In Figure 7, the galaxy density is expressed in two different flavors: (1) the luminosity of the brightest galaxy among its 15 closest neighbors, normalized by the luminosity of the target galaxy, $L_{\text{max}}/L$; and (2) the surrounding galaxy density, $\Sigma_{15}$, defined as the number of galaxies per square degree within a projected region that includes the 15 closest neighbors to the target galaxy. These two values for our sample galaxies are presented in Table 3. The first result that emerges from these plots (Figure 7) is that the five low-mass galaxies that depart most dramatically from the main mass-size sequence (VCC 1178, VCC 1192, VCC 1199, VCC 1297, VCC 1627) are all found in regions of high galaxy density (i.e., high $\Sigma_{15}$; see panel (b)) and, most importantly, that also contain a massive galaxy (i.e., high $L_{\text{max}}/L$; see panel (a)), as expected because they are in close proximity to either M87 (NGC 4486), M49 (NGC 4472), or M89 (NGC 4552). The fact that most galaxies above $10^{10} \, M_\odot$ have low $L_{\text{max}}/L$ parameters is a natural consequence of the galaxy luminosity function; the probability that such a galaxy will be found next to an even more massive galaxy is lower than for low-luminosity objects. In the low-mass regime ($<10^{10} \, M_\odot$), we indeed see a much wider range of $L_{\text{max}}/L$ values, which makes the high $L_{\text{max}}/L$ value of the more compact low-luminosity galaxies even more relevant. Interestingly, these five objects have very small numbers or no globular cluster systems (Peng et al. 2008), suggesting indirectly that they could have experienced tidal stripping events. If, rather than using $L_{\text{max}}/L$, we use the normalized total luminosity $L_{\text{tot}}/L$, the results do not change.

To better reveal the first-order relations in the three-dimensional space, we also smoothed the data using the two-dimensional locally weighted regression (LOESS) method (Cleveland & Devlin 1988), implemented as described in Cappellari et al. (2013b). The results are shown in the two bottom panels of Figure 7 (panels (c) and (d)). This analysis used a regularization factor of 0.3.

Ultimately, we performed the same exercise with a various number of closest neighbors $N$ (i.e., $N = 3, 10$, and 25), and we did not see any significant changes in the trends, except a systematic increase of $L_{\text{max}}/L$ with $N$ (as expected from the cluster luminosity function).

5.2. Rotational Support: The $\lambda_R - \epsilon$ Diagnostic

Emsellem et al. (2011) used the specific stellar angular momentum versus ellipticity diagram ($\lambda_R - \epsilon$) to classify massive ETGs, reporting an empirical criterion with which to identify slow and fast rotators (that represent $\sim 15\%$ and $85\%$ of the ATLAS3D sample, respectively). This scheme has been used subsequently to constrain the properties of possible low-mass ETG progenitors (Ryš et al. 2013; Toloba et al. 2014c). According to the method given in Emsellem et al. (2007) to derive $\lambda_R$ profiles for all galaxies in our sample (up to the maximum radius coverage of the GMOS-IFU FOV). Our FOV limit corresponds to $R_{\text{eff}}$ for all galaxies in our sample, except for VCC 1440 and VCC 1475, which are only covered up to $R_{\text{eff}}/3$. The measured values of $\epsilon$ are presented in Table 1, and $\lambda_R$ in Table 3. The $\lambda_R$-$\epsilon$ diagram is shown in Figure 8.

We find six fast rotators (75\%) among our sample of eight galaxies: VCC 1178, VCC 1192, VCC 1199, VCC 1297, VCC 1440, and VCC 1627. The two remaining galaxies are classified as slow rotators: VCC 0032 and VCC 1475. The fraction of slow rotators in low-mass compact ETGs (25\%) is slightly higher than that found among high-mass ETGs, but given the small number of objects in our sample, the difference is not significant. Still, it is worth pointing out that the fraction of slow rotators among the entire low-mass ETG population (i.e., the Ryš et al. 2014, Toloba et al. 2014c, and present GMOS-IFU sample combined) is still at least 25, or 10\% higher than in high-mass ETGs. Interestingly, VCC 0032 shows gradual but large variations in both ellipticity and position angle within its inner 40", as well as disky isophotes. It may therefore represent a true slow rotator, as opposed to a more face-on fast rotator. The low $\lambda_R$ value of VCC 1475 is not unexpected because we have shown it to be an unambiguous $2\sigma$ galaxy (Krajnović et al. 2011; see Section 4.3.2).

Our sample galaxies are found to have $0.1 \lesssim \lambda_R/\epsilon \lesssim 0.4$ and relatively low ellipticities: $\epsilon \ll 0.4$. This is similar to what has been found for more extended low-mass ETGs by both Ryš et al. (2014) and Toloba et al. (2014c). Note that the Ryš et al. (2014) $\lambda_R$ values are derived at $R_{\text{e}}$, creating a systematic, but not significant, positive offset. None of our targets reach the high values of $\lambda_R/\epsilon > 0.4$ or $\epsilon > 0.4$ that are commonly observed in higher mass ETG samples (Emsellem et al. 2011).

Toloba et al. (2014c) suggested the existence of a correlation between $\lambda_R$ and the projected distance to the center of the cluster (e.g., M87), as well as the presence of subtle disky
structures in fast rotators. Among our targets, VCC 0032, VCC 1475, and VCC 1440 are the outermost galaxies. They are the most extended objects and are located in regions of relatively low galaxy density. The five remaining objects (VCC 1178, VCC 1192, VCC 1199, VCC 1297, and VCC 1627) are found close to either M87 or a large companion (see Section 5.1) and are all fast rotators. More interestingly, they are faster rotators than the three remaining objects and are also the most compact objects of our sample. While these results may appear in contradiction with the trend suggested by Toloba et al. (2014c)—that, on average, \( \lambda_\text{E} \) normalized by \( \sqrt{c} \) (see Emsellem et al. 2011; Toloba et al. 2014c) is lower at small distances from M87—their trend seems weaker, or even absent (see their Figure 5), for galaxies with disk-like structures. Three of the five compact galaxies may have such disk features, suggested by their disky isophotes, so it may not be surprising if they do not participate in such a trend. Observations of larger galaxy samples are definitively needed to confirm, or not, these possible trends.

5.3. Stellar Content and Star-formation History

We now analyze the age and metallicity of the stellar populations in our target galaxies as tracers of their formation and assembly history. Because the SSP-equivalent ages and metallicities were derived from the stacked spectra, they reflect the SSP that dominates the light within the central regions, i.e., \( R_e/2 \) or \( R_e/3 \) (see Table 3). No trend is found between the stellar population parameters and the location of our targets within the cluster (the local galaxy density) or their \( \lambda_\text{E} \) parameter. This is qualitatively in agreement with Toloba et al. (2014b). It is, however, interesting to note that all objects with underlying disky isophotes, aside from VCC 0032, show the oldest SSP.

As emphasized in Section 5.1, the galaxies in our sample are more compact than those examined in other studies of low-mass ETGs. Thus, we investigated the potential link between their compactness and their stellar population age and metallicity, as shown in Figure 9. Here we present the GMOS-IFU sample in terms of their SSP-equivalent age and metallicity distributions in the mass–size diagram. To compare our sample to more extended low-mass ETGs, we have added the objects from Toloba et al. (2014b), shown as triangles. No clear trend appears between the age and the location of the objects in the mass–size plane, although, on average, the compact ETGs are older than less compact systems (panel (a) of Figure 9). A possible trend is visible between the metallicity and the compactness of low-mass ETGs (panel (b) of Figure 9); for example, more compact objects tend to be more metal-rich. In the context of low-mass ETGs being formed through stripping and harassment, Ryš et al. (2014) showed that these objects become more compact than their progenitors, which are often assumed to be late-type, low-mass spiral galaxies. The GMOS-IFU sample includes more compact objects than those in Toloba et al. (2014c) and Ryš et al. (2014), so we would expect our objects to have been further processed. Our findings of older and more metal-rich stellar populations in the most compact ETGs are fully consistent with this picture.

In the broader context of galaxy formation, there exists a longstanding debate on whether low- and high-mass ETGs show a dichotomy in their properties, i.e., whether they represent two distinct populations (as first advocated by Kormendy 1985), or whether they form a more continuous sequence in terms of their structure, kinematics, and stellar populations. Most recent studies of photometric scaling relations and isophotal parameters suggest a continuity between the low- and high-mass regimes (Jerjen & Binggeli 1997; Graham & Guzmán 2003; Gavazzi et al. 2005; Ferrarese et al. 2006; Côté et al. 2007), but an alternative view is favored by Kormendy et al. (2009). Recent surveys, especially those using IFU spectroscopy, have characterized the detailed kinematics and stellar population properties of more massive ETGs. Using them as a reference sample, we have combined the 260 massive ETGs (10^{10} M_\odot < M < 10^{12} M_\odot) by Kormendy et al. 2009 with the 39 low-mass ETGs from Toloba et al. (2014b) and our eight compact low-mass ETGs. We focus here on the SSP-equivalent stellar population information (e.g., age and metallicity) as projected onto the mass–size diagram (see Figure 10). As in Figure 7, we smoothed the raw data (panels (a) and (b) of Figure 10) using the LOESS method with a regularization factor of 0.3 to reveal the first-order relationship in the three-dimensional space (panels (c) and (d) of Figure 10).

The first striking result from this figure is that there is a level of continuity in age and metallicity for ETGs between 10^8 M_\odot and 10^{12} M_\odot. As observed in McDermid et al. (2015), at fixed size, more massive galaxies are older; alternatively, at fixed mass, larger galaxies are younger. In terms of metallicity, low-mass ETGs that are more compact are also more metal-rich, and more massive galaxies in general tend to have a more metal-rich stellar population (Thomas et al. 2010; McDermid et al. 2015). It is also interesting to note that the ages and metallicities of the most compact low-mass ETGs are more representative of more massive ETGs, rather than of less compact galaxies with comparable mass. This similarity between compact low-mass and massive ETGs has already been observed, in term of metallicity only, by Chilingarian (2009) for a sample of 21 compact ellipticals in the local group. This is in agreement with McDermid et al. (2015), who showed that the stellar population parameters of massive ETGs in the mass–size plane roughly follow lines of isovelocity dispersion (see also Cappellari et al. 2011), as indicated by the light-blue dotted lines in Figure 10. In fact, we find that this result can be extended to low-mass ETGs, as shown in Figure 10 (albeit with a large scatter in the age distribution), with the transition between low- and high-mass ETGs being smooth. Taken at face value, this naively suggests that low-mass ETGs (10^8 < M < 10^{10} M_\odot) may have been shaped by the same secular or environmental mechanisms as their massive counterparts (M > 10^{10} M_\odot). However, this does not necessarily imply that galaxies evolve along either isovelocity dispersion lines or constant-metallicity lines. Only detailed simulations focused on stellar population and kinematic parameters would give us clues about the evolutionary track in each scenario (e.g., tidal stripping, ram-pressure stripping, harassment). Figure 10 mostly confirms that velocity dispersion is a good predictor of the age and metallicity of galaxies (Graves & Faber 2010; Wake et al. 2012; McDermid et al. 2015), even for low-mass ETGs.

Finally, if we consider the two-dimensional, mass-weighted age and metallicity maps for our objects (see Figure 5 and Section 4.2), we see that nearly half our program objects contain a younger and more metal-rich stellar population in
their cores. This result is in agreement with what has been previously observed in “dwarf” galaxies (e.g., Lisker et al. 2006; Michielsen et al. 2008; Chilingarian 2009; Spolaor et al. 2010a; Ryš et al. 2013), as well as in many more massive ETGs by Kuntschner et al. (2010). This finding adds further support to the notion of a continuity among low-mass and high-mass ETGs.

5.4. Formation Scenarios

Over the past decade, many studies have argued for a scenario in which the low-mass (“dwarf”) ETGs in clusters originated from late-type, star-forming galaxies that were transformed by the cluster environment (Moore et al. 1998; Boselli et al. 2008; Toloba et al. 2009, 2014c; Ryš et al. 2014). Two main mechanisms are usually invoked to transform the infalling objects. First, ram-pressure stripping removes gas in about 100–200 Myr and rapidly quenches the star formation on a timescale of ∼1 Gyr (Boselli et al. 2008). Second, gravitational tidal harassment dynamically heats the low-mass ETG progenitors, lowering their angular momentum and concentrating the stellar component (leading to more compact systems; Ryš et al. 2014). A third process is certainly also at play: starvation (Larson et al. 1980), which is a form of gas stripping but acts on a much longer timescale (>5 Gyr), as shown by Boselli et al. (2009) (see their Figure 4), and affects more efficiently the gaseous halo rather than the inner regions. This process tends to significantly decrease the surface brightness of the affected object but keeps its characteristic size rather unchanged, in contrast to the effect of ram-pressure stripping (see Figure 3 of Boselli et al. 2009). Starvation is therefore not able to solely explain the properties of low-mass ETGs, especially for the more compact ones. However, it certainly helps in stopping their star formation, especially in clusters where a high rate of interactions can easily remove the gas (Rasmussen et al. 2012).

The exact nature of the progenitors is still a matter of debate. Lisker et al. (2013), based on a comparison between Virgo observations and Millenium II simulations, pointed out that late-type galaxies in the local universe may not be representative of the progenitors of today’s low-mass ETGs. They computed the time spent by a low-mass ETG inside a high-mass (M > 10^{12} M_☉) halo, as well as the mass loss since first entering the halo (see their Figure 4). According to their analysis, and using the galaxy density parameter Σ_{10} derived from the NGVS (see Section 5.1), our sample galaxies would have spent, on average, ∼7 Gyr inside a halo more massive than 10^{12} M_☉. Because our objects have a median age of 9 Gyr, this suggests that they have spent most of their lives inside a massive halo, experiencing a variety of environmental effects (i.e., from close pair to group interactions) that would certainly have helped shape their present-day structure. Because the scatter in these correlations is quite large, it is hardly surprising for some galaxies to undergo infall at later times or experience quite different interaction histories. This stochasticity could explain the diversity in kinematics and stellar populations observed in low-mass ETGs, as well as the highly compact nature of some (rare) objects in dense regions.

The galaxies in our sample have λ_R values that are lower than more massive galaxies but are consistent with “typical” values found for low-mass ETGs. Gravitational harassment (including tidal stripping) could explain such a decrease in angular momentum, and one might naively expect that the longer a given galaxy stays in the cluster, the more angular momentum it loses and the more compact it becomes. However, our galaxy sample does not show a systematically lower specific angular momentum than less compact, low-mass ETGs. This may suggest either that their compactness is not related solely to gravitational harassment, or that this process (especially tidal stripping) can sometimes raise the stellar angular momentum of the system.

Several of our program galaxies harbor younger and more metal-rich stellar populations in their center compared to their
outskirts. This is consistent with what one would expect from ram-pressure stripping, where the pressure of the intracluster medium can remove gas from a galaxy but its efficiency depends on the relative strength of the gravitational potential of the object. The gas is thus more easily removed from the outskirts of a galaxy than from its center, where it can stay bound to its host and continue forming stars (see Fumagalli et al. 2014, in the case of a late-type galaxy). Gravitational tidal forces could also be responsible for younger stellar populations in the centers of low-mass ETGs as they promote the formation of bars (Mayer et al. 2006) that are known to induce gas infall.

Other scenarios could potentially explain these observations, though: simple secular evolution or external accretion of gas, i.e., from the intergalactic medium or from a gas-rich companion (interaction, merger). The latter is more likely to occur in small groups, before a galaxy enters the dense regions of the present-day cluster where the relative velocities are high. The existence of $2\sigma$ galaxies in the low-mass ETG population may also provide some constraints pertaining to their formation and evolution. The counterrotating disk in VCC 1475, as revealed by our two-dimensional spectroscopy, appears as a rather thin, central structure. N-body simulations predict that $\approx1\%$ of the dwarfs in Virgo could exhibit counterrotation due to harassment (González-García et al. 2005). However, the formation of such a counterrotating structure via this process would make the outer part of the galaxy ($R > R_e$) counterrotating, and this is not what is observed for VCC 1475. A pure stellar merger event is also unlikely in this case because the inner disk is more metal-rich than the surrounding stellar component. A gas-accretion event is a more promising hypothesis, probably the result of an interaction with a gas-rich galaxy (see Toloba et al. 2014a for more details about KDC formation scenarios in cluster environments). The exact origin of this $2\sigma$ galaxy is unclear, but its appearance in a low-mass ETG sample certainly adds a level of complexity to the stripping and harassment scenario, emphasizing the importance of the precluster environmental history of cluster galaxies.

In summary, we have shown that the properties of the stellar populations in low-mass ETGs show a level of continuity with more massive ETGs drawn from the ATLAS$^3D$ survey (which itself is representative of the local volume within 40 Mpc). The age and metallicity follow the lines of isovelocity dispersion ($\sigma = 20, 30, 50, 100, 200, $ and $250$ km s$^{-1}$ (from left to right) as implied by the virial mass estimator $M = 5R_e \sigma^2/G$. The gap between the low- and high-mass ETGs is due to sample selection effects.

Figure 10. Location of our GMOS-IFU galaxies (circle symbols) in the mass–size diagram. Samples from Toloba et al. (2014b) observed with a long slit (triangle symbols) and from McDermid et al. (2015) from the ATLAS$^3D$ survey (square symbols) have been added to the diagram. The colors of each symbol correspond to the SSP-equivalent age (left panel) and metallicity (right panel) as indicated by the color bars in each panel. The light-blue dotted lines represent the lines of constant velocity dispersion $\sigma = 20, 30, 50, 100, 200,$ and $250$ km s$^{-1}$ (from left to right) as implied by the virial mass estimator $M = 5R_e \sigma^2/G$. The gap between the low- and high-mass ETGs is due to sample selection effects.
6. SUMMARY

We have presented and analyzed spectroscopic observations for eight low-mass compact ETGs in the Virgo cluster using the GMOS-IFU instrument mounted on the Gemini North 8 m telescope. These objects were selected from Bingelli et al. (1985) and our next Generation Virgo Cluster Survey (NGVS; Ferrarese et al. 2012) to probe a regime of ETG size and surface brightness that has largely been unexplored with IFU instruments. Our goal has been to characterize their basic kinematics and stellar populations in order to examine possible connections between this rare class of galaxy with more massive ETGs. We performed kinematics and stellar population analysis using full spectral fitting. Our main results can be summarized as follows:

1. We calculated the dynamical mass inside one effective radius for each of our objects and confirmed that these galaxies are more compact than most ETGs of comparable mass (Toloba et al. 2014c; Rys et al. 2014). The sample galaxies span a dynamical mass range of $4.5 \times 10^8$ to $1.1 \times 10^{10} M_\odot$ and have effective radii of 165–740 pc. Using the parameters $L_{\text{max}}/L_{\text{gal}}$ and $\Sigma_{15}$ as proxies for the local galaxy density, we have found that the most compact low-mass ETGs are preferentially found in high-density regions and often close to a very massive galaxy.

2. The two-dimensional maps of stellar radial velocity, $V$ and velocity dispersion, $\sigma$, of our objects show a large variety of kinematic structures: from nonrotating systems to those with well-organized and high rotation, as well as velocity dispersion profiles that vary from flat to centrally peaked. Our data also provide unambiguous evidence for the $2\sigma$ nature of the low-mass galaxy VCC 1475. In most cases, low-mass compact ETGs with organized and high radial stellar velocity exhibit disky isophotes, as revealed by the analysis of the NGVS deep images.

3. We assessed the rotational support in these galaxies by calculating their specific apparent angular momentum, $\lambda_{R_e}/r_e$, finding two slow rotators and six fast rotators. Our sample galaxies have $\lambda_{R_e}/r_e$ values similar to those found previously in more extended low-mass ETGs (Rys et al. 2013; Toloba et al. 2014c), and none of them reach values higher than 0.4, as is sometimes observed in more massive galaxies (Emsellem et al. 2011). They are generally round objects, and we do not find very flattened galaxies ($e > 0.4$). Three of the five most compact low-mass ETGs have disky isophotes, and all of them are fast rotators with the highest specific angular momentum of our sample.

4. We found that our program galaxies contain old stars, between 6 and 11.5 Gyr, with metallicity between $-0.7$ and 0.2. Half of our sample galaxies contain younger and more metal-rich stellar populations in their centers. Interestingly, low-mass compact ETGs with underlying disky isophotes are found to have the oldest stellar populations among our sample.

5. We derived SSP-equivalent ages and metallicities within $R_e/2$ for our program galaxies, finding a striking continuity between the low-mass and high-mass ETGs (Cappellari et al. 2013a). The more compact galaxies, at a fixed mass, are found to have more metal-rich and older (albeit with a larger scatter) stellar populations. We also extended the results from McDermid et al. (2015) to low-mass ETGs, showing that the velocity dispersion is a relatively good predictor of the stellar population properties.

Our results are consistent with a scenario in which low-mass, compact ETGs have spent a large fraction of their lives in the cluster environment and have been strongly shaped by environmental mechanisms such as ram-pressure stripping, tidal stripping, starvation, and gravitational harassment. This picture is quantitatively supported by a comparison of our data to the study of Lisker et al. (2013), who jointly analyzed Millennium II simulations and Virgo galaxy observations. Our study underscores the importance of environmental history for low-mass ETGs, such as close pairs and groups before the present-day cluster epoch. Perhaps most significantly, our study adds to a growing body of evidence that a continuity exists in the structural, kinematic, and stellar population properties of low- and high-mass ETGs, which in turn suggests that ETG formation and evolution processes vary smoothly with mass, size, and environment across the full range in galaxy mass. A more detailed account of the relative weight of each evolutionary process should wait for observations of larger galaxy samples and realistic numerical simulations.

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Facilities: Gemini: Gillett, CFHT

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