Asymptotic giant branch evolution and its impact on the chemical evolution of the Milky Way and the Magellanic Clouds

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ABSTRACT

The asymptotic giant branch (AGB) phase of stellar evolution is common to most stars of low and intermediate mass. Most of the carbon and nitrogen in the Universe is produced by AGB stars. The final fate of the AGB envelopes are represented by planetary nebulae (PN). By studying PN abundances and compare them with the yields of stellar evolution is possible to quantify carbon and nitrogen production, and to study cosmic recycling in galactic and Magellanic Cloud populations. In this paper we present the latest results in PN chemical abundance analysis and their implication to the chemical evolution of the galaxy and the Magellanic Clouds, with particular attention to carbon abundance, available only thanks to ultraviolet spectroscopy.

Key words: UV astronomy, AGB and post-AGB stars, planetary nebulae, carbon abundance

1. Introduction

Low- and intermediate-mass stars ($M_{\text{MS}} \sim 0.8 - 8 \, M_\odot$, where $M_{\text{MS}}$ is the main sequence mass) and their ejecta are excellent probes of stellar populations in galaxies, and have been detected in all types of galaxies as well as in the intracluster space. Stars in this mass range constitute a major component (by mass) of the stellar material in the Universe, thus a correct understanding of their evolution in different environments has the potential to advance many astrophysical fields. Furthermore, these stars play a fundamental role in cosmic recycling, being major contributors to the carbon and nitrogen abundances for the next generation of stars. Stars in this mass range go
through the asymptotic giant branch (AGB) phase, and through their evolution they
enrich the interstellar medium with helium, carbon, nitrogen, and other elements.
Typically the abundances of oxygen, argon, and neon are unaffected during AGB
evolution in most stars, thus these elements can be used to probe the environment at
the time of progenitor formation.

The AGB phase is characterized by the periodicity of nuclear burning phases and
dredge-up phases, and, as a result, the products of stellar evolution are carried to
the stellar outer layers. Planetary nebulae (PN) are the stellar envelopes of AGB
stars, ejected at the tip of the AGB, carrying the products of stellar evolution to
the interstellar medium. Thus by analyzing PN abundances one can constraint the
AGB evolutionary models, and the environment at the time of the formation of the
AGB progenitors. Since the models of stellar evolution predict that the chemical
yields form AGB stars depend on initial stellar mass and metallicity, large samples of
PN and in different metallicity environments should be compared with evolutionary
models to obtain the best constraints. Since PN are ubiquitous and bright, and
easily recognizable due to their unique spectra, they are ideally suited to probe AGB
evolution and populations in nearby galaxies. In this paper we present the state of
the art of planetary nebulae abundance analysis in the Galaxy and the Magellanic
Clouds, in particular the impact of model constraining through carbon abundance,
as derived from ultraviolet spectroscopy. We review large and homogeneous data sets
that we used for our analysis, both for the Galaxy (§2) and the Magellanic Clouds
(§3). We also present the comparison with the corresponding stellar evolution models.
A look at the galactic disk population and the gradients of elements in the galactic
disk is shown in §4. In §5 we give a summary of the results, and describe the future
challenges of this field.

2. Galactic planetary nebulae

Abundances of planetary nebulae in the Milky Way disk and bulge have been derived
by many Authors. Here we focus on large, homogeneous data sets that have been
published recently ([1], [2], [3], and [4]). Individual abundances calculated by these
Authors may be different by as much as 20 %, but the differences can be ascribed, for
the most part, to different ionization correction factors (ICF). Averages of elemental
abundances are also very different across these papers, for the reason that some Au-
thors include bulge PN in the galactic averages, while others [4] distinguish the bulge
contaminants from the disk PN analyzed. For example, the average oxygen abundance
for the whole samples presented in papers [2], [3], and [4] are respectively 5.6×10^{-4},
4.3×10^{-4}, and 3.5×10^{-4} (in terms of O/H, by number). If we chose to compare
only the common PN the averages converge respectively to 3.7×10^{-4}, 3.9×10^{-4}, and
3.5×10^{-4}, with ranges of the order of σ ∼ 2 × 10^{-4}. The bulge PN have been statisti-
cally analyzed by Exter and collaborators [5]. In the following analysis we privilege
the sample of papers [4] and [5], respectively for the galactic disk and bulge, using the
Figure 1: Log (N/O) versus log (O/H) for galactic disk PN. Open symbols: non type I PN; filled symbols: type I PN. Lines: models [7] for z=0.0126, 0.0159, 0.02, 0.0252, and 0.00317 respectively from right to left.
data of paper [4] for the disk since it excludes explicitly the bulge population, and it is homogeneously chosen from the IAC morphological catalog of PN [6]. For carbon abundances in galactic PN we use selected data from [2], and references therein.

In Table 1, columns 3 and 4, we give the average abundances of key elements, in terms of the hydrogen abundance, for the galactic bulge and the disk PN. In parenthesis we give the range of the selected diagnostic. We define as type I PN those nebulae whose N/O has been enriched with respect to the Orion nebula. Determination of carbon abundances for bulge PN are sparse, thus we do not report their average. The data show that the oxygen abundance is higher in bulge than in disk PNe, with an offset of about 0.1 dex, while the difference in helium abundance is much lower. Nitrogen is also more abundant on average in the bulge, making the N/O ratio almost identical in the two environments.

In Figure 1 we show the N/O versus O/H relation for all the galactic disk PN analyzed in [4]. This plot is a good diagnostics to check weather the nitrogen in AGB stars is produced by ON cycle. In this case, oxygen would be destroyed to produce nitrogen, and a strong anti-correlation should be detected between these two ratios. The plot shows a large spread of oxygen abundances, as expected in the galactic disk, and the models by [7] for $M_{MS} < 8 M_\odot$ lead the eye to show that oxygen depletion occurs as nitrogen is produced, especially in type I PN.

In Figure 2 we show the diagnostic evolutionary plot of N/O versus He/H again for galactic disk PN, showing very clearly that the type I PN correspond to the locus of the high mass models ($M_{MS} > 4.5 M_\odot$ in Marigo’s [8] models). The C/O versus N/O diagram for galactic disk PN would be sparsely populated. Carbon abundances derive from UV lines of IUE spectra, and more recent carbon determination for disk PN are unavailable.

3. Magellanic Cloud planetary nebulae

Abundances of the most common elements except carbon have been acquired over the past by several Authors ([9], [10], [11], [12]). On the other hand, only a handful of carbon abundance determinations were available [13] until recently. Together with my collaborators we started a series of HST observations aimed at expand the dataset of carbon abundances in LMC and SMC PN. For the LMC, among about 350 PN known [14] only 20 IUE spectra are available, with only 10 sound carbon abundance determinations [13]. We increased this sample by observing 24 LMC PN with STIS [15]. The SMC is also poorly sampled, with only 12 IUE spectra for 60 SMC PN known [16]. We have obtained 12 ACS prism spectra and were able to determine the carbon lines. Our work on SMC PN carbon determination is in preparation. The STIS UV spectra of LMC PN show that the volume where the carbon emission originates is the same that the volume where the hydrogen recombination lines and the oxygen forbidden lines originate as well [15], and the morphology of the nebulae is the same through the UV and the optical lines.
Figure 2: The relation between N/O versus He/H, for galactic disk PN (data from [4]). Open circles: non type I PN; filled circles: type I PN; stars indicate models [8] with $M_{\text{MS}} < 4.5M_{\odot}$; large stars with $M_{\text{MS}} > 4.5M_{\odot}$. 
The references above were used to obtain the averages of the elemental abundances of Magellanic Cloud PN in Table 1, columns (5) and (6). The carbon abundances for the LMC includes the samples published in [13] and [15], while the SMC carbon average only includes the SMC PN in [13].

| Element | Bulge | Disk | LMC | SMC |
|---------|-------|------|-----|-----|
| He/H | whole sample | 0.11 (0.03) | 0.12 (0.04) | 0.10 (0.03) | 0.09 (0.02) |
| | type I | 0.12 | 0.15 | 0.11 | 0.09 |
| | non type I | 0.11 | 0.11 | 0.10 | 0.09 |
| C/H \(10^4\) | whole sample | ... | 5.7 (6.5) | 3.3 (3.5) | 4.3 (2.5) |
| N/H \(10^4\) | whole sample | 2.7 (2.3) | 2.4 (3.5) | 0.94 (0.94) | 0.41 (0.31) |
| O/H \(10^4\) | whole sample | 4.6 (1.2) | 3.5 (2.0) | 2.1 (1.1) | 0.99 (0.84) |
| | type I | 4.3 | 3.1 | 1.8 | 0.48 |
| | non type I | 4.7 | 3.7 | 2.4 | 1.2 |
| N/O | whole sample | 0.68 | 0.66 | 0.66 | 1.1 |
| | type I | 1.1 | 1.9 | 1.3 | 2.9 |
| | non type I | 0.35 | 0.32 | 0.22 | 0.13 |

By examining Table 1 we see that the oxygen abundance is, on average, decreasing from the galaxy to the LMC and the SMC, as expected. We continue seeing the oxygen to be depleted in type I PN, as possible consequence of the ON cycle activity. We also notice low helium abundances in LMC and, to a larger extent, SMC PN. Finally, carbon production is less efficient, on average, in the Magellanic Cloud PN with respect to the galaxy. We should note that preliminary analysis of our ACS prism spectra seem to indicate that carbon production in SMC PN is similar, and not larger, than that of LMC PN.

In the two upper panels of Figure 3 we show the N/O versus O/H plot for Magellanic Cloud PN. It is remarkable how the oxygen gets depleted in nitrogen rich type I SMC PN, while the effect is much milder in the LMC PN. It looks like whatever the mechanism at work, possibly the ON cycle, it is much more efficient at low metallicities than predicted by Marigo’s models [8].

By examining the carbon and nitrogen production in LMC and SMC PN (lower panels of Figure 3) we note that in both galaxies the effect of carbon depletion in favor of nitrogen enrichment is noticeable. The models by [8] for the LMC and the SMC PN are also shown in the figure. We note that the low mass models well encompass...
the non type I PN locus, while for higher masses the models are not adequate. Some other mechanisms must be at work that deplete the nitrogen (or better the N/O ratio) in type I PN.

4. Probing stellar populations

Another very important aspect of abundance analysis in planetary nebulae is the study of the elements that are not affected (or mildly affected) by stellar evolution. Recent models (e.g., [7], [8]) predict that at galactic metallicities oxygen, neon, and argon should not vary considerably during the evolution of these stars through the AGB, at least in the lower mass range. These elements are thus probes of the galactic chemical evolution, and of the environment at the epoch of progenitor formation. We use here the sample of abundances derived in [4] to explore the relations between these elements, and to determine galactic gradients and their evolution though time.

We used the oxygen and the neon abundances of PN to determine the metalicity gradients in the galactic disk. For this study it is essential to exclude bulge PN from the samples, since bulge PN may tip the gradients given their average higher metallicity, as seen in table 1. The gradients from the sample of [4] are shown in Figure 4. We derived gradients of the order of -0.01 dex kpc$^{-1}$ for oxygen and neon. These gradients agree with other recent independent determinations of galactic gradients from PN [17], as long as the PN sample adopted did not include bulge contaminants. Given that the PN gradients are rather flat, and that PN represent the progeny of evolved stars, this picture does not reconcile with flattening of galactic metallicity gradients with time.

Since models of AGB evolution show that nitrogen is enriched especially in high mass AGB stars via ON cycle, we can use the nitrogen abundance to select a more massive sample of PN, and to show the differences in gradients through the galactic disk. We found no noticeable differences between gradients of type I and non type I PN, indicating an overall invariance of gradients with time.

5. Conclusions and future challenges

Stellar evolution of low- and intermediate-mass stars is well probed by studying AGB stars and their remnants. In this paper we have shown how diagnostic abundance plots of PN can be used to constraint stellar evolution through the AGB. Carbon abundances offer a further challenge, since the carbon emission lines correspond to the UV part of the spectra. The Magellanic Cloud PN allow the comparison with stellar evolution models at lower metallicities. We have shown that the bulge oxygen and nitrogen abundances are higher, on average, than those of the galactic disk, suggesting the existence of two distinct stellar populations. We have also shown that the galactic disk population presents a very large spread in environment metallicity (or metallicity at the formation of the progenitors), and that galactic disk PN have an
Figure 3: Diagnostic diagrams for LMC (left panels) or SMC (right panels) PN. Small stars are $M_{\text{MS}} < 3.5$ (LMC) or 3.0 $M_\odot$ (SMC) models from [8]; Large stars represent models with $M_{\text{MS}} > 3.5$ (LMC) or 3.0 $M_\odot$ (SMC).
effective ON cycle, especially at low metallicity. This result is somehow strengthened by the analysis of LMC and SMC PN, where the destruction of oxygen in favor of nitrogen appears clear for SMC PN of type I. The N/O versus C/O (and versus He/H) diagnostic plots indicate that the type I PN are the remnant of the evolution of more massive AGB stars. For the Magellanic Cloud PN the diagrams are sparsely populated, and new data of carbon abundances are essential for model constraining at low metallicity. Galactic gradients of oxygen and neon have been found to be shallow, in agreement with other recent and independent PN gradient studies.

The major future challenge in the field of AGB and post-AGB evolution is twofold: on the theoretical side, models should take into account the fraction of AGB stars that are within a binary system, and account for yields of binary evolution; on the observational side, the acquisition of larger, homogeneous sets of UV spectra to determine carbon and neon abundances in galactic and local group PN would be essential for progress in this field. The study of gradients could be extended also to other local group galaxies. Finally, PN have been observed also outside galaxies, in the intracluster medium. A better characterization of these extragalactic sources would be essential to constraint the mass of dark halos in galaxies [18], and to determine whether the evolution of these peculiar PN is different [19] from that of galactic PN.

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