The outer regions of the giant Virgo galaxy M87

II. Kinematic separation of stellar halo and intracluster light*

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ABSTRACT

Aims. We present a spectroscopic study of a sample of 287 Planetary Nebulas (PNs) around the brightest cluster galaxy (BCG) M87 in Virgo A, of which 211 are located between 40 kpc and 150 kpc from the galaxy center. With these data we can distinguish the stellar halo from the co-spatial intracluster light (ICL) and study both components separately.

Methods. PN velocities were obtained with a high resolution FLAMES/VLT survey targeting eight fields in a total area of ~ 0.4 deg². PNs were identified from their narrow and symmetric redshifted $\lambda$5007Å [OIII] emission line, the presence of the second $\lambda$4959Å [OII] emission line, and the absence of significant continuum. We implement a robust technique to measure the halo velocity dispersion from the projected phase-space to identify PNs associated with the M87 halo and ICL. Using photometric magnitudes, we construct PN luminosity functions (PNLFs), complete down to $m_{9000} = \approx 28.8$.

Results. The velocity distribution of the spectroscopically confirmed PNs is bimodal, containing a narrow component centered on the systemic velocity of the BCG and an off-centred broader component, that we identify as halo and ICL, respectively. We find that 243 PNs are part of the velocity distribution of the M87 halo, while the remaining subsample of 44 PNs are intracluster PNs (ICPNs). Halo and ICPNs have different spatial distributions: the number density of halo PNs follow the galaxy’s surface brightness profile, whereas the ICPNs are characterised by a shallower power-law profile, $I_{\text{ICL}} \propto R^{-\alpha}$ with $\alpha = -0.34 \pm 0.04$. No evidence is found for an asymmetry in the halo and ICPN density distributions when the NW and SE fields are studied separately. Study of the composite PN number density profile confirms the superposition of different PN populations associated with the M87 halo and the ICL, characterised by different PN specific numbers $a$. We derive $\alpha_{\text{halo}} = 1.06 \times 10^{-8} N_{\text{halo}} L^{-1} \odot$ and $\alpha_{\text{ICL}} = 2.72 \times 10^{-8} N_{\text{ICL}} L^{-1} \odot$, respectively. The M87 halo PNLF has fewer bright PNs and a steeper slope towards faint magnitudes than the IC PNLF, and both are steeper than the standard PNLF for the M31 bulge. Moreover, the IC PNLF has a dip at ~ 1-1.5 mag fainter than the bright cutoff, reminiscent of the PNLFs of systems with extended star formation history such as M33 or the Magellanic clouds.

Conclusions. The BCG halo of M87 and the Virgo ICL are dynamically distinct components with different density profiles and velocity distributions. Moreover, the different $\alpha$-parameter values and PNLF shapes of the halo and ICL indicate distinct parent stellar populations, consistent with the existence of a gradient towards bluer colours at large radii. These results reflect the hierarchical build-up of the Virgo cluster.

Key words. galaxies: clusters: individual (Virgo cluster) - galaxies: halos - galaxies: individual (M87) - planetary nebulae: general

1. Introduction

Galaxy halos are faint stellar components made of stars gravitationally bound to the individual galaxies. In galaxy clusters these halos may be surrounded by intracluster stars. The existence of a diffuse population of intergalactic stars was first proposed by Zwicky (1937, 1952). Due to its low surface brightness it was only with the advent of CCD photometry that this diffuse stellar component could be studied in a quantitative way, thus becoming a topic of interest for observational and theoretical studies.

The formation of intracluster light (ICL) and of the extended halos around the brightest cluster galaxies (BCG) is closely related to the morphological transformation of galaxies in clusters. Two of the main physical processes describing the gravitational interaction between galaxies during cluster formation and evolution are dynamical friction (Ostriker & Tremaine 1975; Merritt 1985; Taffoni et al. 2003; Boylan-Kolchin et al. 2008; De Lucia et al. 2013) and tidal stripping (Gallagher & Ostriker 1972; Moore et al. 1996; Gregg & West 1998; Willman et al. 2004; Read et al. 2006). Depending on its mass, central distance and orbit, these processes determine the fate of a cluster galaxy. Dynamical friction is the primary mechanism dragging a massive satellite towards the host halos centre, where it will merge with the BCG. On the other hand, tidal forces strip stars from satellite galaxies which will end up orbiting the cluster as unbound ICL (Gnedin 2003; Murante et al. 2004, 2007; Mihos 2004; Rudick et al. 2006). In the ICL and the outer regions of BCGs where the dynamical time-scales are long, fossil records of accretion events can be preserved over extended periods (Willman et al. 2004; Rudick et al. 2009; Cooper et al. 2014). Hence, the study of the luminosity, distribution and kinematics of galaxy halos and ICL may provide information on the evolution of galaxies and their host clusters.

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In the last ten years the analysis of simulated galaxy clusters has shed light upon the nature and origin of the diffuse stellar component and its connection with the BCG (Napolitano et al. 2003; Murante et al. 2004, 2007; Willman et al. 2004; Rudick et al. 2006, 2010; Puchwein et al. 2010; Contini et al. 2014). In the framework of cosmological hydrodynamical simulations, Dolag et al. (2010) and Cui et al. (2014) separated stars bound to the cluster potential from those bound to the BCG by adopting a dynamical definition of the main galaxy halo and the diffuse light. Tagging particles as galaxy or intracluster component based on their different velocity distributions, they identified two distinct stellar populations in terms of kinematics, spatial distribution, and physical properties like age and metallicity. Other studies do not adopt such a dynamical definition of the two components and treat the BCG and ICL as a single system at the centre of the cluster, consisting of all stars that are not bound to any satellite subhalos in the cluster (e.g., Murante et al. 2004; Cooper et al. 2014). Galaxy halos, diffuse ICL, and their connection with galaxy evolution in clusters have been the subject of many observational studies. Deep imaging of individual objects (Bernstein et al. 1995; Gonzalez et al. 2000; Feldmeier et al. 2004; Mihos et al. 2005; Krick & Bernstein 2007; Rudick et al. 2010) has shown that the faint ICL around BCGs often has irregular morphology, consistent with predictions from simulations. From stacking images for a large number of objects (Zibetti et al. 2003; D’Souza et al. 2014), average photometric properties were obtained, showing that the ICL extends to many 100s of kpcs from the cluster centre. In the Virgo cluster, Kormendy et al. (2009) analysed a sample of ellipsicals and spheroidal galaxies and studied their halos through the light profiles. Comparing their results with the earliest simulations of van Albada (1982), they argued that light profiles with a large Sersic index (n > 4) are common in many giant ellipticals whose origin can be associated with merger processes.

Kinematics and stellar population parameters have been measured only in a small number of BCG halos, such as NGC 4889 in the Coma cluster (Coccato et al. 2010), which shows a change of stellar population at large radii, the central galaxy NGC 3311 in Hydra I (Ventimiglia et al. 2010, Arnaboldi et al. 2012) where the kinematics as well as the morphology of the outer halo signal on-going accretion events, and NGC 6166 in Abell 2199 (Kelson et al. 2002; Bender et al. 2014) whose velocity dispersion profile blends smoothly into the cluster. ICL kinematics in the Coma cluster suggest an on-going merger of two cluster cores (Gerhard et al. 2007). All these studies aimed at understanding the role of tidal disruption and merger events as the main processes involved in the formation and evolution of central cluster galaxies and the ICL.

In the nearest clusters, single stars can be used to study the stellar populations associated with the outer halos and the diffuse stellar component (Ferguson et al. 1998; Durrell et al. 2002; Williams et al. 2003; Yan et al. 2008). Globular clusters (GCs) have been used to obtain kinematic information in the outer regions of nearby early-type galaxies (Côté et al. 2001, Schuberth et al. 2010; Strader et al. 2011; Romanowsky et al. 2012; Pota et al. 2013). Planetary Nebulas (PNs) have been targeted in several surveys aimed at tracing the light and motions in galactic halos (Hui et al. 1993; Méndez et al. 2007; PEng et al. 2004; Coccato et al. 2009; McNeil et al. 2010; McNeil-Moylan et al. 2012; Cortesi et al. 2013), the Virgo cluster IC component (Arnaboldi et al. 1996, 2003, 2004; Aquevedo et al. 2005; Doherty et al. 2009; Castro-Rodríguez et al. 2009; Longobardi et al. 2013), and the Hydra I and Coma clusters, out to 50–100 Mpc (Gerhard et al. 2005). It was found that the observed properties of the PN population, such as the α parameter which quantifies the stellar luminosity associated with a detected PN, and the PN luminosity function (PNLF) correlate with the age, colour and metallicity of the parent stellar population (Hui et al. 1993; Ciardullo et al. 2004; Cardullol 2010; Buzzoni et al. 2006; Longobardi et al. 2013). Thus PNs can be used to trace these physical quantities of their parent stellar populations at surface brightnesses too faint for other techniques.

The giant elliptical galaxy M87 has one of the oldest stellar populations in the local Universe (Liu et al. 2005), and a stellar halo containing 70% of the galaxy light down to μ_V =27.0 mag arcsec−2 (Kormendy et al. 2009). It is close to the centre of subcluster A in the Virgo cluster (Binggeli et al. 1987), the nearest galaxy cluster, and it is expected to have transformed over larger time scales due to galaxy mergers (De Lucia & Blaizot 2007). Deep imaging (Mihos et al. 2003; Janowiecki et al. 2010) has revealed a complex network of faint, extended tidal features around M87, suggesting that it is not completely in equilibrium. Thus, M87 and the surrounding Virgo cluster core are prime targets to address the formation and evolution of galaxy clusters, ICL, and BCGs. Indeed, M87 has been the subject of many dynamical studies with X-ray measurements (Nulsen & Bohringer 1995; Churazov et al. 2010), integrated stellar kinematics (Murphy et al. 2011, 2014), GC kinematics (Côté et al. 2001; Strader et al. 2011; Romanowsky et al. 2012; Zhu et al. 2014), and PN kinematics (Arnaboldi et al. 2004; Doherty et al. 2009), to estimate its mass and derive the dark matter distribution. Using PN kinematics, Doherty et al. (2009) identified M87 halo and IC PNs and showed the coexistence, at radii > 60 kpc, of a stellar halo bound to the galaxy potential and a surrounding unbound Virgo ICL.

In this work, we report the results of a wide and high resolution spectroscopic survey covering the outer regions of M87 out to a distance of 150 kpc from the galaxy centre. The aim of this project is to investigate the halo-IC dichotomy, making use of a large spectroscopic sample of PNs (approximately fifteen times larger than the previous sample of Doherty et al. (2009)). The paper is structured as follows: in Sect. 2 we describe the spectroscopic survey together with the data reduction procedures and the classification of PN spectra. In Sect. 3 we study the PN phase-space distribution and dynamically separate the halo and ICL populations. Spatial density distributions are derived in Sect. 4 and in Sect. 5 we present the properties of the halo and ICL PN populations in terms of their α—parameters and the morphology of their PNLFs. Finally we discuss our results in Sect. 6 and give our conclusions in Sect. 7.

In this study we adopt a distance modulus of 30.8 for M87, implying a physical scale of 73 pc arcsec−1.

2. The FLAMES M87 PN survey

2.1. Photometric sample

The photometric candidates targeted by our spectroscopic survey come from an earlier imaging survey (Longobardi et al. 2013), covering a 0.43 deg2 region centred on M87. Images were taken through a narrow band filter centred on the redshifted [OIII]λ5007 Å emission line at the Virgo cluster distance (on-band image), and through a broad-band V-filter (off-band image). Because of their bright [OIII]λ5007 Å emission, extragalactic PNs can be identified as unresolved emission sources with
positive flux on the on-band [OIII] image and no detection on the off-band image.

Spectra were obtained in two observing campaigns. For the first spectroscopic campaign, we selected emission line candidates as objects with positive flux on the colour [OIII]-V band image (hereafter difference method, see Feldmeier et al. 2003 for more details). The visual catalogue extracted on the basis of the difference method consisted of 1074 objects that covered a magnitude range $23 \leq m_{5007} \leq 29.8$, and is statistically complete down to $m_{5007} = 28.8$.

For the second spectroscopic campaign, we carried out a more stringent selection procedure described in Longobardi et al. (2013). In this procedure, the PN candidates were selected using automatic selection criteria, based on the distribution of the detected sources in the colour-magnitude (CM) diagram and the properties of their point-spread function (PSF) (for more details see Arnaboldi et al. 2002; Longobardi et al. 2013). This automatic catalogue is complete within the magnitude range $26.3 \leq m_{5007} \leq 28.4$.

The combined total input sample for the spectroscopic survey (visual catalogue plus automatic catalogue) consisted of 1484 emission line candidates.

### 2.2. Observations and data reduction

The spectra were acquired in service mode with the FLAMES spectrograph on the VLT-UT2 telescope, in the GIRAFFE+MEDUSA mode. This observing mode allows up to 132 separate fibres that can be allocated to targets in one plate configuration, covering a circular area of 20’ diameter. The total emission line sample was observed in two observing runs (24h, 088.B-0288(A); 11h, 093.B-0066(A); PI: M.Arnaboldi) which were characterised by clear conditions and seeing better than 0.9”. We used the high-resolution grism HR08, covering a wavelength range of ~ 250 Å centred on 5048 Å with a spectral resolution of $R = 22500$. With this setup, the instrumental broadening of the arc lines has a FWHM of 17 km s$^{-1}$ and the statistical error on the wavelength measurements is 150 m s$^{-1}$ (see Royer et al. 2002). We refer to Sect. 2.5 for discussion of the velocity accuracy estimated from repeat observations of the same emission line candidates.

Because the [OIII] emission lines from PNs are only a few km s$^{-1}$ wide, high resolution spectra are also desirable to reduce the sky contamination, making the FLAMES spectrograph the ideal instrument for LOS velocity measurements of extragalactic PNs.

For our first spectroscopic campaign, the visual catalogue was divided into a bright ($m_{5007} < 27.2$) and a normal ($m_{5007} > 27.2$) sample. The FLAMES plate configurations and exposure times were then optimised in order to reach the maximum number of fibres allocated, as well as optimal signal-to-noise ratio (S/N) for both samples.

In total we defined 12 FLAMES plate configurations, labelled as M87SUB1 Bright F01-F03, M87SUB1 Norm F01-F03 and M87SUB2 Bright F01-F03, M87SUB2 Norm F01-F03 for the NW (SUB1) and SE (SUB2) Suprime-Cam fields respectively. The layout of the FLAMES pointings on the sky, together with the coverage of the photometric Suprime-Cam survey, is shown in Fig. 1. In the second spectroscopic campaign we added two FLAMES plate configurations covering the very central region of M87 and the NW edge of the Suprime-Cam imaging survey, in addition to completing the observations of the 12 FLAMES configurations from the first campaign. These two additional FLAMES configurations are shown in Fig. 3 with the labels

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1. Before the subtraction the continuum off-band image was scaled to the on-band image by a multiplicative scaling factor found measuring fluxes from several bright, isolated stars on both images.

2. The transformation between the AB and $5007$ magnitudes for the photometric narrow band filter is given by $m_{5007} = m_{AB} + 2.49$ (Longobardi et al. 2013).
FCEN and FEGDE, respectively. Table 1 provides an overview of
the FLAMES field configurations and the total exposure
times.

The spectroscopic data were reduced using the GIRAFFE pipeline. The reduction procedure included bias subtraction, flat-fielding, identification of the fibre locations on the CCD, geometric distortion correction, wavelength calibration and extraction of the one-dimensional spectra. The calibrated one-dimensional spectra were then corrected to the heliocentric velocity using the IRAF task dopcor. Finally, we combined spectra from single exposures using the IRAF task scombine to get the targeted S/N for each spectrum.

2.3. Spectroscopic success rates

We define the nominal success rate as the ratio between the number of emission line objects whose line was detected in the spectrum and the number of fibres allocated for a given FLAMES plate configuration. For our observations, it varies from field to field, in a range of values between ~ 20% and ~ 60%. These values are similar to those obtained in the spectroscopic follow-up of GCs in the outer halo of M87 (see Sect. 3 in Strader et al. (2011)). The low success rates for some of the fields (mostly M87SUB2B fields) are caused by guide star proper motions which were not correctly accounted for in the FLAMES astrometry input file for the fibre allocation. We were also able to estimate the fraction of fibre-object misalignments, from the repeat observations of the emission objects in common between adjacent FLAMES plate configurations. From this we determine the spectroscopic completeness $C_{\text{spec.fb}}$. The spectroscopic incompleteness together with the sample characteristics determine the nominal success rate. In Table 2 we report the total number of allocated fibres together with the nominal success rate, the number of spectroscopically confirmed PNs, and the spectroscopic completeness $C_{\text{spec.fb}}$ for all of the FLAMES fields.

The nominal success rates are consistent with the selection criteria for the different samples. The candidates from the automatic sample have higher success rates than candidates from the visual catalogue, reaching > 70% in M87SUB1 BrightF03 and M87SUB2 BrightF01 (see Table 2). On the other hand, about 30% of the confirmed spectra come from targets in the visual catalogue: this is consistent with the results of the simulations by Longobardi et al. (2013) for the fraction of missed true line emission sources with automatic selection criteria.

2.4. Classification of the extracted spectra

The colour selection criteria are based on the strong [OIII] $\lambda$5007Å emission of a PN, with faint or no continuum. Nonetheless, background galaxies like Ly$\alpha$ emitters at $z \sim 3.1$ and [OII] $\lambda$3727,26Å emitters at $z \sim 0.34$ have relatively strong lines that fall within the bandpass of the narrow-band filter. Thus, the extracted spectra were classified on the basis of the shape of the line profile of the strongest emission. The extracted spectra fall into these categories:

- PN spectra: the [OIII] $\lambda$5007Å emission of a PN is characterised by a narrow and symmetric line shape and very low continuum. In high S/N spectra, we detected the redshifted [OIII] $\lambda$4959/5007Å doublet. Typical S/N ratios for the spectroscopically confirmed PN [OIII]$\lambda$5007Å cover a range of 2.5 $\leq$ S/N $\leq$ 8.5. In Fig. 3 we show examples of single PN spectra with different $V_{\text{LOS}}$.

- Ly$\alpha$ spectra: the emission line of a Ly$\alpha$ emitter has a broader and more asymmetric line profile, characterised by a steep drop-off at blue wavelengths. Such a signature comes from the forest absorption bluewards of Ly$\alpha$: the symmetric emission line is truncated below the object redshift by Ly$\alpha$ scattering in the intergalactic medium. Fig. 3 shows an example of an extracted FLAMES spectrum for a Ly$\alpha$ emitter.

- [OII] spectra: the [OII] $\lambda$3727Å emitters are characterised by the redshifted, resolved and broad emission lines of the oxygen doublet at $\lambda$3726–3729Å. Fig. 3 shows an example of an extracted FLAMES spectrum for an [OII] line emitting galaxy.

The final sample of emission line objects consists of 380 sources, of which 287 were classified as PNs and the remaining as background emission line galaxies, either as Ly$\alpha$ or as [OII] emitters. This is the largest sample of spectroscopically

| FLAMES Conf | RA (h:m:s) | DEC (degrees) | Total Exposure time (s) | Single Exposure time $\times$ # of exposures (s) |
|-------------|-----------|---------------|------------------------|-------------------------------------------------|
| M87SUB1 Bright F01 | 12:30:35.015 | +12:13:29.28 | 2700 | 1350 $\times$ 2 |
| M87SUB1 Bright F02 | 12:30:05.323 | +12:43:00.08 | 2700 | 1350 $\times$ 2 |
| M87SUB1 Bright F03 | 12:29:57.347 | +12:30:03.49 | 2700 | 1350 $\times$ 2 |
| M87SUB1 Norm F01 | 12:30:35.015 | +12:13:29.28 | 8100 | 2700 $\times$ 3 |
| M87SUB1 Norm F02 | 12:30:05.323 | +12:43:00.08 | 8400 | 2800 $\times$ 3 |
| M87SUB1 Norm F03 | 12:29:57.347 | +12:30:03.49 | 8400 | 2800 $\times$ 3 |
| M87SUB2 Bright F01 | 12:31:25.426 | +11:57:31.43 | 2700 | 1350 $\times$ 2 |
| M87SUB2 Bright F02 | 12:31:44.477 | +12:12:01.55 | 2700 | 1350 $\times$ 2 |
| M87SUB2 Bright F03 | 12:30:45.170 | +12:02:27.20 | 2700 | 1350 $\times$ 2 |
| M87SUB2 Norm F01 | 12:31:25.426 | +11:57:31.43 | 8400 | 2800 $\times$ 3 |
| M87SUB2 Norm F02 | 12:31:44.477 | +12:12:01.55 | 8400 | 2800 $\times$ 3 |
| M87SUB2 Norm F03 | 12:30:45.170 | +12:02:27.20 | 8400 | 2800 $\times$ 3 |
| M87SUB FEGDE | 12:29:57.854 | +12:41:20.09 | 6800 | 1700 $\times$ 4 |
| M87SUB FCEN | 12:30:05.019 | +12:20:48.88 | 6800 | 1700 $\times$ 4 |
Table 2. Summary of the total number of allocated fibres, nominal success rate, detected number of PNs, and spectroscopic completeness in all fields. Numbers in brackets refer to sources in common with the automatic sample.

| FLAMES Conf. | # of targets with fibres allocated | Nominal success rate | Confirmed PNs | C_{spec,fb} |
|---------------|-----------------------------------|----------------------|---------------|-------------|
| M87SUB1 Bright F01 | 33 (12) | 52% (42%) | 8 (3) | 0.6 |
| M87SUB1 Bright F02 | 41 (19) | 23% (32%) | 4 (4) | 0.5 |
| M87SUB1 Bright F03 | 33 (14) | 42% (71%) | 8 (8) | 0.9 |
| M87SUB1 Norm F01 | 125 (58) | 47% (57%) | 49 (26) | 0.9 |
| M87SUB1 Norm F02 | 130 (65) | 52% (62%) | 55 (35) | 0.9 |
| M87SUB1 Norm F03 | 127 (56) | 53% (64%) | 54 (31) | 0.9 |
| M87SUB2 Bright F01 | 23 (8) | 61% (75%) | 5 (3) | 0.8 |
| M87SUB2 Bright F02 | 31 (16) | 26% (25%) | 5 (4) | 0.6 |
| M87SUB2 Bright F03 | 26 (7) | 54% (57%) | 5 (3) | 0.8 |
| M87SUB2 Norm F01 | 104 (40) | 16% (17%) | 10 (6) | 0.3 |
| M87SUB2 Norm F02* | 144 (71) | 42% (51%) | 44 (27) | 0.6 |
| M87SUB2 Norm F03 | 117 (50) | 24% (30%) | 23 (14) | 0.4 |
| M87SUB CEN | 130 (94) | 54% (60%) | 63 (51) | 0.9 |
| M87SUB FEDGE | 131 (60) | 27% (30%) | 30 (16) | 0.8 |

Notes. Fibre configuration was modified between different exposures.

confirmed PNs around M87 thus far, about a factor 15 larger than the sample of Doherty et al. (2009).

The fraction of background emitters is consistent within one σ with the estimate in the photometric study of Longobardi et al. (2013), amounting to 25% of the total imaging sample when considering objects in common with the automatic catalogue.

2.5. Accuracy of the velocity measurements

From the repeat observations of the same candidates in areas where different FLAMES plate configurations overlap (see Fig. 1) we obtained independent velocity measurements for a subsample of PNs. The median deviation of these measurements is 4.2 kms\(^{-1}\), and the whole distribution covers a range of 0.6 ≤ ΔV_{los} ≤ 16.2 kms\(^{-1}\). The largest errors occur when a cosmic ray falls near the wavelength of the [OIII]λ5007Å emission in one of the exposures.

3. Halo and ICL PN components

When studying the outer regions of M87 out to a distance of ~ 150 kpc from the galaxy centre, we are tracing the light in the radial range where the M87 halo blends into the ICL. Arnaboldi et al. (2004) showed that the M87 stellar halo and the Virgo core ICL coexist for distances > 60 kpc from the galaxy centre, and Doherty et al. (2009) showed that the two components overlap out to 150 kpc. Longobardi et al. (2013) showed that the observed slope of the PN number density profile is consistent with the superposition of two PN populations associated with the M87 halo and ICL, respectively.
In the following subsections, we show that the distribution of LOS velocities obtained from the FLAMES spectra shows evidence for two dynamically distinct PN populations at large radii, confirming this interpretation.

### 3.1. Projected PN phase-space diagram

![Projected phase-space diagram showing V_{LOS} vs. major axis distance R](image)

In this diagram, the velocities of the PNs are represented as a function of their projected distance from the centre of M87. The dotted horizontal line shows M87’s systemic velocity $V_{sys} = 1275 \, \text{kms}^{-1}$ as computed in this work. The shaded area represents the region of the projected phase-space where the blue-shifted [OIII] 4959Å emission line would fall below the wavelength of the blue edge of the FLAMES sort ordering filter HR08.

For each confirmed PN spectrum, we measured $V_{LOS}$ and computed the major axis distance via the formula $R = \frac{x_{PN}^2}{(1-e)^2} + y_{PN}^2$, where $e$ is the isophote’s ellipticity from [Kormendy et al. 2009] and $x_{PN}, y_{PN}$ are the PN coordinates measured in a reference frame centered on M87, where the $y$ axis is aligned with the major axis of the outer elliptical isophotes at $PA = -25.6^\circ$ [Kormendy et al. 2009]. In Fig. 4 we show the projected phase-space diagram $V_{LOS,PN}$ vs. $R$ for the spectroscopically confirmed PNs in the M87 survey (black asterisks).

In this projected phase-space, PN velocities show a concentration around the systemic velocity of M87 ($V_{sys} = 1275 \, \text{kms}^{-1}$; see Sect. 5.2), in addition to a scattered distribution at higher and lower velocities. In Fig. 5 we show the histogram of the velocities for the entire sample, which we fit with two Gaussians. The LOS velocity distribution (LOSVD) (black line) can be represented as the sum of a narrow Gaussian component, centred on $V_{LOS,n} = 1270.4 \, \text{kms}^{-1}$ with velocity dispersion of $\sigma_n = 298.4 \, \text{kms}^{-1}$, and a broad Gaussian component, centred on $V_{LOS,b} = 999.5 \, \text{kms}^{-1}$ with a larger velocity dispersion $\sigma_b = 881.0 \, \text{kms}^{-1}$.

The broad component is shifted from the M87 systemic LOS velocity: both $V_{LOS,n}$ and $\sigma_n$ are consistent with those values determined for the LOSVD of galaxies in the main sub-cluster region A of the Virgo cluster [Rines & Geller 2008]. The LOSVD around M87 is thus bimodal, containing a narrow component associated with the systemic velocity of the galaxy plus a broader component associated with the ICL.

**Fig. 5.** Histogram of the line-of-sight velocities of the spectroscopically confirmed PNs (black histogram) fitted with a double Gaussian (black curve). Red and blue lines represent the two Gaussians associated with the M87 halo and the ICL component.

Different LOSVDs for the halo and ICL are predicted by cosmological simulations of structure formation. Using hydrodynamical cosmological simulations, [Dolag et al. 2010; Cui et al. 2014] identify two distinct populations using the kinematics of the star particles in the cores of their simulated clusters. 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. It is plausible that the halo stars are spatially confined as a consequence of merging processes that led to the formation of the BCG [Murante et al. 2007; Contini et al. 2014].

### 3.2. Robust separation of the M87 halo and ICL

We have seen that the overall LOSVD of the PNs in M87 is characterised by a narrow component associated with the M87 halo, superposed on a broad ICL component with a shifted mean velocity and much larger velocity width. We are now interested in separating halo and IC PNs based on their different LOSVDs. In this analysis we combine our PN sample with that of [Doherty et al. 2009]. We concentrate on those PNs that have a major axis distance $R \leq 190 \, \text{kpc}$, to study the transition between the M87 halo and the Virgo ICL. The combined total sample consists of 299 PNs with measured positions and velocities within $R \leq 190 \, \text{kpc}$; the PNs from [Doherty et al. 2009] further out are classified as ICPNs and will not be discussed further.

In order to separate halo and ICL components we use a sigma clipping algorithm in elliptical radial bins, corresponding to vertical strips in the projected phase-space diagram in Fig. 5. The idea is to separate the velocities in the narrower Gaussian (see Fig. 5 from those in the high and low velocity wings of the distribution. By tagging our sources depending on whether their $V_{LOS}$ belongs to the narrower or wider Gaussian, we assign PNs to either the M87 halo or the ICL.

The velocity dispersion profile of the M87 halo: a robust sigma estimate-- We binned the PN velocity sample in elliptical annuli and, for each bin, we determined the standard deviation of the LOSVD for the PNs in this bin. A $2\sigma$ limit with respect the systemic velocity of M87, $V_{sys} = 1275 \, \text{kms}^{-1}$, is ap-
plied\(^{5}\) and the dispersion is calculated for the PNs within this limit. This dispersion is then scaled by a numerical factor determined from Monte Carlo simulation to correct to the dispersion of a complete Gaussian distribution (see McNeil et al. (2010)). Since we expect the initial estimate for the 2\(\sigma\) to be influenced by the ICPNs, we repeat this process until the dispersion value stabilises.

**Separating M87 halo and ICL PNs: sigma clipping –** We now identify the two components using a sigma clipping algorithm. We begin by classifying as ICPNs all velocity outliers that deviate from the M87 systemic velocity \(V_{sys} = 1275 \text{ km s}^{-1}\) by more than 2\(\sigma\). To obtain the required \(\sigma\) value at the radius of each PN, we took the robust estimates of the velocity dispersions in the elliptical radial bins, and fitted these data with a fourth-order polynomial. This takes into account radial gradients and at the same time reduces the effects of binnning and scatter in the dispersion profile on the separation of the components. Using the 2\(\sigma\) threshold from the interpolated polynomial, we identify 243 objects as M87 halo PNs.

Two further steps are still needed. The 2\(\sigma\) criterion accounts for \(\sim 95.5\%\) of a complete Gaussian distribution; hence we expect it to have missed 11 halo PN candidates. To include these, we considered all outliers within 3\(\sigma\) from the M87 \(V_{sys}\) and from those selected the 11 with the smallest \(|V_{LOS} - V_{sys}|/\sigma\) ratios. This leads to a final sample of 254 M87 halo PNs and 45 ICPNs. In this final sample, 11 halo PNs and 1 ICPN came from Doherty et al. (2009).

Secondly, as can be seen in Fig. 5 the ICL and halo velocity distributions overlap, and as result, when using the sigma-clipping algorithm, the ICPNs at low velocities relative to \(V_{sys} \sim 1275 \text{ km s}^{-1}\) will be considered as part of the halo component. To statistically quantify this effect, we compared the halo and IC velocity distributions in each radial bin (or slice in the phase-space). We approximated the halo distribution in the bin as a Gaussian centred on the systemic velocity of M87 with a dispersion equal to the average value for that bin, and for the ICL component we used the same Gaussian in all radial bins using the parameters as in Fig. 5. We then calculated the fraction of ICPNs that lie inside the halo distribution as the area of overlap between the two curves. With this analysis we obtain a statistical estimate of the number of ICPNs contained in the halo velocity distribution in each bin. For all bins combined we find that \(\sim 10\%\) of the halo sample, i.e., \(\sim 30\) PNs, are to be associated with the IC component.

In Fig. 6 we show the projected phase-space distribution of our PNs as in Fig. 4 with velocities colour-coded to show the membership to the halo (red) and ICL (blue). Since we only know statistically but not individually which PNs in the halo velocity range are ICPNs, these are also shown with the red halo colour.

In Fig. 6 we also show 1/2/2.5\(\sigma\) limit contours for the halo PNs, obtained by fitting a polynomial to the \(\sigma\) values from the robust estimation. The velocity dispersion profile increases from 250” to 1200” and then decreases, showing a colder component at radii \(R > 1200”\). A more detailed analysis of the dispersion profile will be carried in a separate paper (Longobardi et al., in preparation).

Finally, we comment that a few ICPNs are characterised by extraordinary blue shifts relative to M87 (\(V_{LOS} < -1000 \text{ km s}^{-1}\)). Such (hyper-) velocities of \(|V_{LOS} - V_{sys}| > 2300 \text{ km s}^{-1}\) relative to M87, corresponding to several \(\sigma_{V_{sys}}\), could be due to infall from the outskirts of the Virgo cluster, perhaps associated with the infall of the M86 group, or they could be tracers of three-body interactions, as previously hypothesised for the extreme globular cluster observed at a projected distance of \(\sim 80 \text{ kpc}\) from M87 with a velocity of \(V_{LOS} < -1025 \text{ km s}^{-1}\) (Caldwell et al. 2014).

Fig. 6. Projected phase-space diagram, \(V_{LOS}\) vs. major axis distance from the centre of M87, for all spectroscopically confirmed PNs from this work and Doherty et al. (2009). The PNs are classified as M87 halo PNs (red asterisks) and ICPNs (blue asterisks), respectively; see text. Black squares identify spectroscopically confirmed PNs from Doherty et al. (2009). The smoothed 1.2 and 2.5 \(\sigma\) thresholds are represented by the dashed, dotted and dot-dashed lines, respectively. Dashed horizontal line shows the M87 systemic velocity \(V_{sys} = 1275 \text{ km s}^{-1}\) as computed in Section 3.2. At \(V_{LOS} = -220 \text{ km s}^{-1}\) we plot the M86 systemic velocity (long dashed line).

### 3.3. Spectroscopic validation of the PN subsample

In Section 2.4 we classified 287 spectra as PNs on the basis of the line profile of the strongest emission. We will now strengthen this earlier classification based on the detection of the weaker 4959Å line of the [OIII] doublet in the PN spectra.

In 114 out of the 287 spectra, nearly 40% of the sample, we are able to detect the Doppler-shifted [OIII]4959Å line with the expected 1:3 ratio of the [OIII]4959/5007Å line fluxes. In the rest of the sample, the single spectra do not have the required S/N to allow the detection of the weaker 4959Å line. However, following Arnaboldi et al. (2003) we can achieve the required S/N by stacking these spectra, after rebinning their [OIII]4500Å emission to a common reference wavelength. By measuring the [OIII]4500/4959Å line ratio of the coadded spectrum we can statistically constrain the fraction of misclassified PN spectra: if the stacked spectrum contains misclassified PN candidates, the ratio [OIII]4500/4959Å will be larger than 3.

The 287 spectra are further grouped in three classes: M87 halo spectra, ICL high-\(V_{LOS}\) and IC low-\(V_{LOS}\) spectra. One source in the IC low-velocity class is not included, because its Doppler shifted [OIII]4959Å emission would fall at a shorter wavelength than the blue edge of the FLAMES HR08 filter (see Fig. 4). The spectra are shifted and rebinned so that the main

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\(^{5}\) The systemic velocity of M87 is taken as the median value of the entire sample of velocities within two sigma of the original median.
To construct a PN density profile we require a spatially complete completeness function, $C_{\text{phot}}$, hence we must correct the detected PN number using a completeness correction, $C_{\text{phot}}(x_{\text{PN}}, y_{\text{PN}})$, which accounts for the selection function of the sampled PNs over the surveyed area. Our PN sample is affected by four different kinds of incompleteness, that are related to the photometric identification of the candidates and the selection effects in the spectroscopic observations. These are:

**Photometric incompleteness**, characterised by:

i) $C_{\text{phot,sp}}(R)$ - Spatial incompleteness due to the high galaxy background and foreground stars that affect the detection of PN candidates in the images. This was estimated in Longobardi et al. (2013) by adding a simulated PN population to the scientific images and determining the fraction of simulated objects recovered by SExtractor in the different elliptical annuli shown in Fig. 8.

ii) $C_{\text{phot,col}}$ - Colour incompleteness due to the colour criteria adopted for the automatic selection of PN candidates. This colour incompleteness was computed by analysing the properties of the recovered simulated PN population in the colour-magnitude diagram (see Longobardi et al. 2013 for more detail). This incompleteness affects only the M87SUB FCEN and M87SUB FEDGE fields, where
Table 3. Fluxes, FWHMs and line ratios of the [OIII]4959/5007 Å doublet for halo, high VLOS and low VLOS IC PNs sub samples.

| IDs PN subsample | Line Flux_{4959} ( Counts ) | Line Flux_{5007} ( Counts ) | FWHM_{4959} ( Å ) | FWHM_{5007} ( Å ) | Line Ratio |
|------------------|----------------------------|----------------------------|------------------|------------------|-----------|
| halo             | 1528.0±0.2                 | 506.9±0.3                  | 0.60±0.08        | 0.76±0.1        | 3.01±0.02 |
| IC high VLOS     | 64.1±3.0                   | 20.6±1.2                   | 0.60±0.07        | 0.6±0.09        | 3.1±0.2   |
| IC low VLOS      | 106.3±3.0                  | 33.9±3.7                   | 0.60±0.08        | 1.4±0.1         | 3.1±0.3   |

Notes. Columns (1) and (2): fluxes for the [OIII] main and second emission line, respectively. Errors are calculated following Eq.1.

The total completeness function, $C_{\text{tot}}(x_{PN}, y_{PN})$, is the product of the photometric and spectroscopic incompleteness:

$$C_{\text{tot}}(x_{PN}, y_{PN}) = C_{\text{phot}, sp}(R) \times C_{\text{phot}, col} \times C_{\text{spec}, sp}(x_{PN}, y_{PN}),$$

with

$$C_{\text{phot}, col} = \begin{cases} C_{\text{phot}, col} & \text{for M87SUB FCEN, M87SUB FEDGE, elsewhere.} \\ 1 & \end{cases}$$

The completeness-corrected number of PNs in each bin of major axis distance $R$ is then

$$N_c(R) = \Sigma_{i=1}^{N_{\text{tot}}(R)} k_i(R),$$

where the sum extends over all PNs of the halo or ICL component in the bin, respectively, and $k_i(R) = 1/C_{\text{tot}}(x_{PN}, y_{PN})$ is the completeness-corrected specific weight of each observed PN at its position.

4.2. Density profiles of halo and ICL component

In order to construct the PN number density profile and compare it to the galaxy’s surface brightness profile, we bin our PN sample in elliptical annuli. The radial range of the elliptical annuli is chosen such that they include the major axis distance of the innermost and outermost PN candidates in the photometric sample of Longobardi et al (2013). Their P.A.s and ellipticities are taken from Kormendy et al (2009). The sizes of the annuli are determined separately for the halo and ICL components, such that for each component all bins contain at least 10 spectroscopically confirmed PNs. In each annulus and for each component, we compute the completeness-corrected PN number density as the ratio of the completeness-corrected number of PN (Eq.3) and the area of the portion of the annulus intersecting our FOV:

$$\sigma_{PN}(R) = \frac{N_c(R)}{A(R)}.$$  

Here we consider all the spectroscopically confirmed PNs whose magnitudes are within 2.5 mag below the bright cut-off.

overlapping FLAMES plate configurations, whose [OIII] emission was detected in spectra taken with both or only one of the two plate configurations (see Sect. 2.3).

Our spectra are sufficiently deep that we found no dependence of the spectroscopic incompleteness on the magnitude of the PN candidates.

The photometric candidates were selected through colour criteria (see Sect. 2). $C_{\text{phot}, col}$ is magnitude-dependent but for constructing the density profile we use an average value, computed for the whole sample down to 2.5 magnitudes below the bright cutoff, which amounts to 0.7.

Spectroscopic incompleteness, characterised by:

iii) $C_{\text{spec}, sp}(R)$ - Spatial incompleteness due to the limited number of fibres (up to 132) that can be allocated for each FLAMES field. This was estimated by computing the ratio between the number of allocated fibres and the total number of photometric candidates in each elliptical annulus shown in Fig.8.

iv) $C_{\text{spec}, fb}(x_{PN}, y_{PN})$ - Incompleteness due to fiber-target misalignment. This incompleteness was estimated from the detection statistics of objects in common between

The green plus sign indicates the centre of M87. The ellipses (dotted lines) trace the M87 isophotes between photometric major axis radii $R = 2.8$ and $R = 40.7$, for position angle P.A. $=-25.6^\circ$, from Kormendy et al. (2009). The solid squares depict the area covered by our narrow band imaging survey (Longobardi et al 2013). North is up, East to the left.
The value \( \mu_0 \) is a constant to be added so that the PN number density profile matches the \( \mu_{K09} \) surface brightness profile. As described in Sect. 4.4, the kinematic decomposition of the halo and ICL components does not identify IC PNs in the velocity range of the halo, and their contribution must be evaluated statistically for each bin. Averaged over the bins, \( \sim 10\% \) of the halo PN sample is thus estimated to be associated with the ICL, in addition to the ICPNs identified from their large velocities. For each of the radial bins, we subtract the estimated contribution from the halo component and add it to the ICL component. In Fig. 9 the PN number densities for halo and ICL account for this effect. Furthermore, the profiles shown in Fig. 9 are computed using all PNs whose magnitudes are within 2.5 magnitude from the bright cutoff. However, the halo and ICL number density profiles do not change significantly when the fainter spectroscopically confirmed PN are also included.

We find that the \( \mu_{PN,halo} \) agrees well with the surface photometry: the halo PN logarithmic number density profile follows the surface brightness profile. The ICL PN logarithmic number density has a flatter profile, also concentrated towards M87; it decreases towards larger radii as \( I_{ICL} \propto R^\gamma \) with \( \gamma \) in the range \([-0.34; -0.04]\), depending on the choice of binning. These results are consistent with predictions from hydro-dynamical simulations, where the radial density profile of the bound component, i.e. the halo, is observed to be much steeper than that of the diffuse IC component (Murante et al. 2004; Dolag et al. 2010).

Finally, we compute density profiles for the PNs for the NW and SE sides of M87 independently, to search for an NW-SE-asymmetry in the spatial distribution. For this test we now use the total sample of PNs including very faint PNs, in order to increase the statistics in each half annulus (this also changes the binning). Fig. 10 shows the four number density profiles; each pair of profiles is consistent with each other and the halo profiles are consistent with the galaxy surface brightness profile. Thus within the statistical uncertainties, the stellar halo density is NW-SE symmetric and the PN number density follows the light on both sides. The ICL PN density profile pair are again flatter than the halo, and consistent with the previous surface brightness profile \( I_{ICL} \propto R^\gamma \) with \( \gamma \approx [-0.34; -0.04] \); no asymmetry is evident. In Fig. 10 we also plot the differences between the NW and SE logarithmic densities as function of radius (bottom panel). For both the halo (red filled circles) and the ICL (blue filled circles), these differences are consistent with zero within the uncertainties (see further discussion in Sect. 5).

5. Halo and IC populations

5.1. The \( \alpha \) parameter

The total number of PNs, \( N_{PN} \), is proportional to the total bolometric luminosity of the parent stellar population through the luminosity-specific PN density, or \( \alpha \)-parameter for short, such that \( N_{PN} = \alpha L_{bol} \). The \( \alpha \)-parameter determined for this PN sample will be an estimate of the total number of PNs within...
2.5 magnitudes of the bright cutoff of the PN luminosity function (PNLF), because of the magnitude limit of this survey at $m_{5007} = 28.8$ and the bright cutoff at $m_{5007} = 26.3$ (see Section 5.2). The measured value of $\alpha$ will be derived from the scaling factor required to match the PN number density profile to the surface brightness profile in the V band and then taking into account the appropriate bolometric correction.

In Fig. [2] we showed the total PN number density profile for the spectroscopically confirmed PNs sample within 2.5 magnitudes from the bright cutoff, together with the halo and IC PN number densities separately. The total PN profile flattens at large radii compared to the surface brightness profile, suggesting different luminosity specific PN numbers for the two populations, halo and ICL. Following Longobardi et al. (2013) we can model it by two components such that

$$\tilde{\sigma}(R) = \sigma_{\text{halo}} I(R)_{\text{halo, bol}} + \sigma_{\text{ICL}} I(R)_{\text{ICL, bol}}$$ (6)

$$\sigma_{\text{halo}} = \alpha_{\text{halo}} I(R)_{\text{K09, bol}} + \frac{\sigma_{\text{ICL}}}{\sigma_{\text{halo}}} I(R)_{\text{ICL, bol}}$$ (7)

where $\tilde{\sigma}(R)$ represents the predicted total PN surface density in units of $N_{\text{PN}}$ pc$^{-2}$, $I(R)_{\text{halo}}$ and $I(R)_{\text{ICL}}$, with and without subscript bol, are the bolometric and V-band luminosities for the halo and the ICL components respectively, in $L_{\text{bol}}$ pc$^{-2}$; $I_{K09}$ is the M87 luminosity profile in the V band in $L_{\text{bol}}$ pc$^{-2}$, from Kormendy et al. (2009). $I(R)_{\text{halo}}$ and $I(R)_{\text{ICL}}$, respectively, are given by the Sersic fit to the observed M87 surface brightness data ($n = 11.8$, Kormendy et al. 2009), and by the scaled power-law fit to the IC luminosity profile from Sect. 3. They satisfy the relation $I_{K09} = I(R)_{\text{halo}} + I(R)_{\text{ICL}}$, which determines the normalisation of the ICL surface brightness profile. In the surveyed area over a radial range $7 \text{kpc} < R < 150 \text{kpc}$ these profiles give total V-band luminosities $L_{\text{halo}} = 4.41 \times 10^{10} L_{\odot}$ and $L_{\text{ICL}} = 0.53 \times 10^{10} L_{\odot}$, and after the bolometric correction (see below), total bolometric luminosities for the sampled halo and ICL of $L_{\text{halo, bol}} = 9.05 \times 10^{10} L_{\odot, \text{bol}}$ and $L_{\text{ICL, bol}} = 1.1 \times 10^{10} L_{\odot, \text{bol}}$.

The surface luminosity $\tilde{\sigma}(R)$ can be related to the bolometric surface brightness through the formula:

$$\tilde{\mu}(R) = -2.5 \log_{10} \tilde{\sigma}(R) + \mu_0,$$ (8)

where $\mu_0$ is given by the analytical calculation:

$$\mu_0 = 2.5 \log_{10} \sigma_{\text{halo}} + K + (BC_0 - BC_V).$$ (9)

In Eq. 8, $\sigma_{\text{halo}}$ is the specific PN number for the halo, $K = 26.4$ mag arcsec$^{-2}$ is the V-band conversion factor from mag arcsec$^{-2}$ to physical units $L_{\text{bol}}$ pc$^{-2}$, $BC_0 = -0.07$ is the V-band bolometric correction for the Sun, and $BC_V = -0.85$ is the bolometric correction for the V-band (Buzzoni et al. 2000). According to their simple stellar population (SSP) models for irregular, late and early-type galaxies this value can be used with 10% accuracy.

From the offset value $\mu_0 = 16.56 \pm 0.08$ mag arcsec$^{-2}$ determined from the density profile in Fig. 9 we compute $\sigma_{\text{halo}} = (1.06 \pm 0.12) \times 10^{-8}$ PN L$^{-1}_{\odot, \text{bol}}$. From Eqs. 6 and 7 the derived value for $\sigma_{\text{ICL}}$ is then $(2.72 \pm 0.72) \times 10^{-8}$ PN L$^{-1}_{\odot, \text{bol}}$, using the steeper slope -0.34 for the ICL, but the difference for the shallower slope is only 5%.

These luminosity specific PN $\alpha$ values are consistent with those obtained by Longobardi et al. (2013) from the photometric sample, and are now independently validated on the basis of the spectroscopically confirmed PNs. The consistency of the spectroscopic and photometric values confirms the accuracy of the estimated contamination by Ly$\alpha$ background objects in the photometric sample.

We can now compare the $\alpha_{\text{halo}}$ and $\alpha_{\text{ICL}}$ values determined in this work with the known $\alpha$ values for PN populations in nearby galaxies. Galaxies with integrated $(B-V)$ colours smaller than 0.8 are empirically characterised by similar values of the $\alpha$ parameter, $\alpha \sim 3 \times 10^{-8} N_{\text{PN}} L_{-1, \text{bol}}^{-1}$, with a scatter of a factor of two. For redder galaxies with $(B-V) > 0.8$, the spread of the measured values increases, spanning a range from $\alpha \sim 10^{-8} N_{\text{PN}} L_{-1, \text{bol}}$ to $\sim 6 \times 10^{-8} N_{\text{PN}} L_{-1, \text{bol}}$. For these redder galaxies, there is an empirical inverse correlation of the $\alpha$ values with the FUV - V integrated colours of the parent stellar population, such that smaller $\alpha$ values are associated with galaxies with larger FUV-V excess. Hence, observationally, the $\alpha$ values are linked to the metallicity and star formation history of the parent stellar population of the PNs (Peimbert 1998, Hui et al. 1993, Buzzoni et al. 2006, Longobardi et al. 2013).

Our result that the ICL component contributes more PNs per unit bolometric luminosity than the M87 halo light therefore signals a change in the stellar populations from halo to ICL, consistent with the existence of a gradient towards bluer colours of the M87 stellar light at large radii (Liu et al. 2005, Rudick et al. 2010). We interpret this gradient as the result of the gradual transition from the redder halo light to the bluer ICL with decreasing surface brightness.

5.2. PNLFs for halo and ICL

The PNLF of [OIII]$\lambda$5007Å emission line fluxes is often empirically described via the truncated exponential formula (Ciardullo et al. 1989):

$$N(M) = c_1 e^{c_2 M} \left[ 1 - e^{(M-M_*)} \right]$$ (10)

where $c_1$ is a normalisation constant, $c_2 = 0.307$ and $M^*$ (5007) = -4.51 mag is the absolute magnitude of the PNLF bright cutoff. This analytical formula is designed (i) to reproduce the high mass cutoff observed for the PN central stars in nearby galaxies, and ii) to model PNs as uniformly expanding homogeneous spheres ionised by a non-evolving central star (Henize & Westerlund 1963).

Our deep and extended imaging survey of PNs in the outer regions of M87 showed that the PNLF for this galaxy has significant deviations from Eq. 10 in the faint magnitude bins (Longobardi et al. 2013): its slope ~1-2 magnitudes below the bright cutoff is steeper than expected from the Ciardullo et al. (1989) formula. This is also true for the spectroscopically confirmed PN sample, as we show in Fig. 9 where we compare the total PNLF with the analytical formula for a distance modulus of 30.8.

Our data allow us to analyse separately and compare the PNLFs of the two spectroscopically confirmed PN samples for the M87 halo and ICL, from the bright cutoff down to 2.5 mag below. In the upper panel of Fig. 12 we show the PNLF for the spectroscopically confirmed sample of halo PNs, corrected for detection incompleteness as a function of magnitude. The data points trace a smooth function, and the fit of the generalised analytical formula (Eq. 10) to the observed PNLF within the 2.5 mag limit results in $c_2 = 0.72$ and a bright cutoff at $m_{5007} = 26.3$ (overplotted on the data). With $M^* = -4.51$ this corresponds to a distance modulus ($m-M) = 30.8$.

In the central panel of Fig. 12 we present the IC PNLF (full blue circles), corrected for incompleteness. As for the M87 halo PNLF, the IC PNLF is consistent with the same distance modulus as for M87. However, it shows an overall shallower gradient.
than the M87 halo PNLF: the best fit of Eq. (10) to the empirical PNLF returns $c_2 = 0.66$.

In addition to the shallower gradient at fainter magnitudes, the IC PNLF shows a clear dip at 1.5 mag fainter than $m_{\text{cut}}^\text{IC}$. This feature is statistically significant: the difference between the number of PNs in these bins with respect to the magnitude bins before and after the dip is $> 3 \sigma$ on both sides, where $\sigma_{\text{dip}}$ is the uncertainty from Poisson statistics in the magnitude bins where the dip occurs.

Dips in the PNLF are observed for PN populations detected in star forming galaxies (irregular/disks), and are absent in the PNLFs of bulges or early-type galaxies. The magnitude below the bright cutoff at which the dip occurs varies between different PN populations, from $\sim 2$ to $\sim 4$ mag below $M^{*}$ (Jacoby & De Marco 2002; Ciardullo et al. 2004; Hernández-Martínez & Peña 2009; Reid & Parker 2010). We discuss this issue further in Section 6.1. In the bottom panel of Fig. 12 we compare the PNLFs for the Virgo IC PNs and for the spectroscopically confirmed sample of PNs for the outer disk of M33 (Ciardullo et al. 2004). Both LFs are corrected for foreground Galactic extinction, adopting reddening values of $E(B-V)_{\text{ICL}} = 0.02$ (Ciardullo et al. 1998) and $E(B-V)_{\text{M33}} = 0.04$ (Ciardullo et al. 2004) for the Virgo ICL and M33, respectively.

Absolute magnitudes are determined using a distance modulus of 30.8 for the ICL and 24.86 for M33 (Ciardullo et al. 2004). Both PNLFs show dips relative to the smooth luminosity function: the ICL at 1.5 mag fainter than $M^{*}$, the outer disk of M33 at 2.5 mag fainter than the bright cutoff.

Finally, we recall that about 10% of the PNs contained in the M87 halo PNLF shown in Fig. 12 are ICPNs whose velocities fall in the same velocity range of the M87 halo PNs, and can therefore not be individually identified. The hint of a slight dip in the halo PNLF at ~ 1 mag below the bright cutoff may be due to these ICPNs.

To summarise, the observed properties of the M87 halo and Virgo IC PN populations, i.e., their $\alpha$-parameters and PNLFs, show significant differences. Because these quantities depend on the physical properties of the parent stellar populations, these differences imply that the M87 halo and ICL consist of different populations of stars. To understand this better, more work is clearly required for a better theoretical understanding of how metallicity, age and different star formation histories affect the post-AGB phases of stellar evolution and the resulting PN populations.

6. Discussion

6.1. The distinct halo and ICL populations around M87

In Sect. 5 we presented the projected phase-space distribution of the spectroscopically confirmed PNs in our M87 fields (Fig. 6). With a robust procedure we showed that the PN velocity distribution splits into two kinematically very different components, the M87 halo (with mean velocity $V_{\text{LOS}} = 1275$ km s$^{-1}$ and velocity dispersion $\sigma_V \approx 300$ km s$^{-1}$) and the ICL (with $V_{\text{LOS}} \approx 1000$ km s$^{-1}$ and $\sigma_V \approx 900$ km s$^{-1}$). In Sect. 5 we furthermore found that the halo and ICL components were characterized by specific PN numbers ($\alpha$ parameters) that differed by a factor of three, and by different shapes of their PNLFs.

These results demonstrate the coexistence of two distinct PN progenitor stellar populations in this region of the Virgo cluster core: the M87 halo and the ICL. These two populations have very different surface density distributions, with the M87 halo described by an $n = 11.8$ Sersic law, while the ICL follows a
shallow power-law \( \propto R^\alpha \) with \( \gamma \) in the range \([-0.34, -0.04]\). We also have external information on the metallicities and ages of both components. At \( R \sim 35\text{kpc} \), the mean metallicity of the M87 halo obtained with population synthesis models from multi-colour photometry is \( \sim 0.7 \) solar, with a shallow outward gradient, and the mean age is \( \sim 10\text{Gyr} \) [Liu et al. 2005; Montes et al. 2014]. On the other hand, the metallicity and age distributions of ICL red giants in a field at \( R \sim 190\text{kpc} \) from HST ACS star photometry are dominated by metal-poor \([\text{M/H}] \leq -1\), \( \gtrsim 10\text{Gyr} \) old stars [Williams et al. 2007]. Because of the large velocities and shallow surface density profile of the IC stars, these IC population parameters are likely to be similar in the radial range probed by our observations, \( R \sim 50 - 140 \) kpc, whereas the M87 halo stars might reach \( \sim 0.5 \) solar in the outer regions if the outward gradient continues as inferred by [Liu et al. 2005].

Currently there is no good theoretical understanding of how the properties of a PN population are related to the metallicity and age of a stellar population. Observationally, star forming and bulge populations have \( \alpha \) numbers such as we find for the ICL, while only the most massive early-type galaxies have \( \alpha \) numbers as low as we find for the M87 halo (Buzzoni et al. 2006; Cortesi et al. 2013). The primary driver is believed to be increased mass loss at high metallicities. PNLFs are empirically found to steepen from star forming to old metal-rich populations (Ciardullo et al. 2004; Longobardi et al. 2013). The PNLFs of Local Group star forming galaxies such as the SMC (Jacoby & De Marco 2002), LMC (Reid & Parker 2010), M33 (Ciardullo et al. 2004), and NGC 6822 (Hernández-Martínez & Peñal 2009) furthermore show a 'dip' 2-2.5 mag down from the PNLF cutoff for the LMC, M33, and NGC 6822, and 4 mag down from the cutoff for the SMC. A tentative model for this feature is the superposition of a faint PN population with a brighter population of more massive cores from a younger stellar population (Rodríguez-González et al. 2014). We can speculate that as the brighter population fades in older and/or more metal-rich populations, the dip might move towards brighter magnitudes. This could explain why in the Virgo ICL population we find the dip 1.5 mag down from the cutoff. No other PN population with this PNLF is known; however, PNLFs as deep as for M87 have only been obtained in the Local Group so far. Clearly, more observational and theoretical work on the nature and location of the dip in the PNLF is needed.

### 6.2. The ICL in Virgo: nature and number of its progenitor galaxies

The combined properties of the Virgo ICPN population - the fairly small inferred bolometric luminosity, the relatively large \( \alpha \) parameter, and the dip in the PNLF - as well as the low mean metallicity from [Williams et al. 2007], appear to be most readily explained if this population derives from a faded population of low-luminosity, low-metallicity, star forming or irregular galaxies, such as M33 or the LMC, very different from M87 itself.

In Section 5.1 we determined the total V-band and bolometric luminosities of the ICL component sampled by our survey fields: \( L_{\text{ICL}} = 0.53 \times 10^{10} L_\odot \), and \( L_{\text{ICL,bol}} = 1.1 \times 10^{10} L_\odot \). Using the total V-band luminosities for M33 and the LMC listed in NED, \( L_{\text{M33}} = 3.65 \times 10^{9} L_\odot \), and \( L_{\text{LMC}} = 1.26 \times 10^{9} L_\odot \), we find that the IC stars sampled in our survey fields corresponds to \( \sim 1.5 \) M33-like galaxies or \( \sim 4 \) LMC-like galaxies.

8 The total luminosity at all radii corresponding to the detected IC stars will be much larger; their large measured velocity dispersion implies that the orbits of these IC stars will reach to much larger radii in the cluster. We note here that the M87 PN sample cannot be contaminated by Milky Way halo PN, as these would have \([\text{OIII}]\lambda 5007\text{Å} \) fluxes about 12 mag brighter than M87 PN.

We can now also check whether the Virgo ICL associated with the ICPN population could be related with the blue GC population that is found around M87, with a shallower and more extended surface density profile than the red GCs which trace the stellar halo light (Côté et al. 2001; Tamura et al. 2006; Strader et al. 2011; Forte et al. 2012; Durrell et al. 2014). To do this, we need to estimate the total number of GCs associated to M33 and LMC-like systems. [Harris et al. 2013] studied GC populations in a large sample of galaxies and analysed the correlation of the total number of GCs, \( N_{\text{GC}} \), with global galaxy properties and type. They find that \( N_{\text{GC}} \) increases roughly in direct proportion to host galaxy luminosity, with a scatter of a factor of \( \sim 2.5 \). For an LMC-like system with luminosity \( L_{\text{LMC}} = 1.3 \times 10^{9} L_\odot \), the expected mean number of GCs is \( N_{\text{GC}} \sim 20 \), while for an M33-like galaxy with \( L_{\text{M33}} = 3.7 \times 10^{9} L_\odot \) the expected mean number of GCs is \( N_{\text{GC}} \sim 60 \). This leads to an estimated number of blue GCs associated to the sampled ICL of \( N_{\text{GC,ICL}} \sim 80 - 90 \), with a scatter of a factor \( \sim 2.5 \). If a fraction of the ICL is due to the accretion of even lower luminosity galaxies, the estimated number of GCs would increase [Harris et al. 2013; Coccato et al. 2013].

The recent survey of the GC population in the Virgo cluster around M87 by Durrell et al. 2014 showed the presence of an IC GC population, mostly associated with blue GCs (see further discussion in Section 6.3). This intracluster component has a density equal to \( \Sigma_{GC,ICL} = 0.2 \times 10^{13} \text{pc}^{-2} \text{arcmin}^{-2} \). In our surveyed region this would lead to a total number of 100-430 ICGCs. This is larger than but consistent within the uncertainties with the value estimated above, suggesting that a substantial fraction of the blue GC population around M87 could have been accreted with the galaxies which we now see in the ICL.

### 6.3. Is there an intracluster component of globular clusters around M87?

There has been some controversy in the recent literature about the existence of intracluster GCs in the halo of M87. The most extensive photometric study of the distribution of GCs in the Virgo cluster so far was carried out by Durrell et al. 2014 as part of the NGVS. They studied density maps of the GC population, selected using colour criteria, and statistically accounted for the contamination to the GC sample by subtracting a modelled map for the expected background, from both Milky Way stars and background galaxies8. The blue GCs in their map have a shallower and more extended profile than the red GCs. Durrell et al. 2014 also found that the total GC (blue plus red) density profile is in good agreement with the number density profile of photometrically selected PNs from Longobardi et al. 2013, including a change of slope and a flatter profile at large radii. They suggested that their blue GCs at distances \( > 215 \text{kpc} \) are part of the intracluster component of Virgo. Durrell et al. 2014 also found 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). In Sect. 4 we studied the distribution of M87 halo and IC PNs separately for the NW and SE. We find no clear evidence of asymmetry in either the halo and ICL within major axis distance \( \sim 20' \) (Fig. 10). Inside this radius, both PN populations are more or less symmetrically distributed. This is consistent with the suggestion of Durrell et al. 2014 that the GCs are accreted from external sources, and that the ICL is not a surviving remnant of an early galaxy.
and GC number density profiles are consistent with a symmetric halo and ICL distribution. For the halo component this result is significant, given the number of tracers and radial extent, and indicates that if the halo was the subject to accretion events these were not recent. For the ICL, we may expect asymmetries, given the longer time-scales involved in IC accretion events, but we may not have a large enough sample of ICPNs to see them. Strader et al. (2011) carried out a spectroscopic study of the GCs around M87, using colour criteria to select their candidates. In the same colour and magnitude range populated by globular clusters, \(0.55 \leq (g' - i') \leq 1.15\) and \(20 \leq g' \leq 24\), there is however a large contribution from foreground Milky Way halo stars. To mitigate this contamination, Strader et al. (2011) imposed an additional velocity cut, such that their ‘true’ GC candidates are defined as objects with \(V_{\text{LOS}} > 350\) kms\(^{-1}\). Based on the remaining sample, Strader et al. (2011) reported that the number density profile of the spectroscopically confirmed GCs showed no evidence for a transition between a halo and ICL component, either as a sharp truncation of the halo, or a flattening of the GC number density profile at large radii. From the sample kinematics, they observed that their GCs around M87 have velocity dispersion in the range \(300 \leq \sigma \leq 500\) kms\(^{-1}\) out to 190 kpc, with \(\sim 500\) kms\(^{-1}\) for the GC population at 190 kpc significantly smaller than the velocity dispersion of Virgo cluster galaxies (Rines & Geller 2008). However, from the PN phase-space distribution \(V_{\text{LOS}} R_{\text{PN}}\) in Fig. we see that a large fraction of IC stars near M87 have velocities \(V_{\text{LOS}} < 350\) kms\(^{-1}\). This suggests that the lack of evidence for the ICL component reported by Strader et al. (2011) could be caused by the velocity threshold \(V_{\text{min}} = 350\) kms\(^{-1}\) imposed on the GC sample, which is needed to prevent the contamination from Milky Way halo stars, but may also remove many of the ICL GCs from their analysis.

### 6.4. Relation between BCG and ICL

When studying central galaxies in clusters, one of the main question is to establish where the ICL begins and where the associated BCG ends, or whether any distinction is to be made at all. For M87, the differences in the density profiles and velocity distributions of the halo and IC PN populations, as well as in their \(\alpha\)-parameters and PNLs, are sufficient to argue that the two components must be considered as separate stellar populations with different metallicities and star formation histories, and not as a continuum. As discussed above, published stellar population data suggest that the halo stars are older and more metal-rich than the ICL (see Sects. [5][6.1] for more details).

In more distant BCGs where a kinematic decomposition between BCG halo and ICL is not available, the presence of an additional dynamical component in BCGs is usually inferred from a change of slope at large radii in the SB profile (Zibetti et al. 2005; Gonzalez et al. 2007; D’Souza et al. 2014). Photometric properties or colours are obtained by treating the two components as a continuum, because no differentiation between the underlying stellar populations is normally possible.

Using a particle tagging method to analyse galaxy clusters in \(\Lambda\)CDM simulations, Cooper et al. (2014) consider the BCG and ICL as a single entity consisting of all stars which are not bound to any cluster subhalos. They then split the BCG stars into accreted stars and in situ stars, and find that the large majority of BCG stars are accreted stars. They find double-Sérsic surface density profiles in their simulated BCGs, where the inner component \((R < 200kpc)\) is dominated by ‘relaxed’ accreted components, and the outer component by ‘unrelaxed’ accreted components. Cooper et al. (2014) argue that the accreted/in situ separation is physically meaningful and that the ICL should be naturally considered as a continuation of the BCG to low surface brightness, because both components are formed by similar mechanisms.

In contrast, a dynamical approach based on the velocity distributions of diffuse light particles in hydrodynamical cosmological simulations (Dolag et al. 2010; Cui et al. 2014) is found to separate these stars into two components, one bound to the cluster potential, and the other bound to the BCG. The resulting BCG and diffuse ICL are formed on different time scales, and the simulated stars associated with the two components are different in terms of spatial distribution, ages and metallicities. Cui et al. (2014) showed that it is possible to dynamically differentiate between halo and ICL particles by using the particles’ binding energies. Stars with high binding energy that end up belonging to the BCG were subjected to relaxation and merging processes such that the gravitational potential changed so quickly that these stars lost memory of the kinematics of their progenitors (Murante et al. 2007; Dolag et al. 2010). On the other hand, stars with lower binding energy, that belong to the diffuse component, still reflect the dynamics of the satellite galaxies. Both Dolag et al. (2010) and Cui et al. (2014) observed also that the slope of the surface brightness profile associated with the two components change, with the halo profile being steeper than the ICL profile.

It is likely that the distinct BCG and ICL components found in the hydrodynamical simulations are related to the relaxed and unrelaxed accreted components in the particle tagging analysis, but the inclusion of baryonic processes in the former may accentuate the differences found between BCG and ICL. If we associate the BCG and ICL of Dolag et al. (2010); Cui et al. (2014) with the relaxed and unrelaxed accreted components of Cooper et al. (2014), the progenitors of the stars in the steeper Sérsic (relaxed) component would be accreted from more massive systems at higher redshifts, while the stars in the shallower and more extended ICL (unrelaxed) component would come from the accretion of less massive systems at lower redshifts. More massive progenitors dominate the diffuse light in simulated clusters close to the center (Murante et al. 2007; Puchwein et al. 2010) because they move inwards further by dynamical friction. They cause stronger relaxation of the gravitational potential, and if accreted early they have more time to relax.

To summarise, recent simulations show that a distinction can be made between stars that trace the cluster potential and stars bound to the BCG, based on the physical properties and binding energies of the accreted progenitors. From the study of the PN population around M87, we have shown the coexistence of two discrete components in the Virgo cluster core, tracing different stellar populations, in agreement with these predictions. While the PN population for the ICL component around M87 indicates low-mass dwarf and star-forming galaxy progenitors, the stellar halo has higher metallicity, \(\sim 0.7\) solar, indicating more massive progenitors. This bimodality in the progenitors may be the root of the bimodality in the kinematics and density profiles of the M87 halo and the ICL.

However, we note that such a bimodality need not occur in every cluster of galaxies. For example, it is plausible that, for a more continuous distribution of progenitor masses and a more uniform distribution of binding energies of the debris stars, the final BCG plus ICL system would show continuous radial gradients in kinematics and stellar population properties, rather than appear as the sum of several discrete components. It is possible
that NGC 6166 in the Abell 2199 cluster is closer to this situation: the velocity dispersion in the high-surface brightness halo of this BCG was recently measured to increase up to the cluster velocity dispersion of \( \sim 800 \text{ km s}^{-1} \) at 100'' from the galaxy center (Bender et al. 2014; see also Kelson et al. 2002).

7. Summary and Conclusions

We obtained spectra for 287 PNs in the outer regions of the nearby elliptical galaxy M87, of which 211 are located between distances 40 kpc to 150 kpc from the galaxy center. Spectra were acquired with the FLAMES spectrograph in the GIRAFFE+MEDUSA configuration, with spectral resolution of \( R = 22500 \). We observed 14 different FLAMES plate configurations, using candidates from the catalogue described in Longobardi et al. (2013). The spectroscopic survey aimed at measuring the LOS velocities of PNs in the transition region between the galaxy’s stellar halo and the ICL. PNs were identified through their narrow and symmetric, redshifted \([\text{OIII}]\lambda5007\) emission line, with no or negligible continuum, and verified with the second \([\text{OIII}]\lambda4959\) emission line. Spectra were measured for PNs in the magnitude range from \( m_{\text{PN}} = 26.3 \) down to 28.8. This is the largest spectroscopic sample of PNs at such galactic radii for a central galaxy, in the number of tracers and magnitude depth.

The area covered by the survey allowed us to trace the transition between the M87 halo and ICL in the Virgo cluster core. We separated halo and IC PNs by studying the projected phase-space distribution. We implemented a robust technique to measure the velocity dispersion of the M87 halo, separating its velocity distribution from the broader component, the ICL. We identified 243 PNs for the M87 halo and 44 ICPNs. We found that the logarithmic number density profile for the halo PNs follows the V-band SB profile from Kormendy et al. (2009), while the ICL number density profile decreases towards large radii as a power-law \( \rho_{\text{ICL}} \propto R^{-\gamma} \) with \( \gamma \) in the range \([-0.34, -0.04]\).

The total PN surface density profile is consistent with the surface brightness profile at large radii if the ICL stellar component contributes \( \sim 3 \) times more PNs per unit luminosity than the halo population, with the luminosity-specific PN numbers \( \alpha_{\text{halo}} = (1.06 \pm 0.12) \times 10^{-8} \text{ NPN}^{-1}_{\odot, \text{bol}} \) and \( \alpha_{\text{ICL}} = (2.72 \pm 0.63) \times 10^{-8} \text{ NPN}^{-1}_{\odot, \text{bol}} \) for the M87 halo and ICL PN population, respectively. This is consistent with the known existence of a gradient towards bluer colours at large radii, due to the increased contribution of ICL at large distances and its lower metallicity compared to the halo population.

The spectroscopically confirmed PNLFs for both the halo and IC PNs have a steeper slope towards faint magnitudes than is predicted by the analytical formula of Ciardullo et al. (1989), confirming the result from the photometric sample Longobardi et al. (2013). This steepening is consistent with an old stellar population dominated by PNs with low mass cores. The PNLF of the ICPN population has a slightly shallower gradient than the M87 halo PNLF, and in addition shows dip at about \( \sim 1 - 1.5 \) magnitudes from the bright cutoff. Such a dip is an evolutionary feature observed in star-forming systems, such as M33 and the Magellanic clouds, and may be related to rapidly evolving PNs with massive central cores. The presence of the dip in the IC PNLF but not in the M87 halo PNLF provides additional evidence for intrinsic differences between the halo and IC parent stellar populations.

Using PNs as tracers we showed in this work that the stellar halo of the BCG galaxy M87 is distinct from the surrounding ICL in its kinematics, density profile, and parent stellar population, consistent with the halo of M87 being redder and more metal-rich than the ICL. We note that the ICL in our surveyed fields corresponds to about four times the luminosity of the LMC, spread out over a region of \( \sim 100 \) kpc diameter. It is remarkable that population properties can be observed for such a diffuse component.

In the Virgo cluster, BCG halo and ICL cannot be considered as component with a gradual transition in their kinematics. This supports results from analysis of galaxy cluster simulations, which suggest that the ICL component in Virgo consists of unrelaxed accreted stars bound to the cluster potential, while the stellar halo of M87 appears to be described as a relaxed accreted component bound to the galaxy itself. Based on its PN population properties, we propose that the progenitors of the Virgo ICL were low-mass, star-forming galaxies, which may also have brought with them a significant fraction of the GC population seen in the outer regions of M87.

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