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Planetary nebulae as tracers of accreted stellar populations in massive galaxies in groups and clusters

Johanna Hartke[1,2,3]*

[1]Finnish Centre for Astronomy with ESO (FINCA), University of Turku, Turku, Finland, [2]Tuorla Observatory, Department of Physics and Astronomy, University of Turku, Turku, Finland, [3]Turku Collegium for Science, Medicine and Technology (TCSMT), University of Turku, Turku, Finland

EDITED BY
Marc Sarzi,
Armagh Observatory, United Kingdom

REVIEWED BY
Lucas Manuel Valenzuela,
Universitäts-Sternwarte, Germany

*CORRESPONDENCE
Johanna Hartke,
✉ johanna.hartke@utu.fi

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Planetary nebulae (PNe) are valuable spatial and kinematic tracers of nearby galaxies. In this mini-review, I focus on their role in tracing the halo and intra-cluster/intra-group light assembly in groups and clusters of galaxies within 100 Mpc and, in particular, the link between characteristic PN metrics such as the α-parameter and the PN luminosity function and changes from the underlying *in situ* to *ex-situ* stellar populations. These results from nearby groups and clusters are placed into context with integral-field spectroscopic surveys of galaxies, which allow the co-spatial measurement of PN and stellar population properties. I provide an outlook on upcoming instrumentation that will provide new opportunities for the study of extragalactic PN populations. I address the challenges of reconciling observations of extragalactic PN populations with predictions from stellar evolution models and how revised late-stellar-evolution models have alleviated some of the tensions between observations and theory.

KEYWORDS

Planetary nebulae: general, galaxies: clusters, galaxies: groups, galaxies, elliptical and lenticular, cD, galaxies: halos

1 Introduction

Planetary nebulae (PNe) occur in the very late evolutionary stages of low-mass (initial masses between one and 8 $M_\odot$) stars. The PN phase is considered part of the post-asymptotic giant branch (post-AGB) phase. The spectra of PNe are characterised by the absence of a stellar continuum and strong nebular emission lines. It is predicted that up to 15% of the radiation of their central stars is re-emitted in a single line: the [O III] λ5007A line (Dopita et al., 1992). This line can be used for the identification and radial velocity measurement of *individual* PNe in galaxies at distances as far as 100 Mpc (Gerhard et al., 2005), making them excellent tracers of the spatial distribution and kinematics of galaxies and their haloes.

Extragalactic PN populations are typically characterised with two metrics: the PN luminosity function (PNLF) and the luminosity-specific PN number, α-parameter for short. The PNLF describes the m_{5007} magnitude distribution, where m_{5007} is the magnitude corresponding to the flux of the [O III] λ5007A line (Jacoby, 1989). Empirically, the PNLF is near-universal in early- and late-type galaxies, described by the following relation (Ciardullo et al., 1989):

$$N_{\mathrm{PN}}\left(m_{5007}\right) \propto \left(1 - \mathrm{e}^{3\left(M^{*} - m_{5007} + \mu\right)}\right) \mathrm{e}^{c_2\left(m_{5007} - \mu\right)}, \tag{1}$$

where $M^\star$ denotes the absolute magnitude of the bright cut-off, μ the distance modulus, and c_2 the faint-end slope. To first order, the absolute bright cut-off magnitude has been found to be invariant at $M^\star = -4.5$ (Ciardullo, 2022), facilitating the use of the PNLF as a secondary distance indicator by determining the apparent bright cut-off magnitude $m^\star$ and thus the distance modulus μ. While well-established observationally, the invariant bright cut-off cannot be easily reconciled with predictions from stellar evolution models, in particular for early-type galaxies with old stellar populations that were predicted to have much fainter bright cut-off magnitudes than observed (e.g., Marigo et al., 2004; Ciardullo, 2022) until the advent of revised post-AGB stellar evolution models (Miller Bertolami, 2016; Gesicki et al., 2018). The second term of Equation 1 was originally introduced with the motivation of describing the fading brightness of a gas cloud around the PN central star (Henize and Westerlund, 1963), with the slope fixed to $c_2 = 0.307$ based on observations of M31 and other Local Group galaxies (Ciardullo et al., 1989).

By integrating the PNLF up to a limiting magnitude m_{lim}, one obtains the total number of PNe, N_{PN}, which can be related to the bolometric luminosity L_{bol} of the underlying stellar population via the α-parameter[1] (Jacoby, 1980):

$$\alpha = \frac{N_{\mathrm{PN}}}{L_{\mathrm{bol}}} = \mathcal{B}\tau_{\mathrm{PN}}, \tag{2}$$

where $\mathcal{B}$ is the specific evolutionary flux[2] and τ_{PN} the visibility lifetime of PNe. Accounting for incompleteness effects, and assuming that the bolometric luminosity L_{bol} of the host galaxy can be derived from its broadband photometry with a bolometric correction (Buzzoni et al., 2006), the α-parameter can be straightforwardly obtained from PN surveys. For a chemically homogeneous, coeval stellar population in the single stellar population (SSP) framework, the α-parameter can also be related to the visibility lifetime τ_{PN} (Buzzoni, 1989; Buzzoni et al., 2006). Assuming that the specific evolutionary flux $\mathcal{B}$ does not significantly vary between SSPs with different properties such as metallicity or initial mass function (Renzini and Buzzoni, 1986), the α-parameter can thus be interpreted as a direct proxy for the PN visibility lifetime.

Typical values of α are calculated within a limiting magnitude $m_{\mathrm{lim}} = m^\star + 2.5$ and are of the order of $\sim 10^{-8}$ to $10^{-9}\,L_{\odot,\mathrm{bol}}^{-1}$. If the PN survey is shallower, the α-parameter can be extrapolated:

$$\alpha_{2.5} = \rho_{m_{\mathrm{lim}}}\,\alpha_{m_{\mathrm{lim}}-m^\star}. \tag{3}$$

The extrapolation factor $\rho_{m_{\mathrm{lim}}}$ can be obtained via integration of the PNLF (Equation 1):

$$\rho_{m_{\mathrm{lim}}} = \frac{\int_{m^\star}^{m^\star+2.5} N(m_{5007})\,\mathrm{d}m_{5007}}{\int_{m^\star}^{m_{\mathrm{lim}}} N(m_{5007})\,\mathrm{d}m_{5007}}. \tag{4}$$

In this case, the α-parameter can only be used to provide an estimate of the PN visibility lifetime within the limiting magnitude of the survey.

In the past, the primary target of PN surveys for galaxy kinematics have been early-type galaxies (e.g.,Arnaboldi et al., 1994; Hui et al., 1995; Coccato et al., 2009; Cortesi et al., 2013; Pulsoni et al., 2018), for the simple reason that their identification is facilitated by the lack of other strong [O III] emitters (such as supernova remnants and H II regions) in old stellar populations compared to late-type galaxies with younger stellar populations. Historically, surveys for PNe in galaxies made use of the on-off band technique, where the on band image is taken with a narrow-band [O III] filter, and the off band through an adjacent broad-band filter, for example, the V- or g-bands (e.g., Ford et al., 1973; Ford and Jenner, 1975). The detected PNe candidates are then followed up with spectrographs with high multiplexing capabilities to measure their line-of-sight velocity and identify remaining PN mimics such as Lyman-α emitters at high redshift. Counter-dispersed imaging, a variant of slitless spectroscopy, was developed to remove the need for a two-step process, allowing the detection and velocity measurement in one observation with the custom-built Planetary Nebula Spectrograph (PN.S, Douglas and Taylor, 1999; Douglas et al., 2002). However, due to the lack of full spectral information, this technique was predominantly used in early-type galaxies to limit the contamination from other [O III] emitters until a Hα-arm was installed at the PN.S (Aniyan et al., 2018; 2021).

These classical methods excel at detecting PNe in large areas, spanning several hundreds of square-arcseconds, corresponding to multiple effective radii of galaxies in the local Universe, allowing to map the kinematic transition from *in situ* to *ex-situ* stellar haloes (e.g., Pulsoni et al., 2018) as well as from haloes to the surrounding intra-cluster and intra-group light (ICL and IGL, respectively) as recently reviewed by Arnaboldi and Gerhard 2022, and references therein. In this review, I want to address how these kinematic transitions coincide with observed changes in the PN population properties, how these PN population properties can be linked to the characteristics of the underlying stellar populations, and how both new observing techniques and numerical stellar evolution models are necessary to contextualise these results.

This review is organised as follows: in Section 2, I review recent observational results concerning the link between PN- and stellar populations based on PN-surveys carried out with classical methods and new insights from integral-field spectroscopic surveys, and provide an outlook on new facilities and opportunities. In Section 3, I address new developments in modelling PN populations in the context of updated post-AGB stellar evolution models and numerical models of galaxy evolution. I conclude this review in Section 4.

2 Characterisation of PN populations from observations

2.1 Classical PN surveys

Surveys for PNe with classical techniques, such as ‘on-off’ imaging and slitless spectroscopy, provided first constraints on the link between stellar-population properties and the α- and PNLF-parameters. Ciardullo et al. (2002) suggested an oxygen-abundance-dependent PNLF bright cut-off $M^\star$ based on a small sample of a dozen galaxies with known Cepheid distances. Buzzoni et al. (2006)

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[1] Not to be confused with the α-abundance of elements.

[2] The rate of stars that evolve to the post-main sequence stages, normalised per unit light of the stellar population (Renzini and Buzzoni, 1986).

investigated the variation of the α-parameter with the underlying stellar population in the context of simple stellar population models, and based on those predicted an increase of the α-parameter with galaxy colour, in agreement with the observations available at the time.

In the past two decades, PNe have increasingly been used as kinematic tracers in early-type galaxies as well as to trace the ICL and IGL. Here, I want to especially focus on the transition from "*in situ*" to accreted ("*ex-situ*") stellar populations, which is not only observationally signalled by radially varying light profiles and kinematics but also by changes in the PN population properties. In particular, several studies have found that the α-parameter increases significantly from the inner to the outer halos of the group- or cluster-dominating galaxy to the surrounding IGL or ICL (e.g., Doherty et al., 2009; Longobardi et al., 2013; 2018; Hartke et al., 2017; 2020). Furthermore, motivated by the observed steeper faint-end slope of the PNLF of Virgo ICL-PNe, Longobardi et al. (2013) proposed the modification of Equation 1 to allow a variable faint-end slope c_2, which has since been applied to observations of PNe in nearby groups and clusters (Hartke et al., 2017; 2020) as well as in the nearby M31 (Bhattacharya et al., 2021). While it is difficult to constrain the stellar population properties of the low-surface-brightness haloes, and the surrounding ICL or IGL, pencil-beam surveys suggest that high α-parameters and steep PNLF slopes can be linked with old and metal-poor stellar populations (Williams et al., 2007; Harris et al., 2007; Lee and Jang, 2016), but with the caveat that these measurements are not exactly co-spatial. To interpret the studies of PN populations in groups and clusters of galaxies, it is important to obtain co-spatial measurements of PN and stellar populations, which will be discussed in turn.

2.2 New insights from integral-field spectroscopic surveys

Since the pioneering integral-field spectroscopic studies of Roth et al. (2004) and Sarzi et al. (2011), the Multi Unit Spectroscopic Explorer (MUSE, Bacon et al., 2010) has been transformational (see also the review by Roth et al., 2023) for the study of extragalactic PN populations, especially in late-type galaxies that have been targeted less with classical methods. Furthermore, integral-field spectroscopic observations allow the simultaneous investigation of stellar population properties and discovery and characterisation of PN populations, which are important for putting the results presented in the previous subsection into context.

Kreckel et al. (2017) showed the importance of full spectral information when determining the PNLF distance to NGC 628, as supernova remnants biased previous distance determinations based on narrowband imaging alone (Herrmann et al., 2008) to a shorter distance, despite the MUSE data only covering parts of the disk of the galaxy. With a much higher filling factor, the PHANGS-MUSE survey (Physics at High Angular resolution in Nearby GalaxieS; Emsellem et al., 2022) has been a treasure trove for studying ionized nebulae in nearby star-forming galaxies, with Scheuermann et al. (2022) determining PNLF distances to the 19 galaxies in the sample and can reconcile their derived distances with literature tip of the red-giant branch distances without the need for a metallicity-dependent M^{*}. To facilitate the classification of ten thousands of nebulae in the 19 galaxies into H II regions, supernova remnants, and PNe, Congiuet al. (2023) developed a Bayesian algorithm, but noted that the PNe sample is incomplete compared to that of Scheuermann et al. (2022), attributing the differences to different source-detection methods, but finding consistent classifications for the sources that are in both catalogues. Building on the PHANGS-MUSE strategy, Congiu et al. (2025) built the largest MUSE mosaic to date, covering the Sculptor galaxy (NGC 253), and resulting in the detection of ~500 PNe. This work demonstrates the importance of accounting for dust in the interstellar medium, which can bias the PNLF distance to larger values.

Different techniques have been developed to detect PNe from integral-field spectroscopic data, starting with the 'classical' visual inspection and blinking of on-off images (e.g., Roth et al., 2018). Spriggs et al. (2020). developed a technique based on PSF and pixel-by-pixel spectral fitting to automatically detect PNe from Fornax3D survey data targeting the brightest early-type galaxies in the Fornax cluster (Sarzi et al., 2018). Galán-de Anta et al. (2021) applied this technique to three galaxies from Fornax3D to probe metallicity-dependent variations of the α-parameter in the centres and (inner) haloes of the galaxies, but did not find any evidence for an increase in the α-parameter between metal-rich and metal-poor regions. This differs from the results presented in Section 2.1 on halo and ICL α-parameter variations with stellar populations on significantly larger spatial scales that allowed for probing lower host stellar population metallicities.

Roth et al. (2021) developed the so-called differential emission line filtering (DELF) method with the goal of facilitating photometric measurements precise enough to use PNLF distances to alleviate the Hubble tension. Jacoby et al. (2024) applied this method to a heterogeneous sample of 20 galaxies with MUSE archival data, demonstrating that the method can yield excellent PNLFs and outline the way forward for PNLF distance measurements, both from an observational standpoint, as well as regarding the need for a better understanding and definition of the analytical form of the PNLF.

The aforementioned studies were all carried out with the MUSE integral-field spectrograph, that has a prohibitively small field-of-view (FoV, $1' \times 1'$ in wide-field mode) to study galaxies in the local Universe in their full extent in a single pointing. The SITELLE instrument (Spectrométre Imageurä Transformeé deFourier pour l'É tude en Long et en Large des raies d'Émission; Grandmont et al., 2012), an optical imaging Fourier transform spectrometer, covers an $11' \times 11'$ FoV, comparable to that of the PN.S instrument. However, the larger FoV is compromised by a shorter wavelength range that can be sampled in one observation. The ongoing Star formation, Ionized Gas, and Nebular Abundances Legacy Survey (SIGNALS; Rousseau-Nepton et al., 2019) provides observations of ≈40 late-type galaxies in the local Universe in three filters, SN1 (3650 – 3850 Å, covering [O II] $\lambda 3727$ Å), SN2 (4800 – 5200 Å, covering the $\lambda\lambda 4959, 5007$ Å doublet and Hβ) and SN3 (6510 – 6850 Å, covering Hα as well as the [Ne II]$\lambda\lambda 6548, 6583$ Å and [S II]$\lambda\lambda 6716, 6731$ Å lines), allowing for the detection and classification of extragalactic PNe in these galaxies, as piloted by Martin et al. (2018) and Vicens-Mouret et al. (2023).

2.3 New facilities and opportunities

The coming years and decades will see the arrival of several telescopes and instruments that may open new and exciting discovery spaces for PN populations outside of the Milky Way. BlueMUSE (Richard et al., 2019) at the Very Large Telescope, will have a similar design to MUSE that has been transformative for the study of PN populations in nearby galaxies, but covering important bluer emission lines (for example, [O II]$\lambda 3727$ Å, H$\gamma\lambda 4340$ Å, [O III]$\lambda 4364$ Å, and He II $\lambda 4686$ Å[3]). The bluer [O III] line is crucial for direct abundance determinations and the He II and Hγ lines provide important constraints for the determination of the excitation class of PNe (e.g., Reid and Parker, 2010; Bhattacharya et al., 2019).

Integral-field units will be complemented by spectroscopic facilities with high multiplexing capabilities and large fields of view, such as the Maunakea Spectroscopic Explorer (Sheinis et al., 2023) and the Wide-field Spectroscopic Telescope (Mainieri et al., 2024) at 10m-class facilities in the northern and southern hemispheres. These will be transformative for the study of individual nebulae, the relation between PNe and their host stellar populations, but also for PNe as tracers of galaxy, halo, and ICL assembly.

While the bulk of instrumentation for the upcoming Extremely Large Telescopes will focus on the infrared wavelength range, several spectrographs will still operate in the optical, covering the important [O III]$\lambda\lambda 4959, 5007$ Å doublet from redshift $z = 0$, facilitating unprecedentedly deep surveys for PNe in the local universe, as well as pushing the redshift boundaries of extragalactic PN populations beyond the Coma Cluster. The first light for the first generation of these instruments, the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI, Thatte et al., 2016) at ESO's Extremely Large Telescope (ELT) and the Giant Magellan Telescope Multi-object Astronomical and Cosmological Spectrograph (GMACS, Fabricant et al., 2025) is foreseen for the coming decades. Instruments such as the Multi-AO Imaging Camera for Deep Observations (MICADO, Sturm et al., 2024) at the ELT may furthermore complement existing PN surveys with resolved stellar population information for galaxies beyond 10 Mpc.

3 Modelling PN populations and insights from stellar evolution models

The reconciliation of the observed invariance of the absolute magnitude of the PNLF bright cut-off for galaxies of different morphological types with the predictions from stellar evolution models has been a long-standing issue. Furthermore, the use of the PNLF as a distance indicator requires a better theoretical understanding about the PNe that populate the bright end of the PNLF and their origin. To reconcile observed PN properties with stellar evolution models, one needs to rely on synthetic post-AGB evolution tracks that describe the evolution of low-to intermediate-mass stars following the AGB phase. Historically, two model grids were widely used: Vassiliadis and Wood (1994) and Bloecker (1995). While it was possible to reproduce the observed bright cut-off of the PNLF M^* in galaxies with recent star-formation, the presence of similarly bright PNe in elliptical galaxies with old stellar populations could not be reconciled (e.g., Marigo et al., 2004; Ciardullo, 2012).

Furthermore, based on observations of PNe in the Galactic bulge, Gesicki et al. (2014) found that the Bloecker (1995) tracks[4] evolve too slowly to reconcile the predicted with the observed local white dwarf masses. The post-AGB evolutionary tracks of Miller Bertolami (2016) address this issue, including updated descriptions of micro- and macrophysics, resulting in $3 - 10\times$ faster post-AGB evolution timescales and overall brighter luminosities. Gesicki et al. (2018) were the first to show that with these faster evolving tracks, even populations with ages between three and 7 Gyrs could produce PNe that reach the bright cut-off M^* under the assumption that the brightest PNe are optically thick (maximum-nebula hypothesis). However, combining the new post-AGB tracks (Miller Bertolami, 2016) with the PN population modelling prescription of Mendez and Soffner (1997), Valenzuela et al. (2019) showed that under the maximum-nebula hypothesis too few PNe are produced overall, in conflict with observed PNLFs, and that accounting for optically-thin PNe is important.

The majority of the above models (and others in the literature) use recipes based on solar measurements and abundances, or, on larger scales, values derived based on Milky Way properties. The PICS (PNe in cosmological simulations) framework (Valenzuela et al., 2025) overcomes this limitation by modelling PNe for SSPs with different masses, ages, and metallicities. The PICS models furthermore explore the critical role of dust, using the empirical prescription of Jacoby and Ciardullo (2025), as well as the effect of different prescriptions for the initial-to-final mass relation (IFMR) and for the Helium abundances. While the authors reproduce the general trend from previous models that older SSPs produce less luminous PNe, they also demonstrate that metallicity plays an important role: old SSPs with higher metallicities are able to produce brighter PNe. Furthermore, they find the abundance of the bright PNe to be especially sensitive to the IFMR in old stellar populations, with a flatter IFMR (e.g., Cummings et al., 2018) leading to larger core masses and thus brighter PNe, alleviating some of the long-standing tension between observations and models, as also discussed in Jacoby and Ciardullo (2025).

By producing models normalised to the bolometric luminosity, Valenzuela et al. (2025) also determine the α-parameter for a given SSP in a given magnitude range. To facilitate the comparison with the predictions from Buzzoni et al. (2006), α-parameters are calculated eight magnitudes from a fixed $M^* = -4.5$. While the general trends of α_8 with age and metallicity are similar between the two models, the use of Miller Bertolami's (2016) metallicity-dependent stellar evolution models by Valenzuela et al. (2025) leads to a stronger dependence of α_8 on metallicity. To facilitate the comparison with observations, Valenzuela et al. (2025) also provide predictions for $\alpha_{2.5}$, reducing the need for observers with magnitude-limited data to

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[3] This line can already be observed with MUSE in the extended spectral configuration, but the majority of extant archival data has been observed in the nominal configuration, starting at 4800 Å.

[4] The same holds for the tracks of Vassiliadis and Wood (1994), which evolve on even slower timescales.

make assumptions about the shape of the PNLF for extrapolating α, and better taking into account the effect of metallicity on the amount of bright PNe.

4 Conclusions and outlook

In this review, I discussed advances of linking extragalactic PN populations with the underlying stellar population properties both from an observational (Sect. 2) and modelling (Sect. 3) perspective. Especially on large spatial scales (i.e., comparing galaxy centres and extended haloes or the surrounding ICL in massive environments), there is evidence for a significant change of the α-parameter and PNLF shape. However, these measurements are limited by indirect metallicity inferences. To reconcile observations and theory, systematic surveys where PN and stellar population properties are simultaneously measured are needed, covering the entire mass-metallicity relation. As discussed in Section 2.2, integral-field spectrographs open up a new discovery space for PNe and allow for the co-spatial measurement of stellar population properties such as ages, metallicities, and abundances via spectral fitting.

Ongoing surveys, as well as those planned with new instrumentation at 8-, 10- and 30-m-class telescopes, using integral-field spectroscopy and 'classical' PN detection techniques, will provide constraints on the variation of the important diagnostics α-parameter and PNLF in stellar populations of *in situ* and *ex-situ* origins. For the interpretation of these observations, but also to further constrain theoretical models of late stellar evolution, it is crucial to properly model extragalactic PN populations in cosmological simulations of galaxy evolution, which has finally become possible, as reviewed in Section 3.

In summary, there are promising studies suggesting that, in the coming years, PNe may be elevated to stellar population tracers in low-surface brightness regions such as galaxy haloes and the ICL–where stellar population parameters such as age and metallicity cannot be easily measured directly–in addition to their important role as kinematic tracers. This is fuelled by advances in instrumentation as well as new models of late stellar evolution that will be combined with state-of-the-art numerical simulations of galaxy evolution.

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Johanna Hartke: Conceptualization, Writing – original draft, Writing – review and editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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