The Next Generation Virgo Cluster Survey (NGVS). XXXI. The Kinematics of Intracluster Globular Clusters in the Core of the Virgo Cluster

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Abstract

Intracluster (IC) populations are expected to be a natural result of the hierarchical assembly of clusters, yet their low space densities make them difficult to detect and study. We present the first definitive kinematic detection of an IC population of globular clusters (GCs) in the Virgo cluster, around the central galaxy M87. This study focuses on the Virgo core, for which the combination of Next Generation Virgo Cluster Survey photometry and follow-up spectroscopy allows us to reject foreground star contamination and explore GC kinematics over the full Virgo dynamical range. The GC kinematics changes gradually with galactocentric distance, decreasing in mean velocity and increasing in velocity dispersion, eventually becoming indistinguishable from the kinematics of Virgo dwarf galaxies at $R > 320$ kpc. By kinematically tagging M87 halo and intracluster GCs, we find that (1) the M87 halo has a smaller fraction ($52 \pm 3\%$) of blue clusters with respect to the IC counterpart ($77 \pm 10\%$), (2) the ($q’-r’$)$_0$ versus ($i’-z’$)$_0$ color–color diagrams reveal a galaxy population that is redder than the IC population, which may be due to a different composition in chemical abundance and progenitor mass, and (3) the ICGC distribution is shallower and more extended than the M87 GCs, yet still centrally concentrated. The ICGC specific frequency, $S_{N,ICL} = 10.2 \pm 4.8$, is consistent with what is observed for the population of quenched, low-mass galaxies within 1 Mpc from the cluster’s center. The IC population at Virgo’s center is thus consistent with being an accreted component from low-mass galaxies tidally stripped or disrupted through interactions, with a total mass of $M_{ICL, tot} = 10.8 \pm 0.1 \times 10^{11} M_\odot$.

Key words: galaxies: clusters: individual (Virgo) – galaxies: individual (M87) – galaxies: kinematics and dynamics – galaxies: star clusters: general – globular clusters: general

1. Introduction

Mergers are believed to play a dominant role in the assembly of massive galaxies (De Lucia & Blaizot 2007). A two-phase formation scenario (Naab et al. 2009) predicts that in a first dissipative phase (high redshift, $z \lesssim 2$) stars form quickly and build the compact innermost regions of massive galaxies (with stars rich in $\alpha$ elements; Thomas et al. 2005); later, minor mergers dominate the mass assembly in the outermost regions (Oser et al. 2010), and the accretion of metal-poor stars from smaller stellar systems results in the variation of the galaxy stellar properties. In dense environments, accretion is even more dramatic, such that close to the dynamical center of clusters, central galaxies are expected to have accreted a majority of their stars (Laporte et al. 2013; Cooper et al. 2015).

In galaxy clusters, a fraction of their baryonic content is represented by the intracluster light (ICL), or “diffuse light”, a component that is gravitationally unbound to cluster galaxies but bound to the cluster potential (e.g., Murante et al. 2004; Rudick et al. 2006; Dolag et al. 2010; Puchwein et al. 2010; Contini et al. 2014). Galaxy interactions and tidal interactions between galaxies and the cluster potential are both believed to...
play an important role in the production of the ICL. Hence, the ICL is thought to be intimately linked to the dynamical history of the cluster, so the ICL’s observable features contain information about the evolutionary processes that took place in these dense environments.

Despite its dynamical definition and low surface brightness (SB; its peak in SB corresponds to ~1% of the brightness of the night sky; Vílchez-Gómez 1999), the ICL is usually identified on the basis of its photometric properties. It is either identified as any optical light below a fixed SB limit (Feldmeier et al. 2004a; Mihos et al. 2005, 2017; Zibetti et al. 2005), or as the less-concentrated light profile that overlaps the one of the galaxy’s halo (Gonzalez et al. 2005; Seigar et al. 2007). These studies have shown that the detected ICL is often a discernibly separate entity from the host galaxies, with well-defined transitions in the SB profile, axis ratio, and position angle, and whose evolution is tied to the cluster as a whole rather than to the central galaxy. In theoretical studies, in which the ICL is dynamically identified in terms of either binding energy (stars that are not bound to identified galaxies, including the central one; Murante et al. 2004) or velocity distribution (broader for the ICL than for the galaxy halo; Dolag et al. 2010; Contini et al. 2014), the authors find two distinct stellar populations in terms of kinematics, spatial distribution, and physical properties like age and metallicity, suggesting that the identification of the system galaxy+ICL as a single entity is ill defined. However, in several observational and theoretical analyses (e.g., Gonzalez et al. 2007; Cooper et al. 2015), no separation is made between galaxy halos and the ICL, and the two components are treated as a continuum.

In nearby clusters, individual tracers can be used to study the diffuse cluster light around galaxies. They can trace its spatial distribution, age, and metallicity, and, when spectroscopy is available, they allow us to gather information on the kinematics of this diffuse component, leading to a less ambiguous definition of galaxy halos and ICL (Longobardi et al. 2015a). Individual stellar tracers include supernovae (Gal-Yam et al. 2003; Dilday et al. 2010; Sand et al. 2011; Barbary et al. 2012), red giant and supergiant stars (Ferguson et al. 1998; Durrell et al. 2002; Ohyama & Hota 2013), planetary nebulae (PNs; Arnaboldi et al. 1996, 2004; Feldmeier et al. 2004a; Aguerri et al. 2005; Gerhard et al. 2005; Ventimiglia et al. 2011; Longobardi et al. 2013, 2015a; Hartke et al. 2017, 2018), and globular clusters (GCs; McLaughlin et al. 1994; Jordán et al. 2004; Williams et al. 2007; Lee et al. 2010; Peng et al. 2011; Strader et al. 2011; Romanowsky et al. 2012; Durrell et al. 2014; Alamo-Martínez & Blakeslee 2017; Ko et al. 2017).

GCs are compact groups of stars that are found to inhabit all types of galaxies more luminous than ~3 \times 10^9 L_☉ (e.g., Georgiev et al. 2010), with the most luminous systems characterized by higher GC specific frequencies (e.g., Harris & van den Bergh 1981; Brodie & Strader 2006; Peng et al. 2008; Georgiev et al. 2010). Several GC studies have shown that the properties of these systems are correlated with those of their host galaxies (Brodie & Huchra 1991; Harris 1991; Peng et al. 2006, 2008; Harris et al. 2013), suggesting a link between their formation and the evolution of the galaxy itself. It is now well established that the GC systems, within the majority of large galaxies, possess two or more subpopulations of clusters characterized by very different chemical compositions (e.g., Gebhardt & Kissler-Patig 1999; Puzia et al. 1999; Forbes & Forte 2001; Kundu & Whitmore 2001; Larsen et al. 2001; Puzia et al. 2005a, 2005b; Peng et al. 2006; Leaman et al. 2013; Tonini 2013; Harris et al. 2017). The most popular division uses optical colors to identify a red (metal-rich) and a blue (metal-poor) population of GCs, although the existence of an additional, intermediate, population of GCs has been claimed (Peng et al. 2009; Strader et al. 2011; Agnello et al. 2014). To these different classes correspond different observed properties, so red and blue GCs are measured to have different kinematics and spatial distribution (Zepf et al. 2000; Côté et al. 2001, 2003; Schroder et al. 2002; Perrett et al. 2003; Peng et al. 2004; Schuberth et al. 2010; Strader et al. 2011; Coccato et al. 2013; Agnello et al. 2014; Zhang et al. 2015). Also, the relative fraction of blue-to-red GCs increases with galactocentric radius, probably tracing the hierarchical processes that built up the stellar halos of the galaxies (e.g., Côté et al. 1998, 2000, 2002; Tonini 2013; Lim et al. 2017). It is important to emphasize, however, that the interpretation of a single color as a measure of metallicity is a simplification. Such an interpretation presents the uncertainty driven by the nonlinearity in the relation (Peng et al. 2006; Cantiello & Blakeslee 2007; Richtler 2013) and wrongly assumes that the same stellar population characteristics found in the Local Group apply to dense environments (Blakeslee et al. 2012; Powalka et al. 2017).

As a consequence of their brightness and spatial extension, GCs are powerful tracers of the galaxies’ outer halos, also bridging the transition region between the galaxies and the ICL that surrounds them. Single intragroup/cluster GCs have been detected in A1185 (Jordán et al. 2003; West et al. 2011), Fornax (Firth et al. 2008; Schuberth et al. 2008), Virgo (Williams et al. 2007; Firth et al. 2008; Lee et al. 2010; Ko et al. 2017), Coma (Peng et al. 2011), and A1689 (Alamo-Martínez & Blakeslee 2017). However, the identification of a large sample of tracers has been elusive, mainly due to a significant level of contamination (see Section 2.3).

The Virgo cluster, the nearest large-scale structure in the universe, and its central galaxy M87 have long been the targets of GC studies with the aim of tracing their formation and evolution (e.g., Baum 1955; Mould et al. 1987; Jordán et al. 2002; Côté et al. 2004; Ferrarese et al. 2012; Brodie et al. 2014). Virgo is characterized by both spatial and kinematic substructures (Binggeli et al. 1987). Moreover, the evidence that many galaxies are presently falling toward the cluster core (Tully & Shaya 1984; Conselice et al. 2001; Boselli et al. 2008, 2014) and the presence of a complex network of extended tidal features (Mihos et al. 2005, 2017) suggest that the Virgo core is not completely in equilibrium. Close to its dynamical center lies M87 (Binggeli et al. 1987; Nulsen & Bohringer 1995; Mei et al. 2007). It is considered a cD galaxy (e.g., Carter & Dixon 1978) with an extended stellar envelope that reaches out to a projected galactocentric radius of ~150 kpc (Ferrarese et al. 2006; Kennelly et al. 2009; Janowiecki et al. 2010). Evidence of the galaxy experiencing a gas-rich major merger event can be found in its central regions, hosting a kinematically distinct core (KDC) in its inner 5 kpc (Emsellem et al. 2014). Moreover, Ho studies have shown the presence of prominent filaments of ionized gas extending out to 10 kpc from the galaxy’s nucleus (Arp 1967; Ford & Butcher 1979; Sparks et al. 1993; Gavazzi et al. 2000). Evidence of accretion is traced by age and metallicity gradients in the
galaxy’s inner region (Liu et al. 2005; Montes et al. 2014), together with blue color gradients toward the outer regions (Rudick et al. 2010; Mihos et al. 2017). Furthermore, at large radii, kinematic signatures of accretion events are found in the orbital distribution of GCs (Agnello et al. 2014; Oldham & Evans 2016), in the kinematics of UCDs (Zhang et al. 2015), as well as in the presence of kinematic substructures in the velocity phase space of GCs (Romanowsky et al. 2012) and PNs (Longobardi et al. 2015b). A large accretion event (the crown of M87; Weil et al. 1997; Longobardi et al. 2015b) was found to contribute 60% of the total light at its highest density point (60–90 kpc NW of the galaxy; Longobardi et al. 2015b), showing that M87 is still assembling in a substantial way.

This work follows other recent Next Generation Virgo Cluster Survey analyses with the aim of studying the Virgo core (Zhu et al. 2014; Grossauer et al. 2015; Liu et al. 2015; Zhang et al. 2015; Ferrarese et al. 2016; Sánchez-Janssen et al. 2016; Roediger et al. 2017) and the correlations between the GC properties and the evolution of the environment that surrounds them (e.g., Powalka et al. 2016a, 2016b, 2017).

We make use of the deep and extended photometric information provided by the Next Generation Virgo Cluster surveys (NGVS/NGVS-IR; Ferrarese et al. 2012; Muñoz et al. 2014) in the central 2 × 2 deg² of Virgo, to study the transition region between the central galaxy and the IC space. The aim is to identify and separate the GC populations associated with these components and study their properties separately. The paper is structured as follows. In Section 2 we present our data, the different sources of contamination, and hence our working sample of GCs. In Section 3 we study the GC line-of-sight velocity distribution (LOSVD) and kinematically separate the M87 halo component from the Virgo ICL. The properties of both M87 halo and Virgo intracluster GCs are analyzed in Section 4 in terms of colors and spatial distributions. We discuss our results in Section 5 and finally report our conclusions in Section 6.

Throughout the paper, we assume a distance for Virgo and M87 of 16.5 Mpc (Mei et al. 2007; Blakeslee et al. 2009), implying a physical scale of 80 pc arcsec⁻¹.

2. Observations and Data

This work examines the GC population in the core region of the Virgo cluster through a synergy between optical/near-infrared photometry from the NGVS (Ferrarese et al. 2012)/NGVS-IR (Muñoz et al. 2014) and spectroscopy, the latter coming from a compilation of different campaigns. In what follows, we give a brief description of these surveys and refer the reader to the references therein for additional details.

2.1. NGVS Photometry

The NGVS is an optical imaging survey of the Virgo cluster carried out with MegaCam on the Canada-France-Hawaii Telescope (CFHT; Ferrarese et al. 2012). It covers a total area of 104 deg², covering the two main subclusters (Virgo A centered on M87, and Virgo B centered on M49) out to their virial radii. Ferrarese et al. (2012) adopted several methods of background subtraction and image combination to produce stacked NGVS images. Here we work with the stacks built using the MegaPipe global background subtraction, combined with the artificial skepticism algorithm (Stetson et al. 1989). This provides high-accuracy photometry for sources of small spatial extent, making the NGVS a deep photometric survey in the u’ g’ r’ i’ z’ bands that for point sources reaches a depth of g′ = 25.7 mag.19 In addition, images in all filters have an FWHM that is lower than 1″0, with the best seeing conditions obtained for the i’ band with an upper limit of 0″6. All final images have the same astrometric reference frame, tied to the positions of stars in the Sloan Digital Sky Survey (SDSS), and the same spatial resolution with a physical scale of 0″186 px⁻¹.

For the Virgo core, a 3.62 deg² region centered on M87, a deep, Ks band imaging survey (NGVS-IR) was also carried out with WIRCam on the CFHT (Muñoz et al. 2014). Any raw images with a seeing worse than 0″7 were rejected before stacking. This made it possible to produce stacked images with the same pixel scale as the MegaCam stacks, although the original WIRCam pixel scale is 0″3 px⁻¹. The Swarp software (Bertin et al. 2002) coupled with a Lanczos-2 interpolation method was used to stack the sky-subtracted images. Thus, the NGVS-IR has a limiting magnitude of Ks ~ 24.4 AB mag for point sources and an image quality better than 0″7. Photometry of all objects on the final, stacked NGVS/NGVS-IR images was conducted using Source Extractor (Bertin & Arnouts 1996). The aperture corrections (due to small variations in the stellar point-spread function across the field) were derived using samples of bright, unsaturated stars in each field for each filter (more details can be found in Durrell et al. 2014; Muñoz et al. 2014; Liu et al. 2015).

2.2. Spectroscopy

We have compiled a catalog containing all of the known redshifts within the NGVS footprint. It combines data from the literature (e.g., Binggeli et al. 1985; Hanes et al. 2001; Strader et al. 2011), public archives such as SDSS (DR12, Alam et al. 2015), and NED,20 as well as data from our own spectroscopic surveys dedicated to the detection of compact objects in Virgo. In this work, we only focus on the inner 2° × 2° around M87, and in what follows we will give a brief description of the surveys that provided data for this analysis. Spectroscopic data in the Virgo core:

The literature sample. In addition to our own surveys (described below), the central region of the Virgo cluster has been the target of several spectroscopic campaigns, Strader et al. (2011; S11) combined the pre-2011 published data with their new observations to compile a sample of radial velocities covering M87 within a 40′ radius. As a compilation of different surveys (e.g., Côté et al. 2001; Hanes et al. 2001), data from the S11 catalog come from observations carried out with different instruments, and hence are characterized by different resolutions and spectral coverage. The authors extensively describe the different observational strategies and the compilation procedure that led to the creation of the S11 catalog, so we refer the reader to their work for a detailed description of the surveys. Here we note that we use the radial velocities provided in their catalog, but in some cases we have modified the object classification.

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19 Deep imaging in the u’ and r’ bands does not cover the entire NGVS footprint, with the i’ band limited to the central 2 by 2 square degrees around M87. Magnitudes are on the CFHT MegaPrime photometric system.

20 The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
based on our high-quality photometric information (see Section 2.3.1).

The MMT campaign. In 2009 and 2010, we used the Hectospec multi-fiber spectrograph on the 6.5 m MMT telescope to survey the compact stellar systems in the central 2\° × 2\° area around M87 (Zhang et al. 2015). Data covered the spectral region within 3650–9200 Å with a resolution of R = 1000. By exposing for \~{}2 hr, the survey depth is g' \sim{} 22.5 mag, and velocities have a typical uncertainty of \sigma_{\text{LOS}} = 30 \text{ km s}^{-1}.

The AAT campaign. Compact objects in Virgo were further followed up spectroscopically in 2012 March/April when we surveyed the central region of the Virgo cluster (Virgo A subcluster) using the 2dF AAOmega multi-fiber spectrograph on the AAT. Spectra were obtained in the wavelength range 3700–8000 Å and with a spectral resolution of R = 1300 (Zhang et al. 2015). The survey consisted of nine 2dF pointings with a typical exposure time of 1.5 hr, covering a total sky area of \~{}30 deg\(^2\). At the limiting magnitude of g' \sim{} 20.5 mag and with such an observational setup, the typical uncertainty on the velocity estimates is \sigma_{\text{LOS}} = 30 \text{ km s}^{-1}.

The Keck campaign. In 2013 April, additional data were collected using the DEIMOS spectrograph located at the Keck II 10 m telescope. The instrumental configuration provided a wavelength coverage of 4800–9500 Å with a spectral resolution of 2.8 Å (FWHM). This campaign provided velocity measurements with a mean precision of \sigma_{\text{LOS}} = 10 \text{ km s}^{-1} and down to g' \sim{} 24.7 mag (Toloba et al. 2016). Here, 24.7 must be the faintest object, but it is certainly not representative of the GC population.

The Magellan campaign. Finally, in 2016 March, we used the IMACS multislit spectrograph on the Magellan Baade telescope to obtain spectra for compact objects in Virgo with g' < 22 mag. With a field of view of 27.5 × 27.5, the observations surveyed two regions, one centered on M87 and the second one offset by 30' toward the northwest along the major axis of the galaxy. Data were obtained in the wavelength range 3900–9000 Å with a spectral resolution of 6.5 Å. With a total integration time of 3.5 hr, this survey provided data with a mean velocity uncertainty \sigma_{\text{LOS}} = 30 \text{ km s}^{-1} (Zhang et al. 2018).

As we show below, the NGVS photometry provides vital information needed to select the GC sample that we use to analyze the kinematics of the GC system and identify the LOSVDs of the different dynamical components. Hence our working sample is selected from the matched objects between the NGVS photometric and spectroscopic catalogs in the pilot region, resulting in a total sample of \N_{\text{obj}} = 2809 sources. We further decide to analyze objects down to g' \leq{} 24.0 mag and \sigma_{\text{LOS}} \leq{} 50 \text{ km s}^{-1}. This leads to a total number of sources \N_{\text{obj}} = 2551, with median photometric uncertainties \sigma_{\text{mag}} = [0.01, 0.005, 0.004, 0.005, 0.008, 0.02] in the \u, g', r', i', z', and K\_s bands, respectively. Of these objects, 897 have a high photometric probability of being a GC (see Section 2.3.1). Among these, 592 were gathered by S11, while 232, 9, 29, and 18 radial velocities were observed for the first time in the MMT, AAT, Keck, and Magellan campaigns, respectively (the remaining velocities are from public archives). We emphasize that from repeated measurements in different campaigns the velocity estimates are in agreement within the spectroscopic uncertainty threshold of \sim{} \sigma_{\text{LOS}} = 50 \text{ km s}^{-1}.

Figure 1. \u' / K\_s color–color diagram for the NGVS photometric sample in the pilot region with g' \leq{} 24.0 AB mag. In this plane, background galaxies, GCs, and foreground Milky Way (MW) stars separate into different regions (Muñoz et al. 2014). Magenta dots identify objects with high photometric probability, \P_{\text{gc}} > 0.5, to be GCs (see the text for more details).

The two spectroscopic catalogs with the highest number of GCs in common (67 common objects from the S11 and MMT samples) only present two velocity estimates that deviate by \sim{} 1.5 \sigma_{\text{LOS}}.

2.3. Object Classification

The selection of a bona fide sample of GCs is a crucial first step for our kinematic analysis. The two main types of contaminants in our sample are (1) background galaxies and (2) foreground Milky Way (MW) stars. A third, more subtle, type of potential contaminant is (3) Virgo UCD galaxies. In what follows, we examine such a contamination and its contribution to the sample of GCs.

2.3.1. Contamination by Background Galaxies and Foreground Stars

Muñoz et al. (2014) showed that background galaxies, GCs, and foreground stars define different regions in the \u' / K\_s color–color diagram. In Figure 1, this relation is shown for the photometric sample in the NGVS pilot region. From redder to bluer (i' – K\_s) colors, we can see the different contributions from background galaxies with various star-forming histories at redshifts up to z \sim{} 1, GCs (which merge into the redshift sequence of passive galaxies at the red end), and foreground main-sequence stars. However, a successful compilation of a GC sample implies accounting for the shared contribution between different populations in the transition regions of these three sequences. To do so, we have used the full photometric information gathered by the NGVS/NGVS-IR surveys, and we adapted the “extreme deconvolution” (XD) algorithm from Bovy et al. (2011) to classify our data according to multi-dimensional color and concentration information. The details of this classification procedure will be presented in a future work. Here we give a brief description of the procedure and validate
the results in the next section, with the spectroscopic information we have.

In the pilot region, the XD approach uses multidimensional Gaussians to model the density of objects in the five-dimensional space: $(u^* - g')_b$, $(g' - i')_b$, $(i' - z)_b$, $(i' - K)_b$, and a measure of concentration $iC = i'_4 - i'_5$, where $i'_4$ and $i'_5$ are the point source aperture-corrected $i$-band magnitudes measured in fixed apertures of diameter $r = 4$ pixels ($0''.72$) and $r = 8$ pixels ($1''.44$), respectively. The $i$-band seeing in the NGVS images has FWHM $< 0''.6$ with a median seeing of $0''.54$. For point-like objects, $iC = 0$, and extended objects have $iC > 0$. The Gaussians in the model are convolved with the observational uncertainties of the data. Therefore, each data point is assumed to be drawn from the model convolved with its own set of measurement uncertainties, and at the end of the XD procedure we obtain for each object the probabilities, $p_{\text{galx}}, p_{\text{gc}}$, and $p_{\text{star}}$, of it being either a galaxy, a GC, or a star, respectively. Magenta dots in Figure 1 are objects with high photometric probability, $p_{\text{gc}} > 0.5$, of being GCs.

2.3.2. Spectroscopic Validation of the Photometric Selection

Background galaxies—There is a well-defined gap between the Virgo members and background galaxies at radial velocities $V_{\text{galx}} = 3000$ km s$^{-1}$ (Binggeli et al. 1987; Conselice et al. 2001; Kim et al. 2014). Therefore, the background component is identified by selecting objects with $V_{\text{LOS}} > 3000$ km s$^{-1}$. We find that 721 sources in our sample satisfy this criterion, representing $\sim 28\%$ of our working sample. The XD photometric classification identifies these contaminants successfully: $> 99\%$ of the background objects are assigned high photometric probability of being background galaxies, with mean value $\langle p_{\text{galx}} \rangle = 0.98$, and only $1\%$ would result in having high photometric probability of being GCs.

Foreground stars—The velocity distribution of the Galactic stellar halo is measured to peak at a heliocentric radial velocity of $\sim 40$ km s$^{-1}$ with a velocity dispersion of $\sim 120$ km s$^{-1}$ (e.g., Battaglia et al. 2005). Therefore, the MW star LOSVD overlaps with the LOSVD of objects in Virgo, the latter measured to cover a velocity range $-500$ km s$^{-1} < V_{\text{LOS}} < 3000$ km s$^{-1}$ (Binggeli et al. 1987; Conselice et al. 2001). The contamination by foreground stars is visible as a strong and narrow Gaussian that peaks at around $40$ km s$^{-1}$ in Figure 2 (left-hand panel), where we plot the LOSVD of our working sample with $V_{\text{LOS}} \leq 3000$ km s$^{-1}$.

To isolate this kinematic component, we run a Gaussian mixture model (GMM), that is, a probabilistic model that divides the observed LOSVD into a linear combination of $K$ independent Gaussian probability density functions (PDFs). At the end of the procedure, the posterior probability, $\Gamma$, of a data value belonging to either of the $K$ Gaussian components is returned (Figure 2 right-hand panel, and see Section 3 for details on the GMM). Tests with the Bayesian information criterion (BIC) and Akaike information criterion (AIC) show that the GMM best-fit model is a mixture of three Gaussians (Figure 2 central panel), identifying the Galactic stellar contamination as a component with $V_{\text{galx}} = 41 \pm 4$ km s$^{-1}$ and $\sigma_{\text{galx}} = 114 \pm 3$ km s$^{-1}$. In Section 3, we will show that the remaining two Gaussians are tracing the Virgo cluster and the M87 halo distributions, but because for the moment our goal is to validate the photometric classification, we only isolate the objects with velocities that fall within the stars’ LOSVD, and we consider as one single class the remaining objects.

In Figure 3, the $(u^*-i')$ versus $(i'-K)$ diagram encodes the spectroscopic information in color: objects with higher GMM posterior probabilities of belonging to the star LOSVD are shown in yellow and orange. From this plot, we can see that the majority of these objects are consistent with being foreground stars on the basis of their $u^*i'K_s$ properties (yellow circles). However, a fraction of objects with $u^*i'K_s$ colors consistent with being GCs have velocities that fall within the star LOSVD. Their total number is 32, that is, $\sim 4\%$ of the sample of star candidates based on the probability of membership obtained with the XD method.
Figure 3. Top panel: u′/K color diagram color coded based on the spectroscopic information: yellow dots are objects with higher posterior probabilities of being genuine UCDs based on their photometric properties, such as size and colors. They have photometric probability of being a GC of 99.7% or higher. Blue (cyan) and orange triangles are objects that have photometric probability of being background galaxies. In the bottom panel of Figure 3, where the color–color diagram is replotted by weighting the contribution of each data point by the XD probability, pgc, of being a GC, we show that we can successfully retrieve this fraction using the photometric classification previously described. Going back to the top panel of Figure 3, we also see that there are a few objects that have been misclassified (~9%) of our working sample with VLOS ≤ 3000 km s^{-1} with high photometric probability, pgalx, of belonging to the star LOSVD (cyan and orange triangles). These objects have been visually inspected and reintroduced in the bona fide sample of GCs when their velocity is consistent with the Virgo IC/M87 halo components (cyan triangles, 85 objects). For those whose velocities fall within the star LOSVD (orange triangles, 77 objects), we only reintroduce those that are in the locus of the color–color diagram where the majority of GCs sit (four objects). All of the reintroduced objects have been assigned pgc = 1.0. To summarize, we have shown that the photometric information gathered by the NGVS is enough to properly separate foreground stars and Virgo compact objects, allowing us to avoid hard cuts in the velocity distribution for VLOS < 500 km s^{-1}.

2.3.3. Virgo UCD Contamination

In the last 20 years, evidence has emerged for the existence of a family of compact stellar systems, called “ultracompact dwarfs” (UCDs). Their sizes and luminosities are intermediate between compact elliptical galaxies and the most massive GCs (Hilker et al. 1999; Drinkwater et al. 2000; Hasegan et al. 2005; Misgeld & Hilker 2011), and their colors and stellar populations are similar to GCs and nuclear star clusters (Taylor et al. 2010; Spengler et al. 2017). Recently, Zhang et al. (2015) studied the properties of a sample of UCD galaxies within ~1° of M87 and compared them to the properties of the red and blue GC populations. They found that they do not share the same kinematics as the GC system, but no distinction was made between galaxy halo and intracluster GCs, leading to the question as to whether UCDs may trace the IC component instead, hence sharing properties similar to that of the ICGCs.

The evidence that the Virgo UCDs never reach the cluster dispersion, nor do they trace the Virgo systemic velocity, is enough to argue that these systems are not to be associated with the ICL. However, the argument gets stronger if we consider that at large radii the UCDs behave more like the red GCs (in terms of density profiles and rotational axis). As we will show in this work (see Section 3), the presence of an IC component particularly affects the GC properties at large radii, and it is dominated by the blue GC population (see Section 4). Thus, if the UCDs did trace the ICL, they would rather show density distributions and kinematics similar to that of the blue GC population at large radii, which we do not observe.

We then use the information gathered by Zhang et al. (2015) and Liu et al. (2015) to exclude the UCDs from our sample of bona fide GCs. These authors identified UCDs based on their photometric properties, such as size and colors. By cross-matching the catalogs from Zhang et al. (2015) and Liu et al. (2015) with our sample of compact objects, we identify 85 UCD candidates that we remove from our sample of bona fide GCs. The selection of these objects is reliable, only missing ~6% of genuine UCDs for g′ < 21.5 (Liu et al. 2015; Zhang et al. 2015). However, under the assumption that UCDs are the surviving nuclei of tidally stripped galaxies, Ferrarese et al. (2016) argued that we expect a contribution in the 21.5 < g′ < 24.0 range that amounts to ~100 objects. Given our spectroscopic incompleteness (on average we only observe 10% of the photometric candidates; see Section 4.2), this implies a residual contamination by UCDs of ~10 objects in our spectroscopic sample. Such a fraction is negligible with respect to the final sample of GCs and does not affect any of the scientific results that we present in this study.

2.3.4. GCs Bound to Other Virgo Members

In the previous sections, we have subtracted the contributions of stars, background galaxies, and Virgo UCDs from our working sample. However, as our goal is to study the GC population of the M87 halo and the Virgo IC component, we also have to flag GCs that are likely to be bound to other Virgo members. To do this, we considered GCs to belong to another galaxy if (1) the GC velocity relative to the galaxy velocity, Vgc, is within 3 × σgc, where σgc is the velocity dispersion of the galaxy (assuming a Gaussian LOSVD, 97.7% of the distribution falls within this limit), and (2) their distance from the galaxy’s center is within 10 effective radii, Re, of the galaxy.
This generous radial criterion was chosen to account for possible differences between the galaxy light and the GC spatial distribution. Fits to the SB and surface-density profiles of galaxies’ light and GC systems show that the latter are, on average, more extended than that of the host galaxies’ (e.g., Puzia et al. 2004; Kartha et al. 2014; Forbes 2017; Hudson & Robison 2018). For less-massive dwarf galaxies, the scaling relation can be reduced to $R_{e,Gc} = 1.5 \times R_{e,gal}$ (e.g., Peng & Lim 2016).

Within a $2^\circ$ radius around M87, there are 197 Virgo galaxies with known velocity, 129 of which are early-type dwarf galaxies, as compiled by the GOLDMine project (but see also Gavazzi et al. 2003; Toloba et al. 2014). The GOLDMine catalog also provided us the velocity dispersion for a fraction of galaxies, while the effective radius information was retrieved from McDonald et al. (2011). For those galaxies with no measured velocity dispersion or effective radius, mostly dwarfs, we have given a fixed value of $\sigma = 50 \, \text{km s}^{-1}$ and $R_e = 30''$. At the end of this procedure, we have identified 56 GCs as belonging to other Virgo galaxies. Finally, we are aware that there will be a fraction of galaxies in the surveyed area with no velocity information, so that is not considered in this analysis. However, we note that additional GCs bound to other galaxies would show a correlation in position and velocity that we checked for. This test showed no evidence of any possible spatial or kinematic correlation, so we can state that if there is a contribution from GCs belonging to other Virgo members, in this analysis. However, we note that additional GCs bound to other galaxies would show a correlation in position and velocity that we checked for. This test showed no evidence of any possible spatial or kinematic correlation, so we can state that if there is a contribution from GCs belonging to other Virgo members, this fraction is negligible.

To summarize, in this section we have analyzed and removed the contribution from contaminants in our working sample to define our final sample of bona fide GCs. We have found the following:

1. Background galaxies (i.e., no Virgo members with $V_{los} > 3000 \, \text{km s}^{-1}$) represent ~28% of our working sample.
2. Once the background contamination is subtracted, foreground MW stars contribute ~46% of the data, leaving 975 sources with high photometric probability, $P_{GC}$, of being a compact Virgo object.
3. Among the compact objects, 85, or 9%, are identified as UCDs.
4. Finally, 56 GCs (6% of the total GC sample) are consistent with belonging to other Virgo members.

This selection led to a final sample of 837 confirmed GCs that we will analyze in the next sections. Their spatial distribution is shown in Figure 4 (purple dots) together with the position of the sky of UCDs (blue triangles) and GCs associated with other Virgo members (orange crosses; the centers of other Virgo galaxies are shown by red crosses).

3. The M87 Galaxy Halo and Virgo ICL as Traced by GCs

When studying the light at the center of a cluster reaching out ~300 kpc (15") in radius from the central galaxy, we are tracing the transition region between the central galaxy halo and the IC component. Longobardi et al. (2015a) analyzed a 0.5 deg$^2$ area around M87 using PN kinematics to dynamically identify and separate the galaxy halo and the ICL. They showed that the two components overlap at all radii, but with different PN properties, and hence are consistent with having different parent stellar populations.

In what follows, we will investigate whether GCs trace a similar galaxy halo–IC interface. If there are, indeed, ICGCs, in what systems did they form, and do they show photometric properties that differ from the M87 halo GCs?

3.1. Projected GC Velocity Phase Space

In Figure 5 we show the velocity–position phase space diagram (central and bottom panels) for our GC sample. The GC LOS velocities are plotted against the major axis distance, the latter computed as $R = [(x/(1-e))^{2} + y^{2}]^{1/2}$ for a system aligned along the $y$ axis, with position angle $P.A. = 155^\circ$ and ellipticity $e = 0.4$ (Ferrarese et al. 2006; Janowiecki et al. 2010). The relations for positive and negative $R$ are plotted separately to trace the northwest (NW; central panel) and southeast (SE; bottom panel) halves with respect to the center of M87, respectively (see Figure 4 for a representation of the spatial configuration).

This plot shows a system dominated by random motion, with the GC kinematics concentrated around the M87 systemic velocity $V_{sys} = 1308 \, \text{km s}^{-1}$, together with a scattered distribution of high- and low-velocity objects on both sides of the galaxy. As shown in the histograms of the velocities (side...
panels), the wings (or tails) of the GC LOSVDs are strong and quite asymmetric with respect to a Gaussian distribution (red curve) centered on the M87 systemic velocity and with a velocity dispersion of $\sigma \sim 300 \, \text{km} \, \text{s}^{-1}$.\footnote{Here we consider as a velocity dispersion representative of M87 the one traced by the red GC population over a range 0°5--30°0 (Zhang et al. 2015).} Such behavior contrasts with what is observed for nonrotating early-type galaxies, whose LOSVD are symmetric (i.e., $h_3 \sim 0$) and hence well described by a single Gaussian to within a few percent (Gerhard 1993; Bender et al. 1994). Orbital anisotropy would create a symmetric variation around the mean velocity (i.e., $h_4 \neq 0$) and is unlikely to be measured at all radii (see Figure 6 for a plot of the GC LOSVDs as a function of the distance from M87’s center). On the other hand, strong tails are seen in simulations, observed to characterize the LOSVD of galaxies in dense environments and consistent with the presence of an intracluster/group component overlapping the galaxy halo (Dolag et al. 2010; Longobardi et al. 2015a; Veale et al. 2017; Barbosa et al. 2018). In fact, the relative importance of these “tails” increases as a function of the major axis distance, with the GCs gradually deviating from the central galaxy’s kinematics and merging into the cluster potential. This is shown in the same plot by comparing the GC kinematics with the kinematics of the population of early-type dwarfs in Virgo with measured radial velocities (129 objects; Gavazzi et al. 2003). We study the running average of the LOS velocities of GCs (solid green lines in the central and bottom panels) and early-type dwarfs (solid blue lines); that is, we plot the running mean in bins of $n$ objects, with $n = 30$ for the GCs, $n = 35$ for the NW dwarfs, and $n = 25$ for the SE dwarfs. By comparing the different running-average profiles, it is clear that the GC mean velocity decreases

![Figure 5. Top panel: LOS velocity dispersion profile for the GCs in the NGVS pilot region (dots with the green shaded area delimiting the 1σ region) and for the dwarf early-type galaxies within a 2° radius from the cluster’s center (purple crosses with blue shaded area delimiting the 1σ region). The GC velocity dispersion profile is observed to increase on both the NW (dark dots and dark shaded area) and SE (yellow dots and light shaded area) sides of M87, reaching the velocity dispersion of the dwarfs in Virgo. Central panel: projected velocity phase space that compares the velocity distributions of GCs (black dots) and Virgo dwarf early-type galaxies (purple crosses) in the NW region. The solid lines trace the running average computed from the total GC sample (green) and the dwarf population (blue). The histogram of the velocities, plotted on the side, shows a LOSVD with strong and asymmetric tails compared to a Gaussian distribution centered on the M87 systemic velocity with a velocity dispersion of $\sim 300 \, \text{km} \, \text{s}^{-1}$ and normalized to the total number of GCs (red curve). Bottom panel: same as central panel, but the relation is shown for the SE region with respect to M87. On both sides, the GC mean velocity decreases as a function of the distances, deviating from the M87 systemic velocity ($V_{\text{sys}} = 1308 \, \text{km} \, \text{s}^{-1}$, red line) and merging into the mean velocity of the Virgo dwarfs at $R \sim 320 \, \text{kpc}$. The vertical orange lines separate the phase space into four elliptical bins, as given in the text.}
going toward larger distances, deviating more than $2.5\sigma$ at large distances and on both sides from the M87 systemic velocity (red line) and merging into the mean velocity of the Virgo dwarfs at $R \sim 320$ kpc. At these distances, the GC velocity dispersion reaches its maximum, $\sigma_{\text{LOS}} = 590 \pm 80$ km s$^{-1}$, merging with the cluster potential (Figure 5, top panel). The comparison between the NW and SE fields around M87 shows that the NW has more dE galaxies with negative velocities (red crosses in Figure 4). It is likely that a substantial fraction of these objects comes from the accretion of material that is falling toward the cluster’s center, dragged along by the well-known infalling M86 subgroup, and it is contributing to what we see today as an IC component.

### 3.2. Kinematic Separation between the M87 Halo and ICL

The comparison with the Virgo dE/dS0 galaxies showed that the GC system around M87 is tracing the transition toward the Virgo cluster potential. Hence, we now further analyze the GC LOSVD, and we do it (1) separately for the NW and SE halves, and (2) in four different elliptical bins, or stripes in Figure 6. GMM analysis of the GC LOSVD carried out separately for the GCs located to the SE (left panels) and NW (right panels) of M87. From top to bottom, the sample is divided into four elliptical annuli as given in Figure 5, with $N$ representing the total number of GCs used in the GMM fitting. An AIC analysis (second and fourth panels) prefers a two-component Gaussian mixture out to $R = 216$ kpc, implying the contribution from the M87 galaxy halo and Virgo ICL to the total LOSVD at all distances out to this radius. For $R > 216$ kpc, the best-fit mixture is a model with one component tracing the Virgo cluster potential.
phase space (gray ellipses in Figure 4, or orange lines in Figure 5), covering the entire GC range. The four regions in space are defined as $|R| \leq 32$ kpc, $32 < |R| \leq 80$ kpc, $80 < |R| \leq 216$ kpc, and $|R| > 216$ kpc, with bin size increasing toward the outer regions to ensure a statistically significant sample of tracers even at large radii, where the GC number density is the lowest. Thus, our choice of radial binning represents the best compromise between similar radial extension and statistical noise. We emphasize that the stability of the results was tested against different choices of radial limits: within the uncertainties, the results are consistent with each other. In our analysis, we assume that both the M87 halo and Virgo IC LOSVDs are Gaussians. As argued in the previous section, this is a reliable approximation for the galaxy’s stellar velocity distribution, and, from hydrodynamical simulations (Dolag et al. 2010; Cui et al. 2014), Gaussian shapes also describe well the IC component. We are aware, however, that a Gaussian may be a less good model for the Virgo IC LOSVD if the Virgo cluster is not fully virialized.

We then run a GMM analysis for each of these samples to isolate individual kinematic structures and trace the coexistence of the M87 halo/Virgo IC components. The GMM is a probabilistic model which assumes that a distribution of points, in our case the objects’ velocities, can be described as a linear combination of $K$ independent Gaussian PDFs. The best set of Gaussians is selected by implementing the expectation-maximization (EM) algorithm, an iterative process that continuously updates the PDF parameters until convergence in the likelihood is reached. The process ends with the assignment of posterior probabilities, $\Gamma$, that each data point belongs to each of the $K$ Gaussians. This analysis is based on the public scientific Python package scikit-learn (Pedregosa et al. 2011). However, our estimated Gaussian mixture distribution starts from a weighted sample of data, the weights, $p_{gc}$, being the normalized probabilities of being a GC given its photometric properties (see Section 2.3.1). We then modified the Python GMM routine accordingly, and the details on this will be given in A. Longobardi et al. (2018, in preparation).

Here we only point out that the EM for mixture models consists of two steps. The first step, or E step, consists of calculating the expectation of the component assignments, $\Gamma_{i,k}$ for each data point given the model parameters. Thus, at the $m$th iteration of the EM process, the posterior probabilities of the $i$th particle belonging to the $k$th Gaussian component become

$$\Gamma_{i,k}^{m} = \frac{p_k(x_i | \mu_k, \sigma_k)P_{k}^{m}}{\sum_{k=1}^{K} p_k(x_i | \mu_k, \sigma_k)P_{k}^{m}} \times p_{gc,i},$$

where the Gaussian density function (PDF) is written as $p(x_i) = \sum_{k=1}^{K} p_k(x_i | \mu_k, \sigma_k)P_{k}$, with $p_k(x | \mu_k, \sigma_k)$ being the individual mixture component centered on $\mu_k$, with a dispersion $\sigma_k$, and mixture weight $P_k$. The second step, or M step, consists of maximizing the expectations parameters, that is, updating the values $\mu_k$, $\sigma_k$, and $P_k$ as weighted parameters, the weights being $\Gamma_{i,k}$. In this way, the EM process always takes into account the starting weight of each particle $p_{gc,i}$. Tests with the AIC show that the mixture that best describes the total GC LOSVD is a two-component model in the first three elliptical bins, while in the outermost bin, the GMM identifies only one component. A comparison of the performances of AIC and BIC scores was tested against mock sets of data that mimic different LOSVDs and sample sizes. AIC scores were found to be more reliable, so we only report these scores. Moreover, the stability of the fitted parameters was tested with 1000 GMM runs for different mock data sets and initialization values.

The results of our GMM analysis, the histograms of the data together with the GMM best-fit model, and relative AIC scores are shown in Figure 6, while we summarize the fitting Gaussian parameters in Table 1.

The GMM analysis shows that out to 216 kpc the hotter (broader) and colder (narrower) components coexist, while outside this radius the narrower Gaussian is not detectable, and the GC kinematics are well described by a single broad
Gaussian. Within the uncertainties, the narrow Gaussians describe the galaxy’s kinematics with a mean systemic velocity consistent with $v_{\text{LOS}} = 1308$ km s$^{-1}$, and with a velocity dispersion that decreases as a function of the distance, reaching a value of $230$ km s$^{-1}$ in the outermost bin. The broad Gaussians, instead, are consistent with the kinematics traced by the early-type dwarf population in the core of Virgo, the latter measured to peak at $v_{\text{LOS}} = 1139$ km s$^{-1}$ (Binggeli et al. 1993). The mean velocities and velocity dispersions of the ICGC component are consistent not only with those of the dwarf galaxies, but also with those of the more massive systems in the Virgo core (Binggeli et al. 1993). The mean velocities and velocity dispersions of the ICGC component are consistent not only with those of the dwarf galaxies, but also with those of the more massive systems in the Virgo core (Binggeli et al. 1993). However, (1) very broad, asymmetric wings, like the ones we show in Figures 5 and 6, are only observed for the LOSVD of the dwarf spheroidal galaxies (see Binggeli et al. 1993; Conselice et al. 2001), and (2) in the next sections, we will show that the photometric properties of the detected ICGCs are similar to what is measured for the dE system in Virgo, hence our comparison with the lower mass Virgo galaxies. The broad GC LOSVD component points toward a different kinematic behavior when measured separately in the two halves: SE of M87 the velocity dispersion is larger than in the NW region. However, more kinematic tracers will be needed to reduce the uncertainties associated with these results (see Table 1). For clarity, the NW and SE GC velocity phase spaces, together with the LOSVDs of the M87 halo and Virgo intracluster GCs, are shown in Figure 7.

Different LOSVDs for the galaxy halo and the ICL are predicted by cosmological analysis of structure formation. At the center of simulated clusters, the total LOSVD splits into two Gaussians characterized by very different velocity dispersions (Dolag et al. 2010; Cui et al. 2014). One component is gravitationally bound to the galaxy and more spatially concentrated; the other is more diffuse, and its high velocity dispersion reflects the satellites’ orbital distribution in the cluster gravitational potential. Using this framework, we can identify the narrow and the broad Gaussians traced by the GC kinematics with the M87 halo and Virgo ICL, the latter contributing $\sim 13\%$ of the GC sample within 216 kpc, beyond which the M87 halo component is no longer detected.

In Figure 8 we plot again the comparison between the kinematics of the GC system and the Virgo dE population, but, this time, no separation between NW and SE fields is made. Interestingly, the kinematic behavior of the GC system exhibits a change in dynamics at a projected distance $R = 128$ kpc (see Doherty et al. 2009), where the velocity dispersion reaches its minimum (black dots) and the mean velocity (green line) starts to deviate from the systemic velocity of M87 (red line). Thus, interpreting such a distance as the truncation radius, $R_T$, of the Virgo cluster...
crosses radius, the GC kinematics traces the IC potential: the GC velocity dispersion

\[ \sigma_v \]

(\text{Poissonian statistics}).

At a projected distance \( R = 128 \text{ kpc} \), the GC velocity dispersion (black dots) reaches its minimum, and the mean velocity (green line) starts to deviate from the systemic velocity of M87 (red line). Beyond this radius, the GC kinematics traces the IC potential: the GC velocity dispersion rises until it reaches the velocity dispersion values of the Virgo dE (purple crosses) at \( R \approx 320 \text{ kpc} \); at these distances, the GC mean velocity merges into the mean velocity of the Virgo dwarfs (blue line). The mean velocity values are centered on \( V_{sys} = 1308 \text{ km s}^{-1} \). The error bars show the uncertainties from Poissonian statistics.

![Figure 8. Comparison between the LOS kinematics of the GCs in the NGVS pilot region and of the dwarf early-type galaxies within a 2° radius from the cluster’s center. At a projected distance \( R = 128 \text{ kpc} \), the GC velocity dispersion (black dots) reaches its minimum, and the mean velocity (green line) starts to deviate from the systemic velocity of M87 (red line). Beyond this radius, the GC kinematics traces the IC potential: the GC velocity dispersion rises until it reaches the velocity dispersion values of the Virgo dE (purple crosses) at \( R \approx 320 \text{ kpc} \); at these distances, the GC mean velocity merges into the mean velocity of the Virgo dwarfs (blue line). The mean velocity values are centered on \( V_{sys} = 1308 \text{ km s}^{-1} \). The error bars show the uncertainties from Poissonian statistics.](image)

4.1. Photometric Properties

Both the M87 halo and the Virgo intracluster GCs are characterized by a large spread in \((g'−i')_0\) colors, indicating that both dynamical components have two distinct, red (metal-rich) and blue (metal-poor), subpopulations of GCs. By fitting a double-Gaussian profile to the GC color distributions, we measure that the red and blue GC components cross at \((g'−i')_0 = 0.77\) mag. The relative fraction of blue-to-red GCs differs, however: 77% ± 10% of the Virgo IGC population is blue, while only 52% ± 3% of the GCs bound to the M87 halo are metal-poor.\(^22\) In Figure 9, we show the \((g'−i')_0\) versus \(g'\) color–magnitude diagram for both the M87 halo (green dots) and the Virgo intracluster GCs (black crosses), separately for the SE and NW fields, and as a function of the distance from the galaxy’s center. The M87 halo sample is compared in three different elliptical bins, while, given the lower number of tracers, the ICGCs are analyzed within two elliptical bins with \( R = 216 \text{ kpc} \) representing the boundary. Despite the incompleteness that characterizes our sample of spectroscopically confirmed GCs (higher for \( R > 216 \text{ kpc} \) and with the NW side affected the most), we see that the blue GC component of M87 is higher at larger distances, increasing from 40% close to the center to 70% in the outermost bin. This is not true for the IC component that, independently from the distance, is dominated by the blue GCs.

We also present the \((g'−r')_0\) versus \((i'−z')_0\) color–color diagrams for the M87 halo (Figure 10) and the Virgo intracluster GCs (Figure 11). This analysis was motivated by the recent finding of a correlation between GC color–color relations and environment and interpreted as being driven by different stellar abundance ratios (Powalka et al. 2016b, 2018, although interpretations related to different underlying ages are also given, e.g., Usher et al. 2015; Powalka et al. 2018). In this study, the working sample was selected through a combination of the \(u'g'i'K_s\) color properties and the compactness of the objects, similar to what we described in Section 2.3.1. However, they only studied GCs whose magnitudes were measured with an uncertainty \( \sigma_{mag} < 0.06 \text{ mag} \) in all of the bands, and they also offset the \( z' \) magnitudes to account for known deviations of the SDSS-DR10 magnitudes from the AB magnitude system (Powalka et al. 2016a, 2016b). Hence, we consider the same constraints and restrict our analysis to GCs with the same precision on the magnitude values and apply the same shift to the \( z' \) magnitudes. For each of the color–color diagrams, we fit and plot the relative Gaussian kernel density estimate (kde) and locate its peak identifying the maximum values in \((g'−r')_0\) and \((i'−z')_0\) from the kde PDF.

The M87 halo GCs are shown in Figure 10 (green dots), where we also flag the position of the blue and red class of GCs as identified based on their \((g'−i')_0\) values: green dots in red circles refer to the metal-rich population, while green dots in blue circles represent metal-poor GCs. Within \( R \leq 40 \text{ kpc} \), the SE and NW sides of M87 are characterized by GCs with similar colors, with the high-density peaks in the color–color space measured at \( [(g'−r')_0, \ (i'−z')_0]_{SE} \sim [0.52, 0.15] [0.51, 0.14] \) and \( [(g'−r')_0, \ (i'−z')_0]_{NW} \sim [0.54, 0.14] [0.52, 0.15] \). Similar are also the distributions of blue and red GCs in the color–color plane. At larger distances, \( R > 40 \text{ kpc} \), the

\[ R_T = R_{Virgo} \times \left( \frac{M_{87}}{3 \times M_{Virgo}} \right)^{1/3}, \]

were \( R_T = 127.5 \text{ kpc} \times (1 - e)^{1/2} \) is the average distance within which systems are gravitationally bound to the galaxy, \( R_{Virgo} \) is the distance between M87 and the center of the cluster (we have assumed \( R_{Virgo} = 1^\circ \); Binggeli et al. 1993), and \( M_{Virgo} = 4 \times 10^{14} M_\odot \) is the total Virgo dark matter mass (McLaughlin 1999). Moreover, we can also speculate that the different velocity dispersions measured for the IC component, higher in the south than in the north, are tracing the unrelaxed nature of the Virgo cluster. Young galaxy clusters still in the process of assembly are expected to show signs of dynamically nonrelaxed substructures.

4. M87 Halo and Virgo Intracluster GC Populations

The statistical analysis we have carried out allows us to assign membership to either the M87 halo or the Virgo ICL. In this section, we further analyze the properties of the M87 galaxy and intracluster GCs that have spectroscopic information to investigate whether the different kinematic components also correspond to two different populations in terms of photometric properties and spatial distributions.

\(^22\) Such red-to-blue cluster ratios are consistent with those we would obtain by integrating the extrapolated number density profiles for the red/blue populations related to the two dynamical components (see Section 4.2).
Figure 9. \((g' - i')_0\) vs. \(g'\) color–magnitude diagram for the M87 galaxy (green dots) and the Virgo intracluster (black crosses) GCs, at increasing distances from the galaxy’s center (see legend) and for the SE and NW halves around M87. As a consequence of the smaller number of objects, the ICGC color–magnitude diagrams are compared in two different elliptical bins, with \(R = 216\) kpc being the border. Both dynamical components have a blue and a red population of GCs. In the M87 halo, the number of blue GCs increases as a function of the distance: in the outermost bin it equals \(\sim 70\%\).
Figure 10. $(g'-r')_0$ vs. $(i'-z')_0$ color–color diagrams and corresponding kde density contours for the GC populations associated with the M87 halo. Left panel: the relation is shown for the GC population that lies in the SE side with respect to M87, and from top to bottom for GC subsamples at increasing distances from the center of the galaxy. Independent of galactocentric distance, the high-density peaks are close in value, as shown by the green lines. Right panel: same as in the left panel but for the sample of GCs in the NW half of M87. In this region the GCs show bluer $(i'-z')_0$ colors. In this diagram, we flag the position of the blue and red class of GCs as identified based on their $(g'-i')_0$ values: green dots in red circles refer to the metal-rich population, while green dots in blue circles represent metal-poor GCs. The linear maximum-likelihood fits to the color–color relations, the $\Delta$ values, and the mean $(g'-z')_0$ colors for each GC subsample are given in the legend. The uncertainty on the magnitudes is less than 0.06 mag.
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The same as in Figure 10 but for the Virgo ICGCs. The ICGCs are characterized by bluer colors than the galaxy GCs (the green dashed line shows a representative peak at \((g'-r')_0, (i'-z')_0 \sim [0.51, 0.14]\), with the bluest population found at \(R > 216\) kpc. The magenta dashed lines show the color–color high-density peak for a sample of GCs associated with Virgo early-type dwarfs. The linear maximum-likelihood fits to the color–color relations, the \(\Delta\) values, and the mean \((g'-z')_0\) colors for each GC subsample are given in the legend. The uncertainty on the magnitudes is less than 0.06 mag.

Color–color diagram extends to bluer \((i'-z')_0\) colors, with a significant fraction of objects with \((i'-z')_0 \leq 0.1\). We note, however, that the average behavior differs between the SE and NW regions. NW of M87 the blue GCs define the high-density peak in the color–color diagram at \((g'-r')_0, (i'-z')_0 \sim [0.50, 0.11]\). SE of M87 the blue GC population occupies a larger area, and the high-density peak is measured at \([(g'-r')_0, (i'-z')_0] \sim [0.48, 0.14]\).

The same analysis is carried out for the ICGC sample (we use the same binning as in Figure 9). The results are presented in Figure 11, where this time black dots in red and blue circles identify the metal-rich and metal-poor populations of GCs, respectively. The ICGC concentration in the color–color space differs from the one observed for the M87 halo GCs: independently from the distance, a large fraction of ICGCs extend to \((i'-z')_0 \leq 0.1\), the distribution is dominated by the blue ICGCs, and the few red GCs are bluer in the \((g'-r')_0\) versus \((i'-z')_0\) plane. This implies blue high-density peaks measured at \([(g'-r')_0, (i'-z')_0]_{\text{SE}} \sim [0.44, 0.12] [0.48,0.11]\) and \([(g'-r')_0, (i'-z')_0]_{\text{NW}} \sim [0.47, 0.13] [0.49,0.07]\). These are bluer than the one measured for the M87 halo GCs, of which we show a representative peak as a green dashed line. We also compared the ICGC color–color distribution with the one measured for the 33 GCs that in Section 2.3.4 we identified as being bound to Virgo early-type dwarfs. Their peak (magenta dashed line in Figure 11) is measured at redder colors. Besides the offset in the color peaks, the comparison between Figures 10 and 11 also shows different slopes for the M87 halo and Virgo intracluster GCs color–color relations. A maximum-likelihood linear fit to the \((g'-r')_0\) and \((i'-z')_0\) results in a galaxy component that is usually steeper than the ICL. Also, by computing the median deviation of the GC \((i'-z')_0\) colors from the fitted linear relation, \(\Delta\), the locus of the M87 halo GCs is tighter (i.e., stronger color–color relation) than the one of the ICGCs (fitted parameters and \(\Delta\) values are given in the legends of Figures 10 and 11). Such properties can be interpreted in terms of different metallicity distributions (Powalka et al. 2016b).

Finally, Peng et al. (2006) find that the mean \((g'-z')_0\) colors of the GCs in ACSVCS galaxies define a color–magnitude sequence, such that more luminous or massive galaxies host, on
average, redder GC systems. We then computed the mean \((g'-z')_0\) colors for the M87 halo and Virgo intracluster GCs and as a function of the distance. The GC systems bound to the M87 halo show redder mean \((g'-z')_0\) values. Averaged across the distance, and with no distinction between NW and SE halves, we find \(\langle(g'-z')_0,M87\rangle = 1.07 \pm 0.01\), while for \(R > 40\) kpc we find \(\langle(g'-z')_0,M87\rangle = 1.00 \pm 0.01\). The Virgo ICGCs are constant, within the uncertainties, to a mean color \(\langle(g'-z')_0,IC\rangle > 0.94 \pm 0.02\). Such a result is consistent with the galaxy-accreted component dominating the outer regions and reinforces our conclusion that the ICL is built up by less massive systems than the one contributing to the size growth of the M87 halo.

4.2. Density Profiles

We are now interested in studying the spatial distributions of the M87 halo and Virgo intracluster GCs to analyze their density profiles. This is because differences in their radial profiles may imply differences in the evolutionary paths of these two components as different progenitors are expected (Dolag et al. 2010; Cui et al. 2014) and observed (Longobardi et al. 2015a) to contribute differently to the resulting density distribution.

4.2.1. Spatial Completeness

In order to analyze the GC density profiles, we need to compute a completeness factor as a function of the distance, \(C_{\text{spec}}(R)\), that accounts for the spatial incompleteness of our spectroscopically selected sample of GCs. Such a completeness is estimated against the photometrically selected GCs, that is, objects with high \(p_{\text{gc}}\) probability (see Section 2.3.1), that we recall being 100% complete down to our limiting magnitude, \(g' = 24.0\) mag. We then estimate the completeness function by computing the ratio between the number of photometric GCs with spectroscopic information, \(N_{\text{GC,spec}}\), and the total number of GCs in the photometric sample, \(N_{\text{GC,phot}}\), in each elliptical annulus.\(^{23}\) Hence, the completeness function as a factor of the distance from M87’s center, \(C_{\text{spec}}(R)\), can be written as

\[
C_{\text{spec,j}}(R) = \frac{N_{\text{GC,spec,j}}}{N_{\text{GC,phot,j}}},
\]

where \(R\) is the average major axis distance of all GCs falling within each elliptical annulus. The subscript \(j\) indicates the two different GC components, red and blue. Averaged over the elliptical bins, the completeness factor amounts to \(C_{\text{spec}} = 0.1\), but the NW field is more affected by incompleteness than the SE region. This effect is measured at larger distances so that in the last bin we miss 40% more GCs NW of M87 as compared to the SE. This is due to observational strategies that observed the SE region more, but it is also related to the fact that the NW region has more photometric objects per unit area.

In Figure 12 the sky positions of our sample of data (both M87 halo, green dots, and Virgo intracluster GCs, yellow dots) can be seen overplotted on the NGVS \(g'\)-band image.

\(^{23}\) The completeness function \(C_{\text{spec}}(R)\) is computed using the spectroscopic sample of objects retaining those GCs that we flagged as bound to other Virgo members. This is because the photometric sample of GCs we use to complete our observations does contain such a contribution, and in this way the ratio is still conserved.

4.2.2. Density Profile for the M87 Halo and Virgo Intracluster GCs

The density profiles for the M87 halo and intracluster GCs are constructed by binning our GC samples in elliptical bins that have as major axis distances the same as what we used for our GMM analysis in Section 3 (see also orange lines in Figure 5) and as position angle and ellipticity \(P.A. = -25^\circ\) and \(e = 0.4\), respectively (Ferrarese et al. 2006; Janowiecki et al. 2010). Hence, for each of the two dynamical components of GCs and as a function of the distance, the density is computed as

\[
\rho_{\text{M87,j}}(R) = \frac{(N_{\text{obs,M87,j}}(R) - N_{\text{ov,j}}(R))}{A(R)} \times \frac{1}{C_{\text{spec,j}}(R)}
\]

\[
\rho_{\text{ICL,j}}(R) = \frac{(N_{\text{obs,ICL,j}}(R) + N_{\text{ov,j}}(R))}{A(R)} \times \frac{1}{C_{\text{spec,j}}(R)},
\]

where \(N_{\text{obs,M87,j}}(R)/N_{\text{obs,ICL,j}}(R)\) is the observed number of M87 halo and Virgo intracluster GCs in the elliptical bin, respectively; \(A(R)\) is the annulus area, estimated via Monte Carlo integration techniques if only a portion of the annulus intersects our FOV, and \(C_{\text{spec}}(R)\) is the spectroscopic completeness factor. The observed numbers of clusters together with the completeness factor differ for the two, red and blue, populations of GCs, which in Equations (2) and (3) are denoted with the subscript \(j\). As can be seen in Figure 6, the ICL and M87 halo velocity distributions overlap, and as a result, the GMM algorithm assigns the ICGCs at low velocities relative to the galaxy systemic velocity to the galaxy halo component. We statistically quantified this effect by comparing the M87 halo and IC velocity distributions in each elliptical bin. The LOSVDs of the two components were approximated by Gaussian functions with mean values and dispersions as given in Table 1. Hence, we calculated the fraction of ICGCs that lie inside the galaxy halo distribution as the area of overlap.
being the final number of GCs counted in each radial bin. The density profiles are shown separately for the blue and red populations of GCs (blue and red solid dots for the M87 halo and blue and red stars for the Virgo intracluster GCs, respectively). Note that the normalization factors differ for the red and blue populations associated with both the M87 halo and ICL.

We find the red component of the M87 halo GCs agrees well with the galaxy’s light, following its SB profile, while the blue component is more extended and flatter, in agreement with results from previous studies (e.g., Harris et al. 2009; Pota et al. 2013; Durrell et al. 2014). As discussed in the previous section, the total fraction of blue GCs in the M87 halo component amounts to 52% of the entire sample. However, Figure 13 shows that its relative contribution increases as a function of the distance: close to M87’s center, 32 < R ≤ 80 kpc, and this fraction increases to 50% and reaches 70% at larger distances. The ICGC density profile, which is flatter than the galaxy halo distribution, is still centrally concentrated. These findings are consistent with predictions from hydrodynamical simulations, where the radial density profile of the component bound to the galaxy halo is much steeper than that of the diffuse IC component (Murante et al. 2004; Dolag et al. 2010; Cui et al. 2014).

Finally we compute the difference in GC counting for both the M87 halo and IC objects, and for the red and blue populations in the NW and SE fields with respect to M87’s center (Figure 13, bottom panel). At all distances, the galaxy halo component is consistent within the uncertainties with no asymmetry between the northern and southern fields (ΔN = 0, dashed line). The cluster component, instead, shows asymmetry in the number of ICGCs when the NW and SE fields are studied separately, implying a higher fraction of IC components in the NW field in the outermost bin. This observation is consistent with what is measured by Durrell et al. (2014) from the photometric sample and is now validated on the basis of the spectroscopically confirmed GCs.

4.2.3. The Virgo ICGC SN

The number of clusters per unit luminosity quantifies the GC specific frequency, $S_N$, that numerically is defined as

$$S_N = 2 \times N_{\text{GC,TO}} \times 10^{0.4(M_V + 15)}$$

for a system with absolute $V$-band magnitude $M_V$. Here, $N_{\text{GC,TO}}$ is the number of GCs down to the GC luminosity function turnover magnitude, $M_{\text{TO}}$, and, multiplied by two, it is used to represent the total cluster population using a symmetric parameterization of the GC luminosity function (Harris & van den Bergh 1981). Assuming $M_{\text{TO}} = 24.0$ mag for the GC system at the center of Virgo (Jordán et al. 2007), $N_{\text{ICGC,TO}}$ in our surveyed area can be computed by fitting a power law to the measured ICGC density distribution and extrapolating inward such a profile. Doing so, we find that the expected number of ICGCs in the central $2° \times 2°$ of Virgo, and down to $g' \leq 24.0$ mag, is $N_{\text{ICGC,TO}} = 2503 \pm 430$, where the error accounts for the uncertainty in the integrated density profile. The entire population of ICGCs can then be retrieved by multiplying by two $N_{\text{ICGC,TO}}$. However, such a choice is not free from caveats: we are assuming a constant GCLF turnover.

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**Figure 13.** Top panel: azimuthally averaged density profiles as a function of the major axis distance from M87 for the galaxy halo (circles) and IC (crosses) GCs, with the red and blue symbols identifying the red (metal-rich) and blue (metal-poor) populations of GCs. The M87 GCs show a distribution that is steeper than the ICL counterpart, the latter being more extended and shallower, but still centrally concentrated. The red GCs bound to the M87 halo (red circles) follow the ICL-free galaxy’s surface brightness profile (green dots). The blue GCs bound to the M87 halo (blue circles) are more extended, deviating from the M87 light profile for $R > 30$ kpc. Bottom panel: difference in number of GCs between the NW and SE regions of M87 as a function of the major axis distance from M87 (legend as in the top panel). A value of zero (dashed gray line) implies symmetry in number counts of GCs between the NW and SE fields. A significant deviation from such a symmetry is measured in the last bin for the ICGC population, implying a higher fraction of intracluster components in the NW region of M87.
$g'$-band magnitude for the systems that contributed to the IC component that might result in a over- or underestimation of $N_{\text{ICGC}}$ for brighter and fainter $\mu_{R,\text{TO}}$, respectively. Thus, we computed the number of GCs we would add or lose if the “true” GCLF would have a magnitude cutoff in the range $\mu_{R,\text{TO}} \in [23.8,24.2]$ with dispersion values $\sigma_{\text{bright}} = 1.3$ and $\sigma_{\text{faint}} = 0.8$. The latter represent the dispersion values found to be representative of the GCLF for bright and faint galaxies in Virgo, respectively. The range of $\mu_{R,\text{TO}}$ traces, instead, the uncertainty on the $g'$-band turnover magnitude for the GCLF of Virgo galaxies, estimated to be constant to a value $\mu_{R,\text{TO}} = 24.0 \pm 0.2$ (Jordán et al. 2007). Hence, we expect a total ICGC population of $N_{\text{ICGC}} = 5006 \pm 1021$, where the error now accounts for the 11% uncertainty due to the choice of the GCLF.

To estimate the total ICL luminosity, we integrate the IC light profile traced by the ICPNs as given in A. Longobardi et al. (2018, in preparation) and in Longobardi et al. (2015a). Analyzing a sample of ICPNs in the inner 0.5 square degree of Virgo, these authors computed the $V$-band SB profile for the IC component in units of $L_{\odot,\text{SB}}$ as the scaled power-law fit to the IC PN surface density data (more details can be found in Longobardi et al. 2015a). They found that $I(R_{\text{ICL}}) \propto R^{-\gamma}$, with $\gamma = -0.79$ (A. Longobardi et al. 2018, in preparation) or $\gamma \in [-0.34, -0.04]$ (Longobardi et al. 2015a). Integrated over the NGVS pilot region, this profile gives a total $V$-band luminosity $L_{\text{ICL}} = 4.2 \pm 0.1 \times 10^{10} L_{\odot}$, with the error on $L_{\text{ICL}}$ computed as the variation in luminosity values when the different light profiles are used. This leads to our estimate for the ICGC specific frequency of $S_{N,\text{ICL}} = 10.2 \pm 4.8$. Peng et al. (2008) presented specific frequencies for the GC systems of 100 early-type galaxies in the ACS Virgo Cluster Survey and found that luminous early-type galaxies have higher $S_N$ than intermediate-luminosity early-type galaxies by a factor of $\sim 2$–3, with the latter class of objects ($-20.5 < M_V < -18$) generally having $S_N \sim 1.5$. Early-type dwarf galaxies have a large spread in $S_N$, characterized by an average value $S_N = 3.1$, but reaching estimates as high as $S_N = 14$. They also observed that nearly all dwarf galaxies with high GC fractions are within 1 Mpc of M87, so the GC fraction that we associate with the Virgo ICGC component is as high as the one measured for dwarf ellipticals that have yet to be subjected to tidal stripping or disruption (Peng et al. 2008).

5. Discussion

5.1. The Virgo Intracluster Population of GCs

Durrell et al. (2014) presented a large-scale study of the distribution of GCs in Virgo, statistically accounting for background and foreground contamination to the GC sample. By analyzing the two-dimensional maps of the GC distribution, they showed that the blue GCs represent an extended population, still significant beyond several effective radii from the hosting galaxy’s center. In the case of M87, they interpreted the GC population beyond 215 kpc as part of the intracluster component of Virgo, also suggested by a change in slope of the density profile of the blue GCs at major axis distances $R > 240$ kpc and the evidence for a spatial asymmetry of GCs surrounding M87 for major axis distances larger than 20', with an excess of tracers in the NW region (mostly the blue population).

On the spectroscopic front, the contamination by foreground MW stars has not allowed a clear identification of Virgo ICGCs. Strader et al. (2011) compiled a large catalog of GCs to study the halo of M87 and reported no evidence of an IC population of GCs, neither in terms of a flattening of the GC density distribution nor in terms of a steep rise in the velocity dispersion. They find a low value of $\sigma \sim 300 \text{ km s}^{-1}$ in the galaxy’s outer regions with no difference in kinematics between the red and blue GCs. However, despite their efforts to reduce the MW star contamination, the information they gathered was insufficient to disentangle contaminants and genuine GCs in the most ambiguous velocity range $V_{\text{LOS}} < 350 \text{ km s}^{-1}$, forcing them to classify all ambiguous objects as stars.

More recently, Ko et al. (2017) identified a sample of Virgo ICGCs that they associated with a main body of the cluster and with an infalling substructure. ICGCs with $V_{\text{LOS}} < \sim 400 \text{ km s}^{-1}$ were considered as representative of the infalling component, probably tracing systems that are dragged along by the M86 subgroup that is currently approaching Virgo’s center with negative LOS velocities. We describe a similar phenomenon in Section 3.1, where the comparison between the NW and SE LOSVDs shows a higher fraction of dE galaxies with negative $V_{\text{LOS}}$ north of M87 (toward M86). However, our interpretation is that, in the process of falling, the M86 subgroup is contributing GCs to the IC component through the stripping of material coming from low-mass galaxies that are being accreted into the Virgo core. These clusters hold the memory of the dynamics of their progenitors, but they are not spatially associated with them, and we consider them as a genuine component of the ICL. We also note that the ICGC LOSVD in Ko et al. (2017) does not extend below $V_{\text{LOS}} \sim -200 \text{ km s}^{-1}$, so it is possible that they are missing some of the low-velocity ICGCs due to their selection criteria, which were chosen to reduce foreground star contamination.

It is clear that the study of the Virgo ICGC component requires a proper accounting of contamination by foreground stars. In Section 2 we showed that the photometric information provided by the NGVS in the pilot region resulted in a clean photometric-based selection of GCs, thus allowing us to avoid hard cuts in velocity and explore the entire Virgo cluster velocity range. We showed that the IC component, overlapping the one of the central galaxy, results in a total LOSVD with strong and quite asymmetric tails, also making the GC kinematics gradually deviate from the one of M87 at larger distances until it merges with the Virgo cluster values as traced by the early-type dwarf galaxies. The Virgo IC component, then, has a distinct dynamical population of GCs representative of a dynamically young system. This is shown by the ICGC velocity distribution, which does not show signs of point symmetry: independent of the distance, the ICGC velocity dispersion is higher in the SE region than in the NW region. Although more data are needed to make the latter statement statistically stronger, this result, together with the measured spatial asymmetry (see Section 5.2), is consistent with the growing observational evidence of the ongoing assembly of Virgo. However, we note that Weil et al. (1997) argued that SE of M87 there is a spray of material as the result of a past interaction that could be responsible for the twisted and flaring outer isophotes to the SE of M87 as measured in the recent work by Mihos et al. (2017). Thus it is possible that there are multiple kinematic components in this region (see also Powlaka
et al. 2018), which manifest as a high velocity dispersion due to the limited number of tracers.

Finally, the Virgo ICGC component is not responsible for the high specific frequency measured for M87 (∼3 times higher than the average value observed for elliptical galaxies; Peng et al. 2008). West et al. (1995) suggested that ∼70% of the total M87 GC population was associated with cluster GCs. Although the results presented in this work do identify a Virgo ICGC population that overlaps with the M87 halo GCs, we find that the cluster only accounts for roughly 13% of the total number of GCs out to 216 kpc (see Table 1), a distance beyond which we do not predominantly trace the galaxy component anymore. Hence the presence of the Virgo ICGC population cannot explain the high M87 $S_N$.

5.2. Properties of the M87 Halo and Virgo Intracluster GCs and Their Connection to the System’s Formation

The kinematic separation between M87 halo and Virgo intracluster GCs allowed us in Section 4 to separately analyze their properties. We measured that both components have a red (metal-rich) and a blue (metal-poor) population of GCs. However, while the majority of ICGCs are metal-poor, the red-to-blue GC ratio in M87 is close to 50%. On the other hand, the blue GC component of M87 increases as a function of the radial distance until it dominates in the outermost bin. Different fractions of blue-to-red GCs also affect the $(g'-r')_0$ versus $(i'-z')_0$ color–color relation, which was recently shown to give insights into the evolution history of the host systems (Powalka et al. 2016b). We then find that the Virgo ICGCs peak on average at bluer colors than the M87 halo GCs. However, the color–color regions occupied by the metal-poor GC component of the M87 halo population reach bluer colors when moving toward large radii. In the NW region and for $R > 40$ kpc, the peak for the M87 halo GCs reaches values similar to those representative of the IC population at those distances. A similar trend is observed for the ICGCs, which on the northern side and for $R > 216$ kpc are characterized by the bluest peak in the $(g'-r')_0$ versus $(i'-z')_0$ diagram.

We also have information on the density distribution of the M87 halo and intracluster GCs, with the latter measured to be shallower, although still centrally concentrated around M87. An excess of ICGCs in the NW region reveals the asymmetric nature of this component, while within the error the spatial distribution of the M87 halo does not deviate from point symmetry. Finally, we find a specific frequency for the Virgo ICGC population $S_N^{ICL} = 10.2 ± 4.8$, assigning it to the category of high-$S_N$ systems.

The total number of GCs with respect to the parent stellar light, the relative fraction of blue-to-red objects, the GC color gradients, and the different spatial distributions must relate to the dynamical evolution of the system that hosted these GCs. In what follows, we will review these properties and consider their implications for the formation and evolution of M87, the Virgo ICL, and their GC populations.

The Virgo cluster core—Galaxy interactions as well as tidal interactions between galaxies and the cluster potential are the main mechanisms expected to build the IC component over time. The evidence in Virgo points to an IC component made up of GCs that are stripped from their host systems orbiting in the cluster potential. (1) It is well established that blue GCs have a shallower and more extended distribution than red GCs, and if so they are more likely to be stripped, resulting in an IC component with a high fraction of blue-to-red GCs and blue GC colors. Using $N$-body numerical simulations, Ramos et al. (2015) analyzed the tidal removal of GCs in Virgo-like galaxies and found that on average halos lose ∼16% and ∼29% of their initial red and blue GC populations. On the other hand, observational works (e.g., Smith et al. 2013) also emphasize the effect of the orbital and spatial distributions on the stripping process. (2) The shallow and centrally concentrated density distribution that overlaps a steeper density is found to be representative of the simulated diffuse components at the center of clusters (Dolag et al. 2010; Cui et al. 2014) and representative of the low-mass progenitors that went into building up the ICL at low redshift (Cooper et al. 2015). (3) Numerical simulations (Murante et al. 2004; Dolag et al. 2010) show that the stars that belong to the diffuse component did not lose memory of the kinematics of their progenitors, still reflecting the dynamics of the satellite. Thus, the kinematic result, revealing a GC system merging at large radii with the Virgo dwarf population, makes this class of galaxies the very likely progenitors of the IC component. This statement is also supported by the photometric properties of the Virgo ICGCs. The measured mean $(g'-z')_0$ colors are consistent with the one found to be representative of low-mass systems (Peng et al. 2006). Furthermore, the $S_N$ value and the high blue-to-red ratio are consistent with the values measured for dwarf early-type galaxies found within 1 Mpc of Virgo’s center and are mostly driven by the blue population of GCs (e.g., Peng et al. 2008; Mistani et al. 2016). The extreme environment these galaxies reside in favors a short star-formation period (as indicated by their high [$\alpha$/Fe] abundances), making them very efficient at forming massive star clusters (Liu et al. 2016). Closer to the center (within 40 kpc from M87), however, dwarf galaxies have few or no GCs, suggesting that GCs have been stripped and are contributing to what today we see as the IC population. This picture is consistent with what is observed in deep optical surveys, where the color and morphology of the ICL stellar streams suggest that the objects getting shredded are low-luminosity systems (e.g., Rudick et al. 2010; Mihos et al. 2017). However, it is important to note that we do observe a red GC fraction kinematically associated with the IC component, adding the result that, among the satellites that in the past built up the diffuse light in Virgo, there are also progenitors with $M_{prog} > 10^9 M_\odot$. This is because galaxies below such a mass have no measured red GC population (Peng et al. 2008).

In a recent work, Ferrarese et al. (2016) computed the expected total luminosity resulting from the disruption of galaxies in the Virgo core region, $L_{dis,V} = 7.7 ± 2.0 \times 10^{10} L_\odot$. Hence, our estimate of the Virgo ICL luminosity implies that the IC component can contribute up to ∼58% of the total “accreted luminosity.” Such an estimate assumes that the ICL only originates from galaxies that have been disrupted (and that had GCs), while it is likely that a fraction of the IC component has been stripped from still-existing galaxies or from galaxies that had no GCs.

Finally, as previously discussed, dE galaxies are the most likely progenitors of the Virgo ICL as traced by GCs. Thus, we can convert the total IC luminosity associated with the cluster component into a mass estimate, assuming as a mass-to-light ratio for the ICL the one measured for these systems. Toloba et al. (2011) analyzed a sample of dE galaxies in Virgo and estimated an average dynamical mass-to-light ratio in the I band, $\Upsilon_{1dyn} = 2.0 ± 0.04 \Upsilon_\odot$. This implies a total mass for the IC component in the Virgo core $M_{ICL,tot} = 10.8 ± 0.1 \times 10^{11} M_\odot$. 
which translates into a total stellar mass \( M_{\text{ICC}} = 6.6 \pm 5.0 \times 10^{13} M_\odot \) if \( M_{\text{gal}}/M_\odot = 1.6 \pm 1.2 \) (Toloba et al. 2011).\(^{24}\) Needless to say, these results have important implications for the origin of the diffuse light in cluster cores, essential for a fair comparison with hydrodynamical cosmological simulations.

\( M87 \)—Galaxies like \( M87 \) are thought to form via a two-phase formation scenario in which a first growth via rapid star formation fueled by the infall of cold gas or through major merger events is followed by a series of minor merger episodes that enrich the galaxy outer regions of stars and make them grow efficiently in size. Numerical simulations predict that only very massive systems, like \( M87 \), are going to experience mergers up to \( \sim 5 \) times in their dynamical evolution history (De Lucia et al. 2006; De Lucia & Blaizot 2007), and their halos are built up through the accretion of both massive and small systems (Cooper et al. 2015), so massive galaxies (log \( M_* > 10.5 M_\odot \)) are observed to assemble stellar mass predominantly in their halos (Eigenthaler et al. 2018).

The properties of the GCs associated with \( M87 \) likely reflect the evolutionary path taken by the galaxy itself. (1) The origin of the GC color bimodality was explained as the natural consequence of hierarchical merging. Following this interpretation, the metal-poor population of GCs represents the accreted component as a consequence of the accretion of smaller satellites, which adds to the preexisting (in situ) metal-rich GC population, the latter having formed along with the body of the galaxy itself (Côté et al. 1998; Kissler-Patig 2000; Mackey & Gilmore 2004). In this scenario, while the intrinsic (red) population of GCs dominates near the center of the galaxy, the ratio of metal-poor to metal-rich GCs increases with distance until the outer regions are characterized by an excess of blue clusters, as we measure for the \( M87 \) GCs. (2) On the other hand, the higher fraction of red GCs measured moving closer to the center may also trace the accretion of more massive systems that due to dynamical friction would be dragged toward the central regions and there deposit their redder population of GCs.

Several questions remain unanswered. For example, can simulations of stripping of GCs from cluster dEs reproduce the different dynamical components of GCs that also differ in kinematics and density distributions? Would such a set of simulations be able to reproduce an IC component with a metal-rich population of clusters, and if so would they measure the same ratio of blue-to-red GCs we observe? What would be the dynamical or stellar mass associated with the diffuse component in simulated galaxy cluster cores? On the observational front, what causes the different peak in the \((g'-r')_0\) versus \((i'-z')_0\) color–color relation for the \( M87 \) halo GCs? Is it tracing the presence of the \( M87 \) crown NW of \( M87 \), which we know is not a negligible perturbation of the galaxy halo properties, or is it tracing the accretion of different progenitors that differ in the SE and NW regions? We could argue, indeed, that such a NW–SE division is the residual kinematical signature of progenitor galaxy groups having formed in the center of Virgo, and we can speculate that if or when the M49 group falls in, it will produce a similar structure for some gigayears in the N–S direction. Finally, it is possible that a fraction of the red GC component at the center of \( M87 \) can be traced back to the major merger event that caused the presence of the KDC (Emsellem et al. 2014). In this case, a different chemical composition could differentiate these objects from the red GC component that originated from other formation processes. Future projects focusing on GC stellar population properties derived from analysis of the line strengths of stellar absorption features in deep spectroscopy have the potential to untangle some of these issues.

6. Summary

We have used the full photometric and spectroscopic information of the GCs in the NGVS Virgo core region (the \( 2^\circ \times 2^\circ \) area around \( M87 \)) to identify and separate the \( M87 \) halo GC population from the Virgo ICGCs and study their properties separately. This study can be summarized as follows:

1. We implemented the extreme deconvolution algorithm to model as a sum of Gaussians the multidimensional color–concentration–magnitude space occupied by the objects in the NGVS and reduce the contamination by foreground stars. This allowed us to explore the entire Virgo velocity range, usually affected by hard cuts in velocity for \( V_{\text{LOS}} < 500 \) km s\(^{-1}\) (Figures 2 and 3).

2. The GC kinematics reveal a system that, as a function of the distance from the center of \( M87 \), deviates from the galaxy’s kinematics. On both sides of \( M87 \), the GC system shows a decrease in the mean velocity and an increase in the velocity dispersion until it merges (for distances larger than 320 kpc) with the Virgo cluster potential, as traced by the dwarf early-type galaxies in Virgo (Figure 5).

3. Based on a GMM analysis, the mixture that best describes the total LOSVD is a two-component model, which we then interpret as arising from the Virgo’s IC and \( M87 \)’s halo components. The \( M87 \) halo and ICL overlap out to 216 kpc. Farther out, the GMM identifies only one component with mean velocity and velocity dispersion consistent with tracing the ICL (Figure 6).

This analysis, run separately for the sample of data in the SE and NW regions of \( M87 \), shows an IC component that is not characterized by point symmetry: the SE region shows higher values of velocity dispersion with respect to the NW counterpart. This finding can be interpreted as being the result of an IC component that is not relaxed. However, due to the limited number of GC velocity measurements at these extreme distances, the level of significance is within 1\( \sigma \).

4. The analysis of the \((g'-i')_0\) versus \( g' \) color–magnitude diagram shows that both \( M87 \) galaxy and Virgo ICGC populations have a blue (metal-poor, \((g'-i')_0 < 0.77\)) and a red (metal-rich, \((g'-i')_0 \geq 0.77\)) component of GCs. However, the IC population is richer in blue GCs, the latter representing \( \sim 70\% \) of the IC sample. The fraction of blue GCs in the \( M87 \) component is \( \sim 50\% \) of the sample (Figure 9). On the other hand, the blue GC component of the \( M87 \) halo increases as a function of the distances, reaching \( 70\% \) in the outermost bin.

5. The ICGCs are characterized by bluer colors than the galaxy halo GC population, as shown by the study of the \((g'-r')_0\) versus \((i'-z')_0\) color–color diagrams. Within the \( M87 \) halo population, the GCs in the NW region and for major axis distances \( 40 \) kpc \(< R \leq 216 \) kpc are bluer, and they may be driven by the presence of a recent accretion event which in that region we know is

\(^{24}\) To transform \( V\)-band luminosities into \( I\)-band luminosities, we have used \( V-I = 1.03 \pm 0.04 \) as calculated by van Zee et al. (2004) for dwarf galaxies.
contributing 60% of the M87 halo light (Longobardi et al. 2015b). Within the IC population, the GCs in the NW region and for major axis distances $R > 216$ kpc are the bluest (Figures 10 and 11).

6. The intracluster GC population has a shallower density profile than the M87 galaxy GC population, consistent with results from theoretical simulations of the diffuse stellar component (ICL) around central cluster galaxies (Dolag et al. 2010). The different slopes can also be interpreted as being due to the different origins of the two components: steeper profiles come from the accretion of more massive systems at higher redshifts, while the shallower and more extended ICL component would be the result of less massive systems whose accretion happened at lower redshifts (e.g., Cooper et al. 2015). This is consistent with the measured mean $(g'−z')_0$ colors that are consistent with the one found to be representative of low-luminosity or low-mass systems (Peng et al. 2006). We find evidence for an asymmetry in the number of ICGCs when the NW and SE fields are studied separately, implying a higher fraction of IC component in the NW field for distances larger than $R > 216$ kpc (Figure 13).

7. The population of ICGCs falls under the category of high-$S_N$ systems with a measured specific frequency $S_{N,ICL} = 10.2 \pm 4.8$. This value is consistent with the one observed for the dwarf early-type galaxies that reside within 1 Mpc from the cluster center, supporting a stripping or disruption scenario for the ICGCs.

8. The total V-band luminosity relative to the ICL at the center of Virgo is $L_{ICL} = 4.2 \pm 0.1 \times 10^{10} L_\odot$. This value translates into total (dark plus luminous) and stellar masses $M_{ICC,tot} = 10.8 \pm 0.1 \times 10^{11} M_\odot$ and $M_{ICC,*} = 6.6 \pm 5.0 \times 10^{10} M_\odot$, respectively.

These results show that the GCs successfully trace the galaxy halo–ICL interface, and their properties allow us to understand the formation and evolution of these two components. This work presents a picture in which the M87 halo and Virgo intracluster GCs have different progenitors, with the latter most likely representing the Virgo accreted component from low- and intermediate-mass dwarf ellipticals.

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