The General Assembly of Galaxy Halos: Structure, Origin and Evolution
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PN populations in the local group and distant stellar populations

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Abstract. Our understanding of galactic structure and evolution is far from complete. Within the past twelve months we have learnt that the Milky Way is about 50% wider than was previously thought. As a consequence, new models are being developed that force us to reassess the kinematic structure of our Galaxy. Similarly, we need to take a fresh look at the halo structure of external galaxies in our Local Group. Studies of stellar populations, star-forming regions, clusters, the interstellar medium, elemental abundances and late stellar evolution are all required in order to understand how galactic assembly has occurred as we see it. PNe play an important role in this investigation by providing a measure of stellar age, mass, abundances, morphology, kinematics and synthesized matter that is returned to the interstellar medium (ISM). Through a method of chemical tagging, halo PNe can reveal evidence of stellar migration and galactic mergers. This is an outline of the advances that have been made towards uncovering the full number of PNe in our Local Group galaxies and beyond. Current numbers are presented and compared to total population estimates based on galactic mass and luminosity. A near complete census of PNe is crucial to understanding the initial-to-final mass relation for stars with mass >1 to <8 times the mass of the sun. It also allows us to extract more evolutionary information from luminosity functions and compare dust-to-gas ratios from PNe in different galactic locations. With new data provided by the Gaia satellite, space-based telescopes and the rise of giant and extra-large telescopes, we are on the verge of observing and understanding objects such as PNe in distant galaxies with the same detail we expected from Galactic observations only a decade ago.

Keywords. Planetary nebulae: general, Galaxies: halos, Surveys, Kinematics.

1. Introduction

Access to large telescopes and innovative identification techniques are contributing to an increased number of planetary nebulae (PNe) being discovered and used to trace stellar populations regardless of the type of galaxy. Although distant PN populations have been used as distance indicators by means of the invariant bright cut-off of the PN luminosity function (PNLF, eg. Ciardullo *et al.* 1989) for some time now, they are more recently being used to trace stellar luminosity (eg. Buzzoni *et al.* 2006), galaxy kinematics (eg. Cortesi *et al.* 2013; Longobardi *et al.* 2015a) and undertake chemical tagging (eg. Gonçalves *et al.* 2014; Corradi *et al.* 2015). PNe, through their bright [O III] and H lines have the advantage of being detected and measured across the 3.1 Mpc diameter of our local group and identified up to distances of 30 Mpc in the local universe, providing a snapshot of stellar populations, their luminosity, age, metallicity and their kinematic migrations over periods up to 8 Gyr ago. This makes them very useful tools with which to test a number of theories concerning the evolution of stars and galaxies.

Tidal encounters between galaxies have occurred in many places such as between M31 and M33 (Bekki 2008) and between the LMC and SMC (Bekki *et al.* 2008b), both about 3 Gyr ago. Such encounters can result in vast extended disks, halos and streams where measurements of metallicity are able to reveal progenitor origins. Low stellar surface brightness beyond projected radii of $\sim$2R$_e$ makes it very difficult to study the kinematics and individual properties of stars in elliptical galaxies. The study of the structural, chemical and kinematic properties of PNe in the outer regions of galaxies such as their halos are now revealing previously unseen clues as to galaxy formation and evolution. The properties of stellar halos in the Milky Way and M31 as well as several dwarf galaxies in the LG have already been well investigated (eg. Reitzel, Guhathakura & Gould, 1998; Davidge, 2002). More recently, however, observations have begun extending the physical properties of stellar halos to giant elliptical galaxies such as NGC 2768, M87 and NGC 5128, beyond the LG (eg. Cortesi *et al.* 2013; Longobardi *et al.* 2015a).

High resolution spectroscopic observations of PNe in LG galaxies and beyond permit the measurement of radial velocities and allow the estimate of global mass distributions (eg. Arnaboldi *et al.* 1998; Méndez *et al.* 2001; Romanowsky *et al.* 2003; Napolitano *et al.* 2004; Peng *et al.* 2004; Cortesi *et al.* 2013; Longobardi *et al.* 2015a,b). We can explore the 2D distribution of PNe and the stellar regions they populate, providing clues to the triaxial shapes of galaxies and formation processes. The structure and origin of the outer halo regions of ellipticals is only now beginning to become clear. We now have well constrained methods to separate the halo components from the inter-cluster light (ICL) (eg. Dolag *et al.* 2010; Cui *et al.* 2014; Longobardi *et al.* 2015a).

2. PN populations

There are a number of good reasons for the high increase in the number of PN studies in external galaxies. The PNLF from these objects serves to test distance estimates made through other means and estimate 'α', the luminosity specific number of PNe expected according to the bolometric luminosity of the galaxy (see next section). Visible number densities provide information about past kinematic evolution such as possible ram pressure stripping of PNe by a hot intercluster medium. In addition, the α parameter and the PNLF correlate with the age, colour and metallicity of the progenitor stellar population, providing an effective means of measurement where other tracers may be too faint. The line of sight velocity dispersion (LOSVD) of PNe in a galaxy can indicate tidal disruptions or the relative mass and luminosity of the halo component, where the PN histogram may range from Gaussian to highly non-gaussian and multi-peaked. Table 1 provides an up-to-date estimate of the number of PNe now available for study within the MW and the LG. Table 2 provides an estimate of the number of PNe now available at the outskirts of the LG and beyond.

2.1. *The α parameter*

The PN population size, when scaled to the available completeness limits, directly correlates with the visual magnitude of a galaxy (the number of PNe $L^{-1}_{\odot bol}$) or "α ratio" (Magrini *et al.* 2003). This relation, however, is weakly dependent on the age, metallicity, morphological type of the galaxy (Buzzoni *et al.* 2006) and the degree of star formation at the time the PN progenitors were forming. Please see Reid (2012) for further details. In short, the expected number of PNe (N_{PNe}) for a simple stellar population of total luminosity (L_{bol}) is:

$$N_{PN} = ß\, L_{bol}\, \tau_{PN} \quad (2.1)$$

Table 1. Known planetary nebulae populations in the local group in the years 2011 and 2015 showing the improvement. Local group galaxies newly identified/discovered in the past seven years are indicated by an asterisk next to the name in column 1.

Name	Type	Mv	Dist. [kpc]	PNe 2011	PNe 2015	Ref (old) 2011	Ref (new) 2015
M 31	Sb	-21.5	785	2766	2779	Merrett 2006	Jacoby *et al.* 2013
Milky Way	Sbc	-20.9		∼3000	3288	Parker *et al.* 2006	Parker *et al.* 2015
M 33	Sc	-18.9	795	152	152	Ciardullo *et al.* 2004	
LMC	Ir	-18.5	50	740	740	Reid *et al.* 2006, 2010	Reid *et al.* 2013; 2014
SMC	Ir	-17.1	59	89	105	Jacoby *et al.* 2002	Drašković *et al.* 2015
M 32 (NGC221)	E2	-16.5	760	30	45	Ciardullo *et al.* 1989	Sarzi *et al.* 2011
NGC 205 (M110)	Sph	-16.4	760	35	35	Corradi *et al.* 2005	
IC 10	Ir	-16.3	660	27	35	Kniazev, *et al.* 2008	Gonçalves *et al.* 2012a
NGC 6822	dIr	-16.0	500	26	26	HM[2] *et al.* 2009	
NGC 185	Sph	-15.6	660	5	8	Corradi *et al.* 2005	Gonçalves *et al.* 2012b
IC 1613	dIr	-15.3	725	3	3	Magrini *et al.* 2005	
NGC 147	Sph	-15.1	660	9	9	Corradi *et al.* 2005	
WLM	dIr	-14.4	925	1	1	Magrini *et al.* 2005	
Sagittarius	dSph/E7	-13.8	24	3	4	Zijlstra *et al.* 2006	
Fornax (E351-G30)	dSph	-13.1	138	1	2	Larsen 2008	
Pegasus (DDO 216)	dIr	-12.3	760	1	1	Jacoby *et al.* 1981	
Leo I (DDO 74)	dSph	-11.9	250				
Andromeda I	IDsPH	-11.8	810				
Andromeda II	dSph	-11.8	700				
Leo A (Leo III)	dIr	-11.5	690	1	1	Magrini *et al.* 2003	
DD 210	dIr	-11.3	1025				
KKs 3*	dSph	-10.8	2146				
Sag DIGD	dIr	-10.7	1300				
Pegasus II (An VI)	dSph	-10.6	830				
Pisces (LGS3)	dIr	-10.4	810				
Andromeda V	dSph	-10.2	810				
Andromeda III	dSph	-10.2	760				
Leo II (Leo B)	dSph	-10.1	210				
Cetus	dSph	-9.9	755				
Phoenix	dSph	-9.8	395		1	Saviane *et al.* 2009	
Sculptor (E351-G30)	dSph	-9.8	87				
Cassiopeia (An VII)	dSph	-9.5	690				
Tucana	dSph	-9.6	870				
Sextans	dSph	-9.5	86				
Carina (E206-G220)	dSph	-9.4	100				
Draco (DDO 208)	dSph	-8.6	79				
Ursa Minor	dSph	-8.5	63				
Canes Venatici I*	dSph	-7.8	220				
Leo T*	dSph	-7.1	420				
Ursa Major*	dSph	-6.7	100				
Hercules*	dSph	-6.6	147				
Eridanus II*	dSph	-6.6	380				
Canis Major Dwarf*	Irr		7.6				
Canes Venatici II*	dSph	-5.8	150				
Boötes I*	dSph	-5.8	60				
Boötes III*	dSph	-5.8	46				
Leo IV	dSph	-5.5	154				
Leo V	dSph	-5.2	175				
Pisces II*	dSph	-5.0	180				
Coma Berenices*	dSph	-4.1	44				
Ursa Major II*	dSph	-3.8	30				
Tucana II*	dSph	-3.8	57				
Indus I*	dSph	-3.5	100				
Horologium I*	dSph	-3.4	79				
Grus I*	dSph	-3.4	120				
Pictoris I*	dSph	-3.1	114				
Phoenix II*	dSph	-2.8	83				
Boötes II*	dSph	-2.7	42				
Reticulum II*	dSph	-2.7	30				
Segue 2*	dSph	-2.5	35				
Eridanus III*	dSph	-2.0	87				

Notes:
[2] Hernández-Martínez *et al.* (2009).

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Table 2. Known planetary nebulae populations in the outer local group and outlying galaxies in the years 2011 and 2015 showing the improvement. Local group galaxies newly identified/discovered in the past seven years are indicated by an asterisk next to the name in column 1.

Name	Type	Mv	Dist. [kpc]	PNe 2011	PNe 2015	Ref (old) 2011	Ref (new) 2015
LG outskirts							
GR8	dSph	-11.8	2200	0		Magrini *et al.* 2005	
Antlia	dSph	-15.8	1330				
NGC3109	dIr	-15.8	1330	18	20	Peña *et al.* 2007	
Sextans B	dIr	-14.3	1600	5	5	Magrini *et al.* 2000	
Sextans A	dIr	-14.2	1320	1	1	Magrini *et al.* 2003	
EGB0427+63	sIr	-10.9	2200				
Beyond LG							
NGC 1316	SAB9s0	-22.0	19000	43	796	Coccato *et al.* 2009	McNeil-Moylan *et al.* 2012
NGC 2768	E6	-21.8	22400		289		Cortesi *et al.* 2013
NGC 5846	E0	-21.7	23100	123		Coccato *et al.* 2009	
NGC 1399	E1	-21.4	18500	37	187	McNeil *et al.* 2010	
M 84 (NGC 4374)	E1	-21.3	18400	450		Coccato *et al.* 2009	
NGC3311	E/S0	-21.3	41000		56		Ventimiglia *et al.* 2011
M 86 (NGC 4406)	E3	-22.1	15000	16		Arnaboldi *et al.* 1996	
NGC 821	E6	21.55	22400		167		Teodorescu *et al.* 2011
M 87	E0p	-21.5	16400		300		Longobardi *et al.* 2015a,b
NGC 5128	gE/S0	-21.0	3800	1141	1267	Peng *et al.*2004	Walsh *et al.* 2015
NGC 1344	E5	-20.92	18400	194		Teodorescu *et al.* 2005	
NGC 3608	E2	-20.7	21300	87		Coccato *et al.* 2009	
NGC 4494	E1	-20.4	15800	255		Napolitano *et al.* 2009	
NGC 3489	SB0-(rs)	-20.2	12100		75		Cortesi *et al.* 2013
NGC 3115	SO	-20.0	9700		186		Cortesi *et al.* 2013
NGC 1023	SB0-(rs)	-19.9	11400		236		Cortesi *et al.* 2013
NGC 3377	E5	-19.8	10400	151		Coccato *et al.* 2009	
NGC 4564	E6	-19.7	13900	49		Coccato *et al.* 2009	
NGC 1023	S0	-19.7	10600	183		Noordermeer *et al.* 2008	
M 105 (NGC 3379)	E1	-19.7	9800	186		Douglas *et al.* 2007	
NGC 7457	SA0-(rs)	-19.6	13200		156		Cortesi *et al.* 2013
NGC 3394	SB0-(s)	-19.4	11600		77		Cortesi *et al.* 2013
NGC 3384	SO	-19.2	10800	68		Tremblay *et al.* 1995	
NGC 4697	E6	-19.2	10900	535		Méndez *et al.* 2001	

where ß is the so-called "specific evolutionary flux" (which approximates to 2×10^{-11} $L_{\odot bol}^{-1} yr^{-1}$); and τ_{PN} is the PN (emission-detectable) lifetime in years.

In addition, the stellar core mass evolution directly affects the PN lifetime since it depends on the central star temperature ($T_{eff} \simeq 10^5$ K) during the hot post AGB phase. With an increase in the hot post AGB lifetime with increasing dynamical ages and metallicities, the τ_{HPAGB} is somewhat equivalent to Fuel/l_{HPAGB}, where l_{HPAGB} is the luminosity of the central star at the onset of the PN stage. The luminosity-specific PN density then becomes:

$$\alpha = \frac{N_{PN}}{L_{SSP}} = ß\,\tau_{PN} = ß \min\{\tau_{HPAGB}, \tau_{dyn}\} \tag{2.2}$$

The luminosity-specific PN number density presented here is calibrated to the near-complete number density and metallicity found in both the LMC and SMC. This calibration is then applied to the estimate PN population expected in similar dwarf or irregular galaxies of varying low metallicity. Data supplied by Reid & Parker (2013) and Reid (2014) suggest there may not be more than 740 genuine PNe in the LMC. Likewise, data and on-going analysis supplied by Drašković *et al.* (2015) suggest the SMC may not support more than 105 PNe. For large galaxies with accordingly higher metallicities, we calibrate to the theoretical luminosity-specific PN density found by Buzzoni *et al.* (2006).

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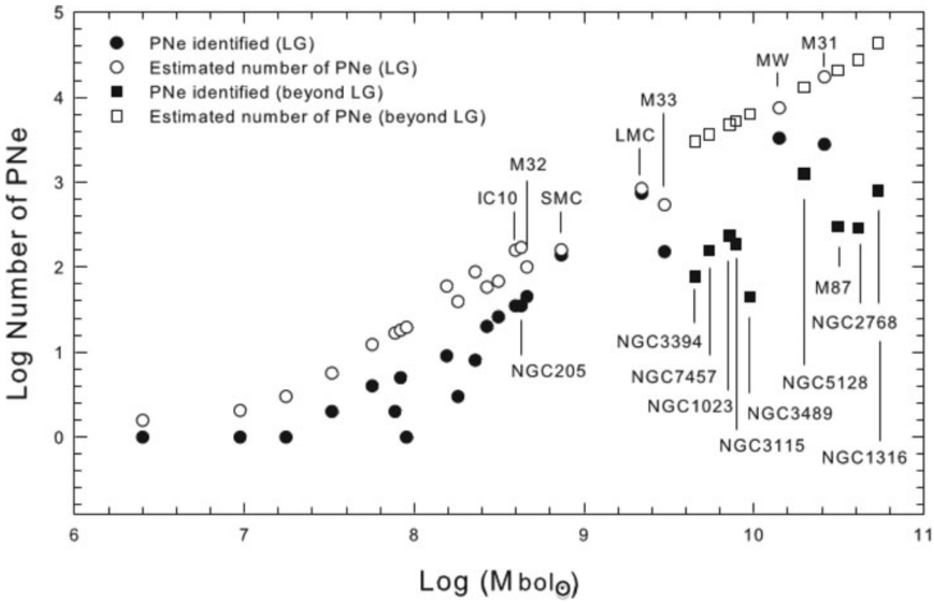

Figure 1. The number of PNe currently known in each galaxy (filled circles for LG and filled squares for galaxies beyond) as a function of the absolute estimated luminosity of their host galaxies. Open circles for LG and open squares beyond represent the possible number of PNe predicted using α, based on the theory of simple stellar populations calibrated to well assessed populations and metallicities.

For calibration we use $\alpha = 1\,\mathrm{PN} \,/\, 1.5 \times 10^6\ \mathrm{L}_\odot$ for M31 (metallicity ∼ –0.6), $\alpha = 1$ PN / $2.5 \times 10^6\ \mathrm{L}_\odot$ for the LMC (metallicity ∼ –1.15) and $\alpha = 1$ PN / $4.6 \times 10^6\ \mathrm{L}_\odot$ for the SMC (metallicity ∼ –1.25).

In addition, Longobadi *et al.* (2015a) found that galaxies with (B-V) colours < 0.8 have small α whereas galaxies with B-V colours > 0.8 have higher α with more spread. With a small bolometric correction applied to the L_v of the galaxies, it is possible to use α to estimate the number of PNe that may exist in each galaxy. This bolometric correction does not amount to much more than -0.2 Mag. In order to compare the number of PNe currently uncovered and the likelihood of further discoveries, the known number of PN for each galaxy is plotted on the same scale and shown in Figure 1.

3. PNe provide information on stellar populations

The vast majority of studies based on extragalactic PNe surveys include a luminosity function (eg. Hernández-Martínez & Peña 2009; Reid & Parker 2010; Cortesi *et al.* 2013; Longobardi *et al.* 2015a). Even if the ultimate goal of the research is aimed at kinematics, the role of the PNLF is key to understanding the characteristics of the sample at hand. For example, the PNLF will quickly suggest the relative completeness of the sample. It will show if the brightest possible PNe in the population have been included and provide a distance estimate. The presence of a dip and its position between two and four magnitudes below the brightest possible PN will indicate the star-forming history of the galaxy and suggest the metallicity by inference. The presence of a peak in the function, 6∼7 mag below the brightest indicates the luminosity at which most PNe reside during their 20 to 30 K yr lifetimes (Reid & Parker 2010).

Using PNe in the Large Magellanic Cloud (LMC) Badenes *et al.* (2015) have compiled a statistical analysis of the relationship between PNe and their parent stellar population. To achieve this they use a delay time distribution (DTD) which is the rate of PN production as a function of time after a hypothetical brief burst of star formation. Given a set of observed PNe in each region of the LMC and a stellar age distribution (SAD) map of the galaxy, the DTD can be recovered for each discrete SAD cell. The mean lifetime of the PNe produced in each time bin of the DTD was calculated by dividing the recovered number of stars that turn off the main sequence by the rate at which stars from a coeval population with a specific same age leave the MS. The study shows that most PN progenitors in the LMC have main-sequence lifetimes in a narrow range between 5 and 8 Gyr, corresponding to masses between 1.2 and 1.0 $M_\odot$ producing PNe visible for 26 $\pm$4 6 kyr. There is also a distinct second population of PN progenitors in the LMC with main-sequence lifetimes between 35 and 800 Myr, corresponding to masses between 8.2 and 2.1 $M_\odot$ and average PN lifetimes of 11 $^{+6}_{-8}$ kyr but no PNe that appear to result from stars in the 800 Myr - 2 Gyr MS lifetime bracket. The DTD-derived PN lifetimes result in an integrated PN formation rate of $\sim$0.02 yr^{-1} in the surveyed area, which includes $\sim$80% of the stellar mass of the LMC. This implies a bolometric luminosity specific PN formation rate of $\sim 7 \times 10^{-12}$ PNe yr^{-1} $L_\odot{}^{-1}$. In the LMC today, 40 $^{+23}_{-29}$% of PNe are generated by young progenitors and 25 $\pm$8% by older progenitors.

Using the CTIO 4-m telescope and MOSAIC-2 wide-field camera on [O III]5007 and Hα, Hernandez-Martinez and Pena (2009) found 26 PNe in NGC 6822, increasing the known number by 8. The PNLF has a similar dip to the one found for the Small Magellanic Cloud at 2.5mag below the maximum. The best fit to the observed PNLF gives a rough estimate of 23.64 $\pm$0.23 mag for the distance modulus. The authors have estimated the number of PNe in the brightest 0.5 mag normalized to the galactic bolometric luminosity ($\alpha_{0.5}$) as 3.8 $^{+0.9}_{-0.71}$ E-9. This value is similar to the values derived from small galaxies (M_B fainter than -18 mag) and galaxies with recent star formation (larger than values obtained for early-type galaxies).

PNLFs were constructed for nine galaxies with various Hubble types by Rodríguez-González *et al.* (2015). They report that all the galaxies except one have a two-mode population where the PNe represent two episodes of star formation in which the second episode is significantly stronger. These authors approach the analysis in an unusual way by using cumulative PNLFs and estimating progenitor mass. Peak starbursts at t_1 = 8 Gyr and t_2 = 11.5 Gyr and the estimated age of $\sim$13.5 Gyr for NGC 6822 are interesting results if one has confidence in the methods and analysis used.

4. Kinematic studies

A paper by Cortesi *et al.* (2013) uses the kinematics of PNe to very large radii to help explain the origins of S0 galaxies. The galaxies surveyed are divided into three groups, the first are isolated S0s (NGC 3115 & NGC 7457), those in poor groupings (NGC 1023 & NGC 2768) and those in the richer Leo group (NGC 2284 & NGC 3489). The authors find that the kinematics are largely dominated by rotational motion with significant random velocities. The spatial distribution of PNe is compared to that of the underlying stellar population. To do this, elliptical isophotes are fitted to images of the galaxies and surface brightness profiles extracted from the fits. The α value varies slightly as the redder ellipticals are poorer in PNe per unit L_{gal} than spirals. A comparison of α to the B-V mag and UV excess show that S0s are indistinguishable from ellipticals but suggest that bluer galaxies have higher specific frequencies of PNe.

A spectroscopic study of 287 PNe associated with M 87 in Virgo A by Longobardi *et al.*(2015a) found that 211 are located between 40 kpc and 150 kpc from the galaxy center. The velocity dispersion is found to be bimodal with a narrow component centered on the systematic velocity of M87 (234 PNe) and a broader off-center component

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identified as halo and ICL (44 PNe). The number density of the galaxy halo PNe and ICL PNe have different spatial distributions where halo PNe follow the galaxy's surface brightness profile and ICL PNe have a shallower power-law profile $l_{ICL} \propto R^y$ with y in the range [-0.34, -0.04]. PN number densities confirm different PN populations in M87 and the ICL, each with a different value for α. The stellar halo is found to extend out to ∼150 kpc while PNe belonging to the ICL overlap outwards from a radius of ∼60 kpc. Both populations are separated on the basis of their velocity relative to the systematic velocity of 1275 km s^{-1} where the V_{halo} = 1270.4 km s^{-1} and has a dispersion of 298.4 km s^{-1} compared to the V_{ICL} which is centered at 999.5 km s^{-1} and has a dispersion of 881 km s^{-1}. Statistically, 10% or 30 PNe from all halo sample bins are likely associated with the IC component.

An imaging and spectroscopic survey of PNe in NGC 5128 (Cent A) by Walsh *et al.* (2015) presented velocities for kinematic and dynamical studies. NTT was used to image 15 fields with EMMI and [O III] together with off-band filters. New discoveries were added to the existing count and observed with FLAMES in MEDUSA. This resulted in 1118 PN candidates and 1267 spectroscopiclly confirmed PNe.

5. Chemistry in PNe

Spectroscopic observations of nine newly discovered PNe in the outskirts of M31 obtained with the 10.4-m GTC telescope by Corradi *et al.* 2015 has extended their previous study to a galactocentric radii of 100pc. None of the observed PNe are members of a classical metal-poor and ancient halo. Two of the outermost PNe have solar O abundances and kinematics similar to the extended disk of M31. Other PNe have slightly lower O content (O/H]∼-0.4) and sometimes large derivations from disk kinematics. In other studies, Hernández-Martínez *et al.*(2009) analysed the chemical behavior of the irregular galaxy NGC 6822 and more recently, Gonçalves *et al.* (2014) analysed the universal mass-metallicity relation and the chemical abundances in dwarf galaxy NGC 205.

6. Summary: The future

- Many more PNe need to be identified and observed in a larger number and range of galaxies in order to measure and separate the halo and IC properties.
- Different stellar populations will be exposed through PN densities and kinematics.
- More abundances need to be determined for external PNe and used to reveal tidal stripping, streams, extended stellar disks and tidal encounters with other galaxies.
- Work is required for a better theoretical understanding of the way in which metallicity, age and different star-fiormaing histories affect post-AGB phases of stellar evolution.
- More theoretical work needs to be done on the physics behind PNLF dips and peaks.

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