Why Galaxies Care About AGB Stars:
A Continuing Challenge through Cosmic Time
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Planetary nebulae in the (extra)-galactic context: Probing chemical evolution in star-forming galaxies

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Abstract. The populations of planetary nebulae (PNe) probe metallicity and chemical content (and its evolution) of the parent galaxy, giving clues to galaxy formation and evolution. This sub-field of extra-galactic PN research has been particularly active in the recent years. Comparison of data and models yielded estimates of global cosmic enrichment and provided constraints to galaxy formation history. In external spiral galaxies, the chemical contents of PNe and H II regions can be compared to disclose possible evolution of the radial metallicity gradient, which is, in turn, a powerful constraint to galactic chemical evolutionary models. In the Milky Way, recent PN progenitor dating and new chemical abundances offer an updated look into our own Galaxy. Collectively, Galactic and extra-galactic radial metallicity gradients from emission-line probes (PNe and H II regions) can be compared to have a cosmological outlook on galactic evolution.

Keyword. Planetary nebulae

1. Introduction

The field of extragalactic planetary nebulae (PNe), or, more broadly, the field of PNe studied as populations rather than individually, has been active since the late 70s, when it became clear that the bright [O III] line at 5007 Å could be observed in PNe of external galaxies, and the first extra-galactic PN catalogues became available (Sanduleak *et al.* 1978). Nonetheless, there have not been many conferences, or journal reviews, dedicated specifically to this field. The most recent meeting on extra-galactic PNe took place in 2015 in Honolulu, within the XXIX IAU General Assembly (Stanghellini *et al.* 2016). We have to look back more than a decade to encounter the previous extra-galactic PN meeting, that took place at ESO in 2004 (Stanghellini *et al.* 2006), and was the first full science meeting dedicated to extra-galactic PNe. Since 1975 the field has produced more than 450 scientific papers (source: ADS), indicating five major sub-fields: (i) surveys and discoveries of extra-galactic PNe; (ii) the study of Magellanic Cloud PNe; (iii) studies that use PNe as dynamical probes; (iv) PNe as chemical evolution and stellar evolution probes; (iv) the PN luminosity function, and the determination of the extra-galactic distance scale. All these sub-fields are currently active, but with peaks of activity that depend on the scientific capabilities available at different epochs. Furthermore, the sub-field of chemical abundances in extra-galactic PNe is reaching the observability limit with the current technology, especially concerning direct abundances. In fact, most of the nearby galaxies where direct abundances of PNe could be measured have already been studied, and a renaissance of this field is to be expected with the advent of extremely large telescopes (ELTs) spectrographs. This is a review of the field of PN populations, both in the Milky Way and in external galaxies, and in particular the studies of chemical abundances as constraints to the evolution of the parental galaxy. Section 2 introduces the aim and goals of this type of research, Sect. 3 covers the characterization of the ages of the emission-line probes, Sect. 4 gives some examples of how PN and H II region abundances can advance our knowledge of galaxy evolution, and Sect. 5 gives an outlook on future advances of this field, especially for what the ELTs will bring to the field.

2. Constraining chemical evolution in star-forming galaxies with emission-line probes

Radial metallicity gradients of populations probing different epochs in the galactic evolution are crucial to constrain chemical evolutionary models of galaxies. PNe have been used to probe the chemistry of the old stellar populations, both in the Milky Way and in nearby galaxies, while H II regions probe the young populations. Direct abundances (i.e., through plasma diagnostics) of individual PNe are currently measurable out to distances of ∼3.5 Mpc. By comparing the metallicity (typically through oxygen abundance) of PN and H II region, one can also trace the global galactic chemical enrichment.

In Fig. 1 we show the radial metallicity gradient comparison for PN and H II regions in M33, which is the best-studied case of a star-forming galaxy. PNe and H II regions have been chosen to spatially sample the whole galactic disk, and their abundances have been measured with the direct method. The resulting gradients are similar for the old and young populations if we used binned abundances (H II regions have slightly steeper gradients than PNe if abundances are left unbinned). A similar analysis can be applied to all local galaxies where we can observe PN and H II regions in a reasonable observing time. A recent review by Bresolin (2017) indicates that, in the current scenario and for galaxies where oxygen gradients have been measured directly, the radial oxygen gradient is often flatter for PN populations than for H II regions or young stars, indicating a steepening of the gradient with time since galaxy formation.

There are challenges associated with this type of studies. First, in order to determine direct PN and H II region abundances one needs to measure the [O III] auroral λ4363 line, which can be done not much farther away than in M81 with 8m-class telescopes. Also, oxygen abundance could vary during AGB evolution; Ar and Cl are safer probes of radial metallicity for the AGB stars, but they are more difficult to measure in PNe (Delgado-Inglada *et al.* 2015). Finally, H II regions probe the ISM chemistry after the galaxy has gone through its whole evolution, and PNe probe the chemistry of the ISM at the time of the progenitor's formation, but it is difficult to date PN progenitors precisely, as illustrated in the next section.

3. Characterizing and dating the progenitors of emission-line probes

Emission-line targets probe both the young and the old stellar populations. H II regions are related to massive stars, whose look-back time is $t_\star = 0$. On the other hand, PN progenitors can be associated with a range of look-back times into the galaxy history, depending on their mass. PN progenitor mass larger than 2-4 $M_\odot$ were formed only 1 Gyr ago (depending on metallicity), thus they mark a time close to that of the H II regions, while PNe whose progenitor mass is smaller than 1.2 $M_\odot$ probe the galaxy 5 Gyr ago or earlier. We will examine a couple of current ways to date PN progenitors, an essential step toward the study of galaxy evolution through emission-line probes.

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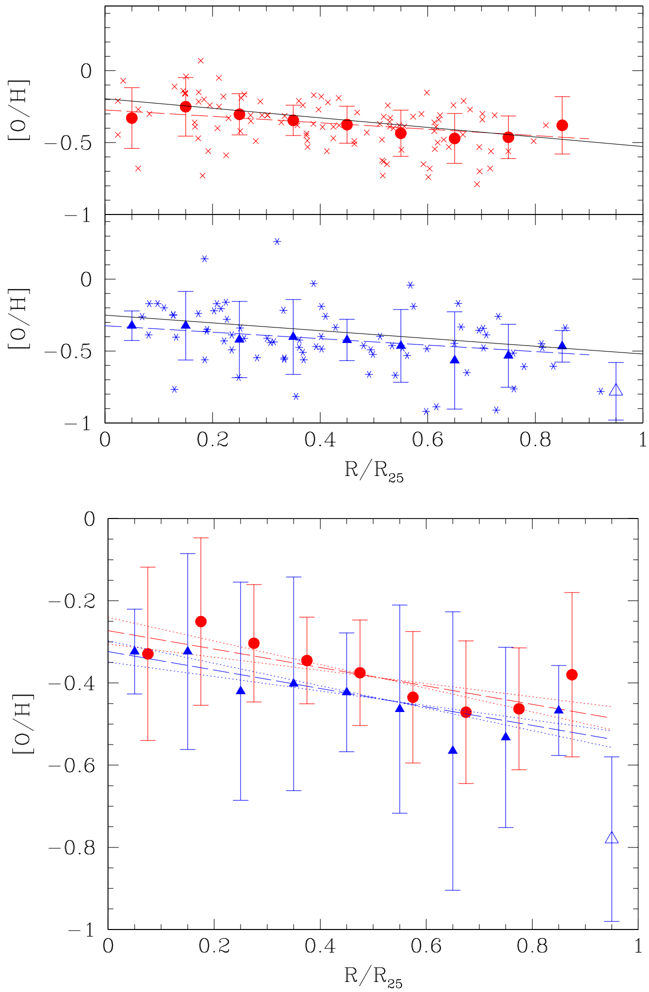

Figure 1. Radial oxygen gradients in M33. Upper panels: Individual and binned results for H II regions (top) and PNe (bottom). The continuous black lines are the gradient of Magrini *et al.* (2010) for H II regions (their whole sample) and the non-Type I PN sample of Magrini *et al.* (2009). Lower panel: weighted linear fits of PN and H II region binned metallicities [adapted from Magrini *et al.* 2016].

3.1. *Dating PN progenitors through the yields of stellar evolution*

In the galaxy and a few nearby galaxies, we can study CNO abundances of individual PNe and compare them with the final yields of stellar evolution models to determine their progenitor ages/masses, given the population metallicity. Let us compare the yields from the late thermal pulses of AGB evolution, such as those in Fig. 1 in Ventura *et al.* (2017), where the calculation is available for a broad selection of initial stellar masses and metallicities. We can select PNe whose observed abundances in the N/H vs. O/H plane correspond to yields of parent stars with $t_\star < 1$ Gyr, and those with $t_\star > 7.5$ Gyr for a broad range of metallicities. In this way we populate two distinct PN groups, one with young progenitors (YPPNe, $t_\star < 1$ Gyr) and another with old progenitors (OPPNe, $t_\star > 7.5$ Gyr). More details on this classification are given in Stanghellini & Haywood (2018). The age separation is essential for the study of the evolution of the Milky Way

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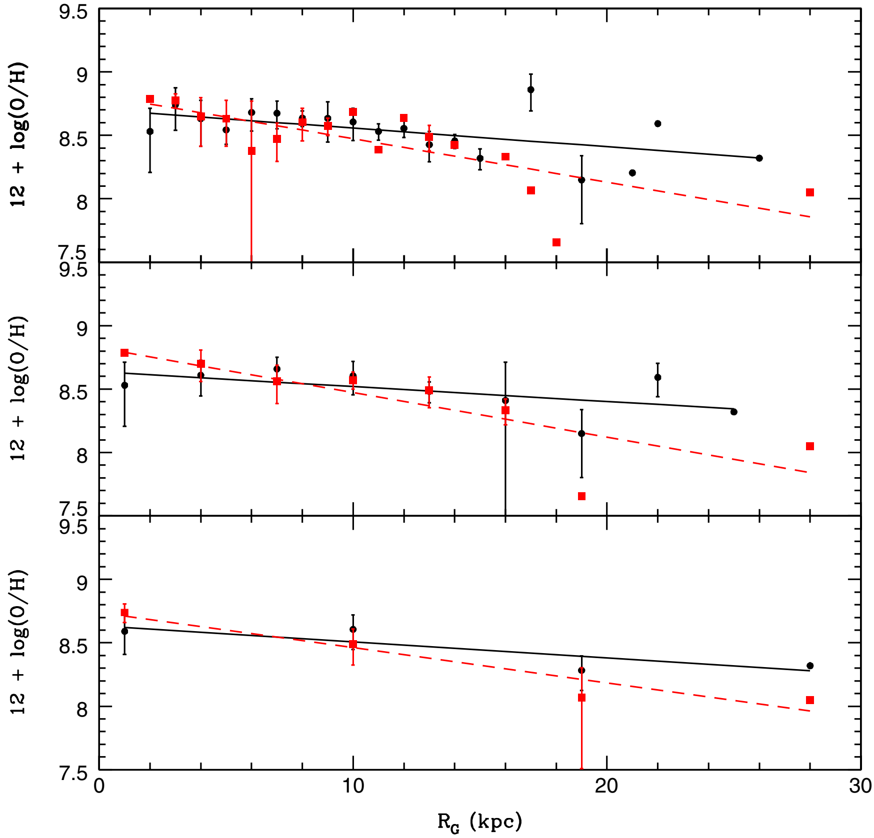

Figure 2. Binned gradients for OPPNe (filled circles and solid lines) and YPPNe (filled squares and dashed lines). Oxygen abundances have been averaged over bins of 1 (top panel), 3 (middle panel), and 9 (bottom panel) kpc. Error bars represent abundance ranges within each bin [adapted from Stanghellini & Haywood (2018)].

and can be applied to the radial metallicity gradients in the Galaxy and in nearby galaxies as well.

3.2. *The Galactic case: evolution of the radial oxygen gradient*

The age discrimination discussed in the previous section has been directly applied to a large number of Galactic PNe. Stanghellini & Haywood (2018) studied two populations of Galactic disk PNe within these progenitor age ranges and found that the radial oxygen gradient measured with YPPNe is steeper ($\Delta\log(O/H)/\Delta R_{\rm G} \sim -0.027$ dex kpc^{-1}) than the one measured with OPPNe ($\Delta\log(O/H)/\Delta R_{\rm G} \sim -0.018$ dex kpc^{-1}), meaning that the gradient has steepened since the formation of the Galaxy. In Fig. 2 we show the gradient obtained with binned data, where the difference in gradient slope between the two populations is independent on the binning and larger than the uncertainties, thus the result is robust.

3.3. *Use target dynamics to date PN progenitors*

While it is possible to date progenitors of Galactic disk PNe through their CNO abundances, this is not always possible with extragalactic PN populations farther away than the Magellanic Cloud. In external galaxies, target dynamics has proven to be the best

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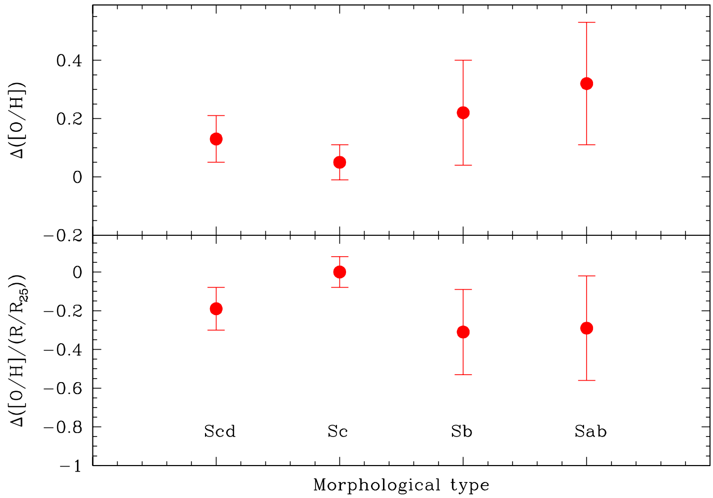

Figure 3. Global enrichment (upper panel) and variation of the slope of the radial oxygen gradient (lower panel) as a function of the morphological type. Galaxies examined are (left to right) NGC300 (Scd), M33 (Sc), M81 (Sb), and M31 (Sab) [from Magrini *et al.* (2016)].

method to determine whether the progenitors of a PN population is old or more recent. For example, Aniyan *et al.* (2018) show the separation of hot (old progenitors) and cold (young progenitors) components of the PN population in NGC628, a face-on nearby spiral galaxy, 9 Mpc away. At this distance, it would be hard to separate OPPNe and YPPNe based on their abundances. PNe in this galaxy have been classified as old or young progenitors based on their dispersions from the PN velocity histogram. Following this classification, one can study for instance the oxygen distribution of the two populations and track their evolution. Given that the PN populations are faint at this distance, it is expected that stacked spectra will be used to determine the metallicity.

4. Galactic and extra-galactic emission-line probes: constraining the chemical evolution of galaxies

The analysis of global enrichment and the radial oxygen gradients from emission-line probes in star-forming galaxies has been explored in several galaxies where the abundances have been measured directly, i.e., through plasma diagnostics. Magrini *et al.* (2016) (see Fig. 3 below) show, in the upper panel, the global oxygen enrichment respectively in (left to right) NGC300, M33, M81, and M31, measured from the relative oxygen abundances in H II regions and PNe. The result is that all studied star-forming galaxies have experienced global oxygen enrichment. The lower panel of Fig. 3 shows the differences between the H II region and PN radial oxygen gradients. For most galaxies the difference is negative (i.e., the radial oxygen gradients from H II regions is steeper than that from PNe), meaning that the gradient is steepening with time since galaxy formation. In the case of M33 the difference is negligible (see also Fig. 1). It is worth noting that the figure includes only the galaxies with plasma diagnostic abundances determined for adequate samples of H II regions and PNe, thus the trend seems universal where tested.

Another way to study these trends is to place the radial oxygen gradients on a time (or redshift) scale. In Fig. 4, the H II region radial oxygen gradients (i.e., the slopes) are placed at the redshift of their parent galaxy. On the other hand, PN populations in the Milky Way and in $z = 0$ galaxies have been placed at the equivalent redshift derived from the look-back time of the parent stellar population of the PNe. In the figure, lines are representative of inside-out chemical galaxy evolution models in a cosmological context:

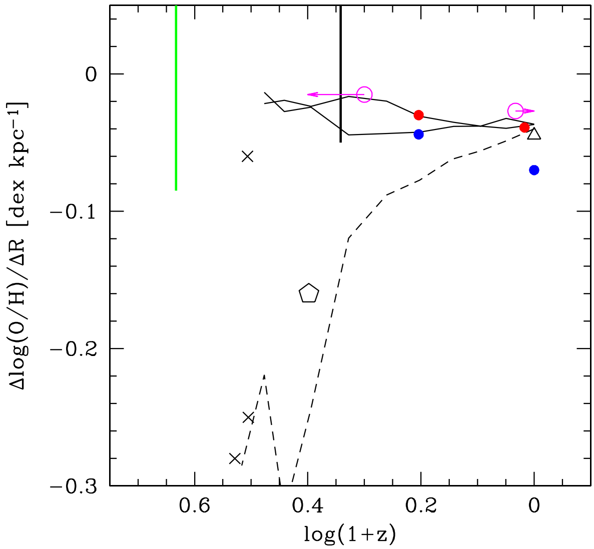

Figure 4. Radial oxygen gradient from star-forming galaxies vs. redshift. Data points: triangle is gradient slope from Galactic H II regions (Balser *et al.* 2011). Red circles: M33 PNe and H II region gradients (Magrini *et al.* 2009, Magrini *et al.* 2010). Blue circles: gradients from PNe and H II regions in M81 (Stanghellini *et al.* 2010, Stanghellini *et al.* 2014). Pentagon: Yuan *et al.* (2011). Crosses: Jones *et al.* (2013). Vertical lines: ranges of gradient slopes from Cresci *et al.* (2010) and Sánchez *et al.* (2014). Open circles: OPPNe and YPPNe (see text) [adapted from Stanghellini & Haywood (2018)].

solid lines, with enhanced feedback; dashed lines, no feedback (Gibson *et al.* 2013). Note that several of the high-redshift galaxies are lensed, thus the plot assumes that we can directly compare external (i.e., lensed) and nearby galaxies. there are a few notable exceptions to this scenario of course, which involve high-redshift galaxies and need to be addressed in the future. From this plot, we infer that measured oxygen gradients agree with enhanced feedback disk formation, and gradients are steepening with time since galaxy formation.

5. Future outlook

Radial metallicity gradient evolution in star-forming galaxies, based on direct abundances of emission-line probes, are currently available for a few nearby spirals and the Milky Way. They could be determined for a few additional galaxies with current technology but need excellent observing conditions and long exposures. PN dating is possible from the comparison of stellar evolutionary yields with observed PN abundances. In more distant galaxies, dynamical dating is also promising. We can then investigate the evolution of metallicity gradients by comparing gradients of nearby galaxies, and those of redshifted galaxies, but it is challenging to understand which $z > 1$ galaxies are comparable to nearby spirals.

Progress can certainly be made in the era of the ELTs. In multi-object spectroscopy (MOS) mode, and by using direct abundances, we can foresee that an instrument such as the WFOS for TMT can make a breakthrough. The FoV allows good sampling of galactic probes across spiral disks, making this mode ideal for this type of science. For example, spectra of the brightest PNe in M81 could be acquired in a few minutes down to auroral lines for plasma diagnostics, as opposed to the two nights used for MMT observations. Much fainter PNe and H II regions are also within reach with reasonable exposures.

Apart from the local galaxies, progress can be made by reaching out to Virgo galaxies, where the variety of galaxy types can be examined in detail for their chemical content though emission-line probes. Direct abundances in Virgo galaxies can be observed rapidly for any resolved spiral galaxy. Another approach to the problem is to populate the gradient slope-redshift diagram with near-IR IFU mode and observing $z > 1$ galaxies. Direct abundances of H II regions in galaxies with $z \sim 1.6$ may be possible ([O II] λ3727; [O III] λ4363, λ4959, λ5007; Hβ, Hα, [N II] λ6548, λ6584 are seen in YJH bands for these redshifts). Finally, for galaxies with $2 < z < 2.6$, strong-line diagnostics lines can be observed in the JHK bands.

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