Session 6: PNe in nearby galaxies and chemical evolution
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Abundances and gradients in nearby galaxies

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Abstract. The study of chemical abundance gradients can provide essential information on the evolution of disk galaxies. Here I briefly review our current observational knowledge concerning the abundances of the ionized gas (H II regions and planetary nebulae) in nearby galaxies, and how they inform us about the time evolution of metallicity gradients.

Keywords. galaxies: spiral, galaxies: evolution, ISM: abundances

1. Introduction

The study of the chemical abundances in external galaxies continues to provide an essential testbed to probe the evolution of galaxies. In particular, for spiral galaxies the radial metallicity gradients and their temporal evolution encode the mechanisms of disk formation, and reflect the presence of inflows and outflows of gas, as well as radial gas flows along the disk, and react to the redistribution of stars (migration) and of metal-enriched gas during galaxy encounters and merger activity.

For observers of the gas-phase chemical abundances, oxygen is the most easily measured tracer of metallicity in galaxies. In this contribution I will therefore use the words 'metallicity' and 'oxygen abundance' (O/H) interchangeably, and will focus on a few of the main results obtained in nearby galaxies when trying to determine observationally the evolution of galactic radial abundance gradients. These measurements constitute essential ingredients for constraining models of galaxy formation and chemical evolution.

Since this is a volume on planetary nebulae (PNe), it is worth reminding ourselves of a few important issues that should be kept in mind when using them to trace the chemical abundances of galaxies and the evolution of gradients with time, and that we can disregard when dealing with chemical abundances derived from H II regions, the most commonly used tracers of α elements in galaxies:

(a) the O abundance we measure from the spectral lines of PNe could differ from the O abundance of the interstellar medium out of which the progenitor stars originated. Mixing and/or nucleosynthetic mechanisms could both produce or destroy oxygen in the stellar progenitors. Evidence that oxygen can be produced at low metallicity has been presented by Delgado-Inglada *et al.* (2015), who suggested that other elements, in particular argon and chlorine, should be considered more reliable metallicity tracers.

(b) the initial progenitor masses of the extragalactic PNe we observe are uncertain, and so are, as a consequence, their ages. The typical masses that are inferred are 1.5–2 $M_\odot$, with corresponding ages of 2–1 Gyr, but of course PNe with slightly lower masses would correspond to ages older by several Gyr.

(c) the effects of stellar radial migration are important when comparing the abundance gradients of old ($>$ 4 Gyr) and young populations (Roškar *et al.* 2008): the gradients would appear flatter at the present time than at the time of stellar birth. In addition, migration acts in the sense of increasing the chemical abundance dispersion with age at a given radius.

Keeping in mind these issues, we can attempt to use PNe to study the history of α elements, such as O, Ne, Ar, and S, in galactic disks. Hopefully, one can obtain a picture of the history of chemical enrichment via a comparison with tracers of the young population (H II regions and massive stars, for example). Since we obtain gas-phase abundances, we should correct, if possible, the derived values for the depletion of these elements onto dust grains. For oxygen this effect is on the order of 0.1 dex (Peimbert & Peimbert 2010).

2. Brief primer on abundance gradients in spiral galaxies

It has been known for decades that spiral disks display exponential decreases, from the center to their outskirts, of light, mass and O/H abundances. Thus, using the traditional units of 12+log(O/H) for the oxygen abundances, one obtains a linearly decreasing trend with radius. The units used to express this gradients are important. Using gradients expressed in dex kpc^{-1}, physically larger spiral galaxies display flatter gradients compared to smaller disks, which finds an explanation in models of the chemical evolution of galaxies as due to a faster evolution for the most massive systems. Such a trend virtually disappears if one normalizes the radial coordinate in terms of, say, the isophotal radius R_{25} or the effective radius r_e. Although with a significant scatter, gradients expressed using these units are similar for different galaxies (Sánchez *et al.* 2014, Ho *et al.* 2015). I would like to note, however, that the result obtained using R_{25} depends on the fact that we typically study spiral galaxies that have similar surface brightness properties. Bresolin & Kennicutt (2015) have shown that low surface brightness spiral galaxies display shallower slopes when these are expressed in dex R_{25}^{-1}, as a consequence of the fact that in these galaxies the typical reduction of O/H from the low surface brightness disk center to the isophotal radius is smaller than for galaxies with higher surface brightness disks. The use of the effective radius, obtained from the exponential distribution of the light in the disk, is not subject to this bias.

The homologous behavior of the gradients described above (similar normalized gradients for all galaxies) and the fact that flatter gradients in dex kpc^{-1} are found for more massive galaxies have been known for a long time, as is the increase of the characteristic O/H value with galaxy mass (or luminosity) and local surface mass density (the mass-metallicity and luminosity-metallicity relations). Investigations of abundance gradients carried out during the past decade have focused on a variety of additional issues, some of which are listed here:

- the use of massive stars, in alternative to the ionized gas (H II regions, PNe), to trace the distribution of metals
- the study of the effect of galaxy encounters, interactions and mergers on the radial metallicity distribution
- the derivation of abundance gradients for high-redshift systems
- the investigation of the metallicity in the extended disks of spiral galaxies, well beyond the isophotal radius
- the determination of metallicity gradients in low surface brightness spirals
- the azimuthal symmetry properties of metals in galactic disks

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• the temporal evolution of the gradients, i.e. whether gradients become flatter or steeper with the evolution of the galactic disk

• the determination of the spatial chemical abundance mapping of large samples of spiral galaxies with the use of Integral Field Units in place of single- or multi-slit spectrographs.

I would also like to stress the importance of looking in regions within galaxies and at galactic systems where deviations from the pure exponential trend in the radial distribution of the metals have been found, since this informs us about interesting processes involving, for example, the interaction of spiral disks with their environment:

(*a*) in interacting galaxies the metallicity gradients can become quite shallow, a result that illustrates the radial redistribution of metals from the inner regions to the outer regions and the dilution of the inner regions as a consequence of gas flows triggered by the encounter. This effect can generate flat abundance gradients out to galactocentric distances of several tens of kpc (see, for example, Olave-Rojas *et al.* 2015).

(*b*) a number of extended disk galaxies display flat abundance gradients in their outskirts (e.g. Bresolin *et al.* 2012). The interpretation in this case involves a combination of low star formation efficiencies and the presence of an enriched gas inflow in the outer regions of the disks.

(*c*) some spiral galaxies show flatter gradients in their inner disks (e.g. Zinchenko *et al.* 2016). The mechanisms leading to this effect are poorly known, and could involve both external and secular processes.

2.1. *A word on nebular abundance diagnostics*

The determination of the chemical abundances of the ionized gas in galaxies relies on the ability of being able to characterize with sufficient accuracy the physical status of the gas, such as its temperature and density, their spatial distribution, and the properties of the ionizing field. In practice, we generally use a relatively simple picture concerning the physical status of the gas. The determination of the temperature, in particular, is critical, because the line emissivity of the forbidden, collisionally-excited lines that we typically use has an exponential dependence on it. The classical way of obtaining the electron temperature in the ionized gas involves the use of auroral lines, such as [O III]λ4363. This line is faint, and other faint lines that can also lead to a metallicity determination and have a shallower dependence on temperature, the metal recombination lines, lead to systematically higher (0.2-0.3 dex) oxygen abundances. In extragalactic H II region work one typically resorts to the use of brighter lines, and to a number of strong-line abundance diagnostics, that should be considered to have a statistical value for the metallicities they provide. A wide variety of such methods exists, with different calibration techniques, leading to very large systematic uncertainties. What is important for this review is to realize that even relative abundances can be affected, albeit to a lesser degree, and therefore the slope of the abundance gradients has a small dependence on the abundance diagnostic employed.

For these reasons it is important to i) use the same abundance diagnostic when trying to use both H II regions and PNe – this reduces the choice virtually to the auroral line method (or 'direct' method) only, since the recombination lines are too faint to be currently measured in PNe located in spiral galaxies beyond the Milky Way; ii) validate the gradients obtained using H II regions with the analysis of massive stars, since the two types of objects represent the same young galactic population. This kind of comparison has been carried out in a small number of nearby galaxies. In some cases the agreement between stellar and gaseous metallicity is excellent. For example, in NGC 300 the direct abundances obtained for H II regions by Bresolin *et al.* (2009) agree very well with the metallicity of both blue (Kudritzki *et al.* 2008) and red (Gazak *et al.* 2015) supergiant stars. Other galaxies, such as M33, show some level of disagreement, on the order of 0.2 dex. It is especially important to carry out this kind of comparison in metal-rich galaxies, since the direct method could fail, for a variety of causes, in high-metallicity environments. For this reason, recently Bresolin *et al.* (2016) have compared metallicities for blue supergiant and H II regions in the metal-rich galaxy M83. They showed that while direct abundances could underestimate the stellar abundances in the high-metallicity (solar and above) regime, there is in fact very little evidence for a systematic effect with metallicity, although one has to be careful in using strong-line methods empirically calibrated from direct abundance determinations. On the other hand, Bresolin *et al.* (2016) showed evidence that the metal recombination lines could provide chemical abundances that appear to be biased to large values in low-metallicity galaxies.

3. Time evolution of the gradients

The question of whether and how radial abundance gradient slopes evolve with time is crucial in understanding how galaxy disks evolve. Chemical evolution models predict changes that could go in either direction: gradients could become steeper or shallower with time. This result can depend on a number of factors, including the radial dependence of the star formation rate and gas infall, and the importance of feedback from supernovae and turbulence in the interstellar medium. Observationally, this issue has been addressed from two different points of view:

(*a*) study the metallicity of nearby galaxies using tracers that represent different population ages, such as young stars (OB stars, Cepheids, red and blue supergiants) or H II regions for the young age bin, and PNe and star clusters for older ages. This method is unfortunately affected by uncertainties in the ages of the old systems, such as PNe, and in their distances in the case of the Milky Way. Radial stellar migration impresses an additional level of uncertainty.

(*b*) obtain the metallicity distribution in high-redshift systems, presumably analogs or precursors of present-day spiral galaxies. In this case the limited spatial resolution has a negative impact on the technique. In addition, one needs to be sure that the young, high-redshift systems are directly comparable to the galaxies we study locally. In particular for the few lensed systems so far analyzed, a significantly steeper gradient than observed for nearby galaxies is found (Jones *et al.* 2015).

3.1. *Milky Way*

For the Miky Way the comparison between young (massive stars, H II regions) and old (PNe, open clusters) gradients during the course of the past several Gyrs has produced contradicting results, i.e. both a steepening (Stanghellini & Haywood 2010) and a flattening (Maciel & Costa 2009) of the gradient have been found to be consistent with the observational data, with additional analysis providing no evidence for either (Maciel & Costa 2013). This situation can be ascribed to uncertainties in distance and ages, and also to poor statistics.

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Table 1. Studies of galaxies with abundance gradient information from different objects.

Galaxy	HII regions	PNe	BA stars
M33	Magrini *et al.* 2007, 2010 Bresolin *et al.* 2010	Magrini *et al.* 2009 Bresolin *et al.* 2010	Urbaneja *et al.* 2005 U *et al.* 2009
M31	Zurita & Bresolin 2012 Sanders *et al.* 2012	Sanders *et al.* 2012	Trundle *et al.* 2002 Venn *et al.* 2000 Przybilla *et al.* 2006
NGC 300	Bresolin *et al.* 2009	Stasinska *et al.* 2013	Kudritzki *et al.* 2008
M81	Stanghellini *et al.* 2010, 2014 Patterson *et al.* 2012	Stanghellini *et al.* 2010	Kudritzki *et al.* 2012

As mentioned before, chemical evolution models can produce both a flattening or a steepening of the gradient. An example of a model that produces a flattening is presented in the work by Kubryk *et al.* (2015), which also illustrates the effects of radial stellar migration on the gradient measured using old stars. This kind of flattening with time is in agreement with several other models present in the literature (e.g. Mollá 2014, Tissera *et al.* 2016). Recent CALIFA data also provide weak evidence for a steeper gradient in old (age $>$ 6 Gyr) stellar populations compared to young (age $<$ 2 Gyr) stars (Sánchez-Blázquez *et al.* 2014).

Recently Anders *et al.* (2016) (see also Xiang *et al.* 2015) used asteroseismology and spectroscopic data of field red giant stars to derive their distances and stellar parameters. They derived an evolution of the gradient with the age of the stars, which goes in the sense that the gradient appears *steeper* at the present time than it did Gyrs ago. This evolution is consistent with models in which the flattening at large lookback time is due to stellar radial mixing and migration.

3.2. *External galaxies*

The comparison betwen young and older gradients is in principle facilitated by examining an external galaxy, where distance uncertainties do not represent a problem, but unfortunately the issue of uncertain ages remains. At the same time, the change in the slope of the gradients predicted by models during the evolution of galaxies of the past few Gyrs is quite small, meaning that the empirical answer is understandably still rather uncertain.

As recently summarized by Magrini *et al.* (2016), there are only four spiral galaxies where the abundance gradients in the disk have been obtained for both H II regions and PNe using the direct method: M33, M31, NGC 300 and M81. Table 1, adapted from their paper, summarizes the references used for the ionized gas work. For the same galaxies we also have information on the massive star metallicities from different authors, as included in the last column of the table.

Fig. 1, also adapted from Magrini *et al.* (2016), but including also the results from the stellar work, shows the difference in the gradient slope, relative to the PN value and expressed in dex R_{25}^{-1}, for both H II regions (full circles) and massive stars (star symbols). The galaxies have been ordered by stellar mass, increasing from left to right. It can be seen that the data are consistent, in all cases, with a negative value of the slope difference, which means that the young population appears to provide a steeper gradient than the PNe. There are some issues, that cannot be dicussed in depth here. For example, the stellar metallicity gradient for M33 is significantly steeper than the abundance gradient from H II regions. Also, for the two most massive galaxies, M81 and M31, the stars indicate a flatter gradient than the H II regions, and in better agreement

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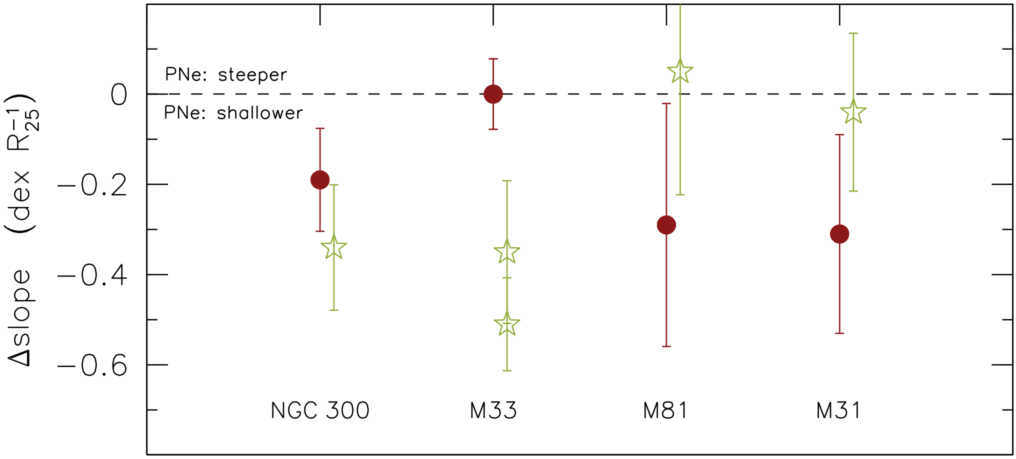

Figure 1. Difference in the abundance gradient slope, expressed in dex R_{25}^{-1}, as measured between H II regions and PNe (full circles) and young stars and PNe (star symbols), for the four galaxies of Table 1. The two stellar values for M33 refer to the works by Urbaneja *et al.* (2005) and U *et al.* (2009). For M31 the stellar-based slope comes from Trundle *et al.* (2002). (Partially adapted from Magrini *et al.* 2016).

with the PNe. In essence, however, the data presented in Fig. 1 shows that there is an indication, albeit weak, that the gradient has evolved into a steeper slope with age. Of course, the sample size is very limited. I should also add that it is possible that galaxies have evolved differently in relation to their environment, with different star formation rates and gas flow properties, and so it is conceivable that we should not expect this to be a general result, valid for all spiral galaxies.

Having shown the empirical result, it is interesting to consider what the galaxy evolution models predict as to the amount of slope change we could expect when comparing young populations with PNe. In order to try and answer this question one could take tailored models for some of the galaxies in Table 1. For example, Spitoni *et al.* (2013) produced a model of the evolution of the gradient with age for the galaxy M31, finding that the slope steepens with time. If we take a representative age for the PNe of 5 Gyrs, the estimated predicted change from these models is ~0.15 dex R_{25}^{-1}, which is in fact smaller than the size of the errorbars in Fig. 1. Similarly for NGC 300, the models by Kang *et al.* (2016) predict that in the main disk of the galaxy there should be quite a small change in the gradient slope, this time flattening with time. In these two models and similar ones the chemical enrichment that occurred between a few Gyrs ago and the present time is on the order of 0.1 dex, which is roughly consistent with the change in the zeropoint of the gradients for the four galaxies examined by Magrini *et al.* (2016).

The small steepening of the gradients for the galaxies in Table 1 is also consistent with the cosmologically-motivated models presented by Gibson *et al.* (2013) and calculated with an enhanced prescription for the feedback from SNe, that predict a very small evolution of the gradients with time. These are, however, at variance with the much stronger evolution needed to explain, with a smaller feedback, the steep gradients measured for a few high-redshift systems. Such tension is exacerbated by observations of stellar clusters in M33 by Beasley *et al.* (2015), that also indicate a strong flattening of the metallicity gradient in this galaxy with time, in contrast with the results shown in Fig. 1.

In summary, different abundance and age tracers can produce opposite results when considering the evolution of the gradients. This can only partly be explained by age uncertainties and the small effect we are trying to measure.

4. PNe in the outer disk of M31

Although the PN population of M31 is discussed more in depth elsewhere in this volume, it is worth to briefly consider this system as an example of the diagnostic power of PNe to probe the α-element evolution in galaxies and the importance of the outskirts of galactic disks to constrain the evolutionary status of spirals. Recent work on the outer disk PN population in M31 has recently been published by Kwitter *et al.* (2012), Balick *et al.* (2013), Corradi *et al.* (2015) and Fang *et al.* (2015). These authors assume, for example based on kinematical information, that these PNe belong to the disk rather than the halo. While a few might actually not belong to the disk of the galaxy, these studies have shown an important number of PNe extending to galactocentric distances of 100 kpc or more, i.e. well beyond the isophotal radius. The abundance properties of these PNe are quite interesting, in that they deviate significantly from the radial trend described by young stars and H II regions in the inner disk, extrapolated to large radii. The radial abundance distribution of the PNe in the outer disk is virtually flat, with a mean O/H value only slightly ($\sim$0.2 dex) below solar. This behavior is in fact reminiscent of the cases presented at the end of Sect. 2, where deviations from a pure exponential decrease of the metallicity with radius were briefly introduced. The idea put forward by Balick *et al.* (2013) that a past galaxy encounter could explain the metallicity trend is consistent with that discussion.

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