Revista Mexicana de Astronomía y Astrofísica, **45**, 127–137 (2009)

PLANETARY NEBULAE AND THE CHEMICAL EVOLUTION OF THE MAGELLANIC CLOUDS

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Received 2009 February 16; accepted 2009 April 16

RESUMEN

La determinación precisa de las abundancias químicas en las nebulosas planetarias (PN) de diferentes galaxias nos permite obtener importantes límites para los modelos de evolución química en estos sistemas. Tenemos un programa a largo plazo para derivar abundancias en las galaxias del Grupo Local, en particular, la Nube Mayor y la Nube Menor de Magallanes. En este trabajo presentamos nuestros resultados para estos objetos,y discutimos sus implicaciones en el contexto de nuevas determinaciones de abundancias reportadas en la literatura. En particular, obtenemos correlaciones independientes de la distancia que involucran al He, N, O, Ne, S y Ar, comparamos los resultados con datos sobre nuestra propia galaxia y otras del Grupo Local. Como resultado de nuestras observaciones, hemos obtenido una gran base de datos, por lo cual podemos obtener límites confiables a los procesos de nucleosíntesis en las estrellas progenitoras en galaxias de diferentes metalicidades.

ABSTRACT

The determination of accurate chemical abundances of planetary nebulae (PN) in different galaxies allows us to obtain important constraints on chemical evolution models for these systems. We have a long-term program to derive abundances in the galaxies of the Local Group, particularly the Large and Small Magellanic Clouds. In this work, we present our new results on these objects and discuss their implications in view of recent abundance determinations in the literature. In particular, we obtain distance-independent correlations involving He, N, O, Ne, S, and Ar, and compare the results with data from our own Galaxy and other galaxies in the Local Group. As a result of our observational program, we have a large database of PN in the Galaxy and the Magellanic Clouds, so that we can obtain reliable constraints on the nucleosynthesis processes in the progenitor stars in galaxies of different metallicities.

Key Words: galaxies: abundances — galaxies: individual (Magellanic Clouds) — ISM: planetary nebulae: general

1. INTRODUCTION

The study of the chemical evolution of the galaxies in the Local Group, particularly the Milky Way and the Magellanic Clouds, can be significantly improved by the consideration of the chemical abundances of planetary nebulae (PN) (see for example Maciel, Costa, & Idiart 2006a; Richer & McCall 2006; Buzzoni, Arnaboldi, & Corradi 2006; Ciardullo 2006). These objects are produced by low and intermediate mass stars, with main sequence masses roughly between 0.8 and 8 $M_\odot$, and present a reasonably large age and metallicity spread. Hence, they provide important constraints on the chemical evolution models applied to these systems, and can also be used to test nucleosynthetic processes in the PN progenitor stars. In particular, the PN abundances in the nearby Magellanic Clouds can be derived with a high acuracy, comparable to that of objects in the Milky Way, so that they can be especially useful in the study of the chemical evolution of these galax-

TABLE 1

AVERAGE ABUNDANCES OF PN IN THE MAGELLANIC CLOUDS

	He	O	S	Ar	N	Ne
IAG/USP						
SMC	0.097 ± 0.035	7.89 ± 0.44	6.98 ± 0.58	5.59 ± 0.36	7.35 ± 0.49	7.14 ± 0.42
LMC	0.119 ± 0.023	8.40 ± 0.20	6.72 ± 0.31	6.01 ± 0.25	7.69 ± 0.50	···
Stasińska						
SMC	0.094 ± 0.025	7.74 ± 0.50	···	···	7.46 ± 0.37	7.10 ± 0.40
LMC	0.090 ± 0.032	8.10 ± 0.31	···	···	7.76 ± 0.45	7.44 ± 0.41
Leisy						
SMC	0.093 ± 0.025	8.01 ± 0.29	6.86 ± 0.67	5.57 ± 0.27	7.39 ± 0.47	7.14 ± 0.36
LMC	0.105 ± 0.035	8.26 ± 0.35	7.13 ± 0.67	5.99 ± 0.26	7.77 ± 0.57	7.46 ± 0.48
Orion	0.098 ± 0.004	8.55 ± 0.07	7.02 ± 0.10	6.52 ± 0.18	7.78 ± 0.12	7.82 ± 0.16
Sun	0.092 ± 0.009	8.80 ± 0.11	7.26 ± 0.08	6.48 ± 0.11	7.97 ± 0.07	8.08 ± 0.01
30 Dor	0.087 ± 0.001	8.33 ± 0.02	6.84 ± 0.10	6.09 ± 0.10	7.05 ± 0.08	7.65 ± 0.06
NGC 346	···	8.15	6.40	5.82	6.81	7.32

ies. In this work, we present some recent results on the determination of chemical abundances from PN in the Large and Small Magellanic Clouds derived by our group, and compare these results with recent data from our own Galaxy and other galaxies in the Local Group. We also take advantage of the inclusion of similar determinations from the recent literature, so that the database of PN in the Magellanic Clouds is considerably increased, allowing a better determination of observational constraints on the nucleosynthetic processes ocurring in the progenitor stars. Preliminary results of this work have been presented by Maciel et al. (2006a, 2008).

2. THE SAMPLE

We have considered a sample of PN both in the LMC and SMC on the basis of observations secured at the 1.6 m LNA telescope located in southeast Brazil and the ESO 1.5 m telescope in La Silla, Chile. Details of the observations and the resulting abundances can be found in the following references: de Freitas Pacheco et al. (1993a), de Freitas Pacheco, Costa, & Maciel (1993b), Costa, de Freitas Pacheco, & Idiart (2000), Idiart, Maciel, & Costa 2007). In these papers, abundances of He, N, O, S, Ne and Ar have been determined for 23 nebulae in the LMC and 46 objects in the SMC. The abundances presented in Idiart et al. (2007) were based on average fluxes obtained by taking into account some recent results from the literature, so that there may be some differences compared with our originally derived values. For details the reader is referred to the discussion in that paper.

In order to increase the PN database in the Magellanic Clouds, we have also taken into account the samples by Stasińska, Richer, & McCall (1998), which included abundances of He, N, O, and Ne for 61 nebulae in the SMC and 139 objects in the LMC, and Leisy & Dennefeld (2006), containing 37 objects in the SMC and 120 nebulae in the LMC. In Stasińska et al. (1998), a collection of photometric and spectroscopic data of PN in five different galaxies, including the Magellanic Clouds, was obtained. Although the original sources of the data are rather heterogeneous, the plasma diagnostics and determination of the chemical abundances were processed in the same way, so that the degree of homogeneity of the data was considerably increased. The Leisy & Dennefeld (2006) sample is a more homogeneous one, in which a larger fraction of the observations were made by the authors themselves, and all abundances were re-derived in an homogeneous way, as in Stasińska et al. (1998). As we will show in the next section, the similarity of the methods in the abundance determinations warrants comparable abundances, so that a larger sample was obtained.

3. RESULTS AND DISCUSSION

3.1. *Average abundances*

Average abundances of all elements in the SMC and LMC according to the three samples considered are shown in Table 1. Helium abundances are given as He/H by number as usual, while for the heavier elements the quantity given is $\epsilon(\mathrm{X}) = \log\ \mathrm{X/H} + 12$. Although the samples considered here are probably the largest ones with carefullly derived abundances in the Magellanic Clouds, they cannot be considered as complete. The total number of PN in these systems is not known, but recent estimates point to about 130 and 980 objects for the SMC and LMC, respectively (cf. Jacoby 2006 and Shaw 2006). Therefore, incompleteness effects may still affect the results presented in this paper.

The He abundances show a good agreement in all samples within the average uncertainties. The IAG and Leisy samples show a slightly higher He abundance in the LMC compared to the SMC, but the differences between these objects are in all cases smaller than the estimated uncertainties.

The O/H abundances, which are in general the best determined of all heavy elements considered here, also show a good agreement among the samples. Moreover, in all cases the LMC is richer than the SMC, as expected, and the average metallicity difference is in the range 0.3 to 0.5 dex, which is consistent with the metallicities given by Stanghellini (2009), namely $Z = 0.004$ and $Z = 0.008$ for the SMC and LMC, respectively.

The Ar/H and Ne/H ratios show a behaviour similar to O/H, noticing that the IAG data do not include Ne abundances for the LMC, and that Stasińska et al. (1998) do not list Ar/H abundances for both galaxies. The sulfur abundances seem to be less reliable, as can be seen from the large standard deviations obtained in the IAG and Leisy & Dennefeld (2006) samples. Moreover, the estimated average S/H ratio in the SMC is slightly larger than in the LMC according to the IAG data, contrary to our expectations, while in the Leisy & Dennefeld (2006) sample the LMC abundance is larger by only 0.27 dex in comparison with the SMC. In fact, these characteristics of the sulfur abundances in Magellanic Cloud PN can be observed in previous analyses, as for example in the summary by Kwok (2000, Table 19.1, p. 202), where the S/H ratios in the SMC and LMC are indistinguishable within the given uncertainties. Clearly, the determination of S/H abundances in the Magellanic Cloud PN –and galactic nebulae as well– is apparently affected by some additional effects, as compared to the previous elements. In the following we will give further evidences on the problem of sulfur abundances in planetary nebulae.

From Table 1, it can be seen that the nitrogen abundances also follow the same pattern as O/H,

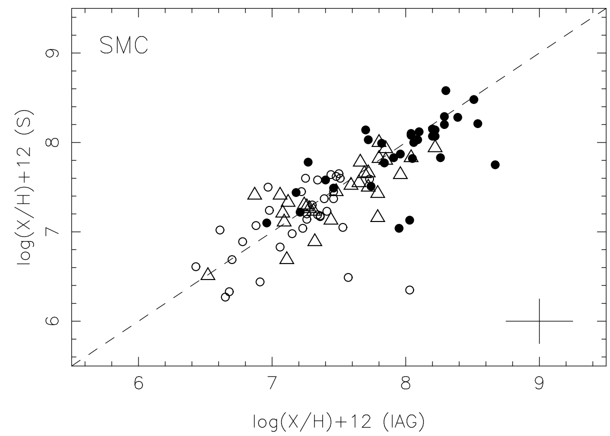

Fig. 1. Abundances of O/H (solid dots), N/H (empty triangles) and Ne/H (empty circles) from the sample by Stasińska et al. (1998) as a function of data from the IAG/USP group for the SMC.

Ar/H, and Ne/H, even though the N/H ratio is affected by the dredge-up episodes occuring in the PN progenitor stars. This is further discussed in § 5, but from the results shown in the last column of Table 1, it is suggested that the average nitrogen contamination from the PN progenitor stars is small. Average N/H abundances of Magellanic Cloud PN are given by Stanghellini (2009), where an effort was made to take into account objects of different morphologies. The average N/H abundances in the whole sample are 1.48×10^{-4} and 0.29×10^{-4} for the LMC and SMC, respectively, which correspond to $\epsilon(\mathrm{N}) = 8.17$ and 7.46, in the notation of Table 1. These results correctly indicate that the LMC is richer in N than the SMC, as also reported in Table 1, and the absolute value of the SMC abundances given by Stanghellini (2009) is very similar to the results of the three samples considered here, but the average abundance for the LMC nebulae is much higher than our results. In fact, the N/H abundances of the LMC given in Stanghellini (2009) are close to the Milky Way values, which is paradoxical, as the LMC has a much lower metallcity than the Galaxy. Part of the discrepancy may be caused by the fact that the sample used in that paper includes a larger proportion of bipolar nebulae, which are ejected by higher mass progenitor stars, which produce a larger nitrogen contamination than the lower mass objects. This problem needs further clarification.

3.2. *Abundances of individual nebulae*

In order to illustrate the internal agreement of the three PN samples considered in this work, we present in Figures 1 and 2 the abundances of O/H (solid

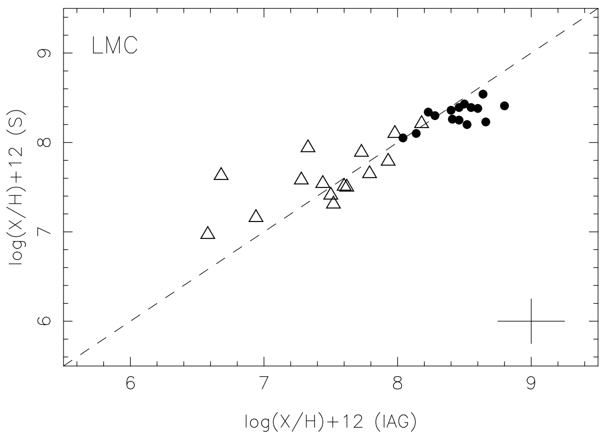

Fig. 2. The same as Figure 1 for the LMC. No Ne/H data are available in the IAG sample for this galaxy.

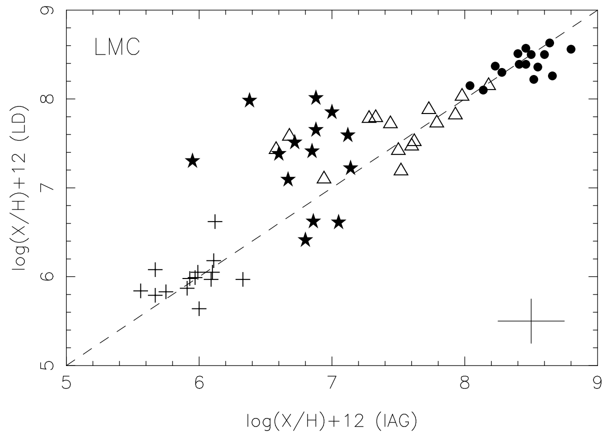

Fig. 4. The same as Figure 3 for the LMC. No Ne/H data are available in the IAG sample.

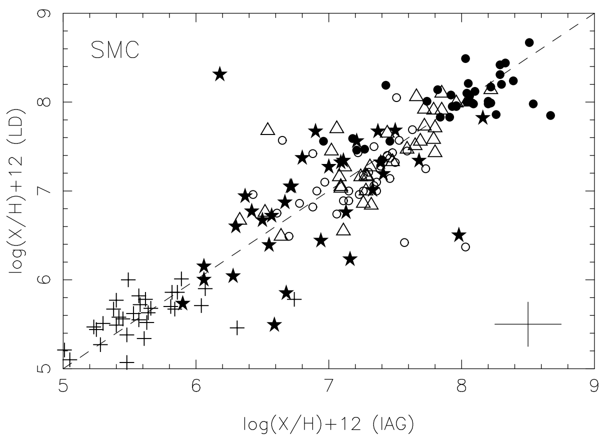

Fig. 3. Abundances of O/H (solid dots), S/H (stars), Ar/H (crosses), N/H (empty triangles), and Ne/H (empty circles) from the sample by Leisy & Dennefeld (2006) as a function of data from the IAG/USP group for the SMC.

dots), N/H (empty triangles) and Ne/H (empty circles) as derived by Stasińska et al. (1998) as a function of the IAG/USP data, for the SMC and LMC nebulae, respectively. The same comparisons are shown in Figures 3 and 4 taking into account the data by Leisy & Dennefeld (2006), in which case we also include abundances of S/H (stars) and Ar/H data (crosses). An average error bar is included at the lower right corner of the figures. The agreement of both samples with our own data is generally very good, within the average uncertainties of the abundance data, which are about 0.1 to 0.2 dex for the best derived abundances, and of 0.2 to 0.3 for the less accurate element ratios. Some scatter is to be expected, especially taking into account that the abundances of several nebulae are flagged as uncertain (:) by Leisy & Dennefeld (2006). The main discrepancies between the IAG data and the results by Stasińska et al. (1998) occur for a few objects in the SMC, for which our O/H and Ne/H abundances differ by an amount larger than the average uncertainty (cf. Figure 1), while for the LMC a small group of nebulae have higher N/H abundances as derived by Stasińska et al. (1998) (cf. Figure 2). Concerning the Leisy & Dennefeld (2006) sample, the main discrepancies are restricted to some S/H data, as can be seen from Figures 3 and 4. The origin of these discrepancies is not clear, but it should be stressed that the vast majority of the objects in common in the three samples have similar results, as illustrated in Figures 1 to 4.

3.3. *Metallicity differences: the Galaxy and the Magellanic Clouds*

The PN abundances of the heavy elements O, S, Ne, and Ar as given in Table 1 are expected to reflect the average metallicities of the Magellanic Clouds, which are a few dex lower than in the Milky Way, as these elements are not produced by the PN progenitor stars. This can be confirmed by comparing the PN abundances with the abundances in the Orion Nebula, which can be taken as representative of the present heavy element abundances in the Galaxy. From the compilation by Stasińska (2004), we obtain the abundances given at the end of Table 1. For comparison purposes, the average solar abundances from the same source are also included. For the Orion Nebula and the Sun the uncertainties given are not the intrinsic uncertainties of the data, but the dispersion of the measurements in the recent literature as considered by Stasińska (2004). It can be seen that the Orion Nebula abundances are higher than

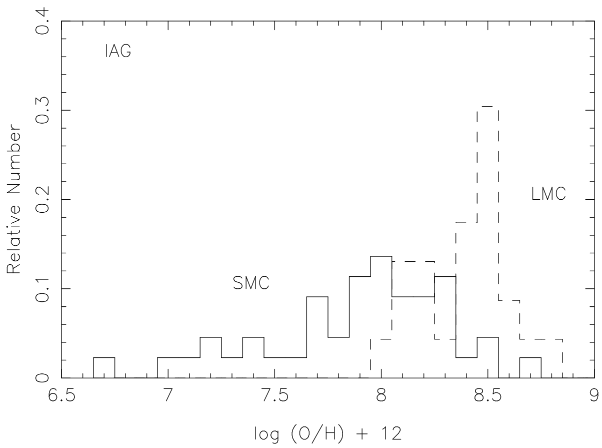

Fig. 5. The O/H abundance distribution of the Magellanic Clouds from the IAG/USP data.

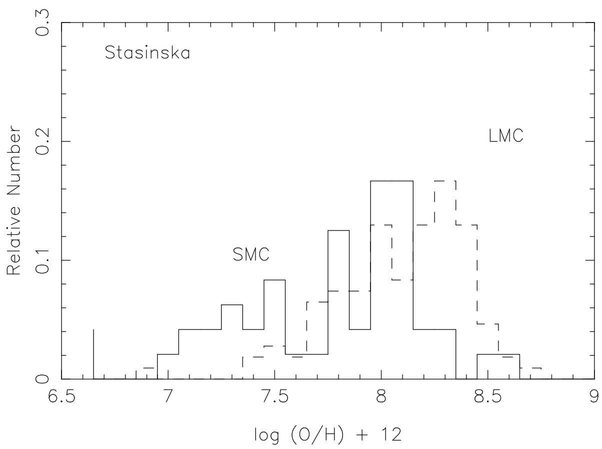

Fig. 6. The same as Figure 5 for the data by Stasińska et al. (1998).

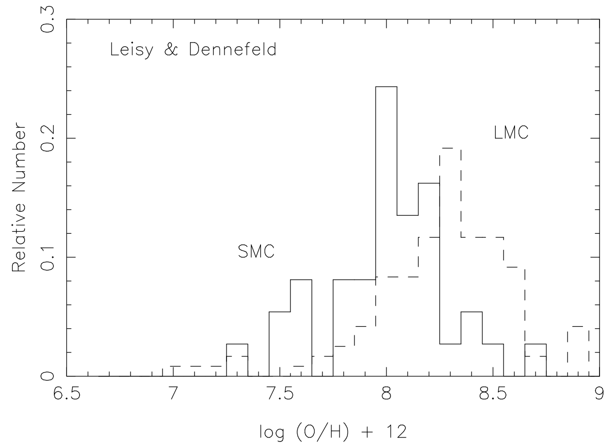

Fig. 7. The same as Figure 5 for the data by Leisy & Dennefeld (2006).

those of the Magellanic Clouds PN by about 0.2 to 0.5 dex for the LMC and 0.5 to 0.8 dex for the SMC in the case of oxygen. The average for the Orion Nebula, $\epsilon_{ON}(\mathrm{O}) \simeq 8.55$, is also essentially the same as in the galactic PN, $\epsilon_{PN}(\mathrm{O}) \simeq 8.65$ (cf. Maciel et al. 2006a). For S, Ne, and Ar a similar comparison is obtained, although the S abundance in the LMC is actually somewhat higher than in the Orion Nebula according to the data by Leisy & Dennefeld (2006). The difference in the abundances is also smaller in the case of nitrogen, which is a clear evidence of the N enhancement in the PN progenitor stars.

3.4. *The metallicity distribution*

The available data on PN in the Magellanic Clouds can be used to infer the metallicity distribution in these systems, on the basis of the derived abundances of O, S, Ne, and Ar. A comparison of the distributions in different systems can be used to infer their average metallicities, with consequences on the star formation rates. As an example, Figures 5, 6 and 7 show the O/H distribution in the Magellanic Clouds according to the three samples considered in this work. The metallicity difference between the SMC and the LMC can be clearly observed in all samples, amounting to about 0.4 to 0.5 dex in average. The difference is especially well defined in our sample, as shown in Figure 5. In a comparison with the Milky Way, the galactic disk nebulae extend to a higher metallicity, up to $\epsilon(\mathrm{O}) \simeq 9.2$, while the LMC objects reach $\epsilon(\mathrm{O}) \simeq 8.8$ and the lowest metallicities in the SMC are about $\epsilon(\mathrm{O}) \simeq 7.0$. Concerning the remaining elements that are not affected by the evolution of the PN progenitor stars, the Ar/H abundance distribution has a similar pattern, while the S/H data is less clear, as already mentioned. We will discuss this element in more detail in the next section. For Ne/H we have no IAG data for the LMC, but the larger Leisy & Dennefeld (2006) sample clearly confirms the 0.4 to 0.5 dex difference between the LMC and the SMC.

The metallicity distribution of the PN as shown in Figures 5, 6, and 7 can also be compared with galactic data, both for disk and bulge PN. Cuisinier et al. (2000) considered a sample of 30 bulge nebulae and a compilation containing about 200 disk PN, and concluded that both O/H distributions are similar, peaking around 8.7–8.8 dex, and extending form $\epsilon(\mathrm{O}) \simeq 8.0$ to $\epsilon(\mathrm{O}) \simeq 9.2$. More recently, Escudero, Costa, & Maciel (2004) obtained a similar distribution using a bulge sample twice as large, which extended to about 7.5 dex (see also Costa, Maciel, & Escudero (2008). According to Figures 5–7, the O/H

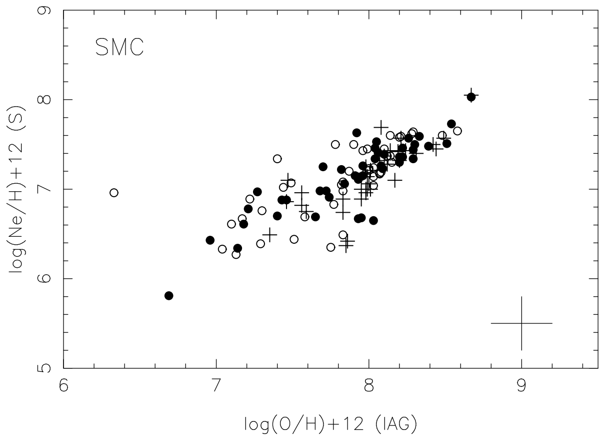

Fig. 8. Distance-independent correlation of Ne/H *vs* O/H for the SMC. Filled circles: IAG/USP data; empty circles: Stasińska et al. (1998); crosses: Leisy & Dennefeld 2006).

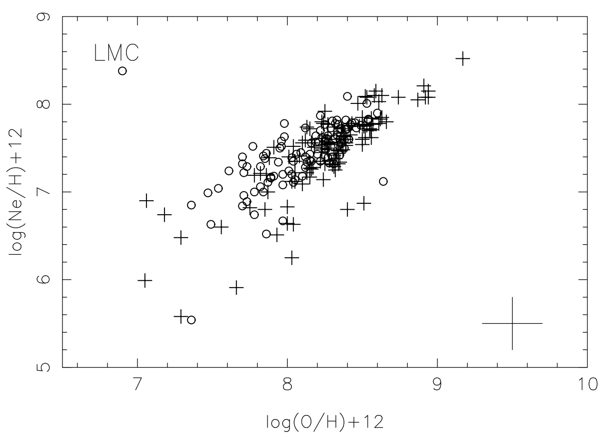

Fig. 9. The same as Figure 8, for the LMC. No IAG/USP data are available for this object.

distributions are displaced relative to the Milky Way by approximately 0.4 and 0.7 dex towards smaller metallicities for the LMC and SMC, respectively, in good agreement with the results discussed in § 4.1.

3.5. *Abundance correlations: elements not produced by the progenitor stars*

Photoionized nebulae, comprising both PN and HII regions, are extremely useful to study chemical abundances in different systems. While HII regions reflect the present chemical composition of star-forming systems, PN are helpful to trace the time evolution of the abundances, especially when an effort is made to establish their age distribution (see for example Maciel, Lago, & Costa 2006b). The elements S, Ar and Ne are probably not produced

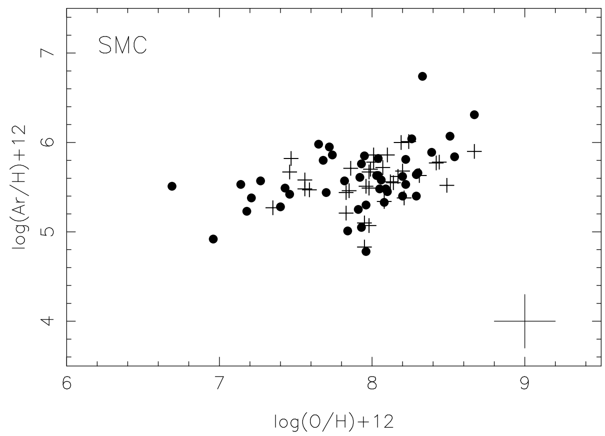

Fig. 10. Distance-independent correlation of Ar/H *vs* O/H for the SMC. Symbols are as in Figure 8.

by the PN progenitor stars, as they are manufactured in the late evolutionary stages of massive stars. Therefore, S, Ar, and Ne abundances as measured in PN should reflect the interstellar composition at the time the progenitor stars were formed. Since in the interstellar medium of star-forming galaxies such as the Magellanic Clouds the production of O and Ne is believed to be dominated by type II supernovae, we may conclude that the original O and Ne abundances are not significantly modified by the stellar progenitors of bright PN.

The variation of the ratios S/H, Ar/H and Ne/H with O/H usually shows a good positive correlation for all studied systems in the Local Group, with similar slopes, close to unity. The main differences lie in the average metallicity of the different galaxies, which can be inferred from the observed metallicity range, as we have seen in the previous section.

Figure 8 shows the Ne/H ratio as a function of O/H for the SMC, while Figure 9 corresponds to the LMC. In these figures we include the combined samples mentioned in § 2 as follows: IAG/USP data (filled circles), Stasińska et al. (1998) (empty circles), and Leisy & Dennefeld (2006) (crosses). Average error bars are included at the lower right corner of the figures. It can be seen that the correlation is very good, with a slope in the range 0.8–0.9 in both cases. The Ne/H *vs* O/H relation is probably the best example provided by PN regarding the nucleosynthesis in massive stars. This correlation is very well defined, as shown in Figures 8 and 9, and is essentially the same as derived from HII regions in different star forming galaxies of the Local Group, including the Milky Way, and in emission line galaxies as well, as clearly shown by Richer & McCall (2006) and Richer (2006, see also Henry et al. 2006).

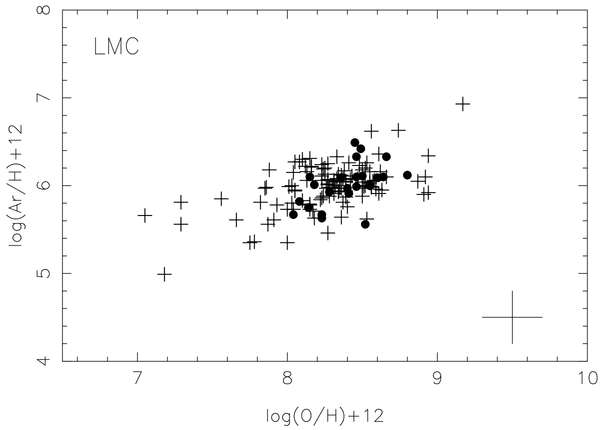

Fig. 11. The same as Figure 10, for the LMC.

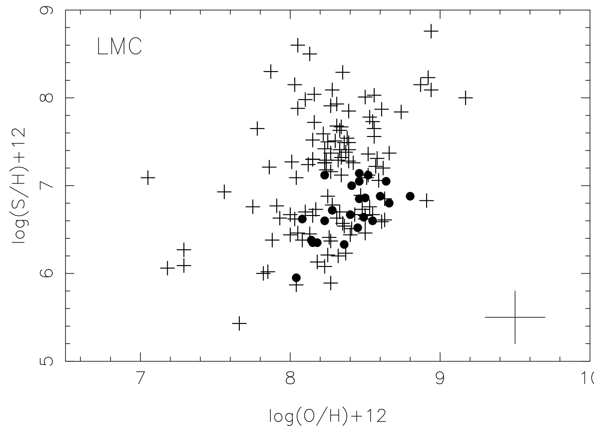

Fig. 13. The same as Figure 12, for the LMC.

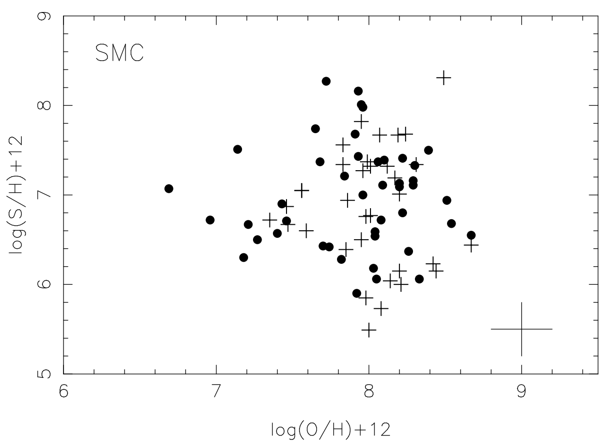

Fig. 12. Distance-independent correlation of S/H *vs* O/H for the SMC. Symbols are as in Figure 8.

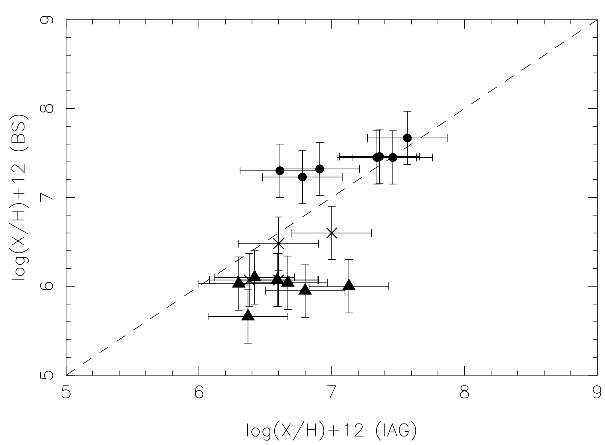

Fig. 14. Comparison of the *Spitzer* results by Bernard-Salas et al. (2008) and the IAG/USP sample. circles: SMC, Ne/H data; triangles: SMC, S/H abundances; crosses: LMC, S/H data.

The Ar/H data shows a similar correlation with O/H, as can be seen from Figures 10 and 11, but the correlation is poorer, which may be due to the fact that the samples are smaller, since Stasińska et al. (1998) do not present argon data. Again, the main discrepancy lies in the S/H data, as can be seen from Figures 12 and 13. Although most objects define a positive correlation, which is especially true for the LMC, the dispersion is much larger in the S/H data compared to the previous elements, again suggesting that a problem remains in the interpretation of the S/H abundances in planetary nebulae. In particular, both the IAG/USP and Leisy & Dennefeld (2006) data suggest a scattering diagram on the S/H *vs* O/H plane for the SMC, with an average abundance around $\epsilon(\mathrm{S/H}) = \log(\mathrm{S/H}) + 12 \simeq 7.0$. A weaker correlation involving sulfur is to be expected, since the diagnostic lines for this element are weaker than e.g. for oxygen or neon. However, the real situation may be more complex, so that a more detailed discussion is appropriate.

A hint on the problem of the sulfur abundances in PN can be obtained by comparing our S/H abundances with the recent determinations by Bernard-Salas et al. (2008), who have presented Ne/H and S/H abundances for 25 PN in the Magellanic Clouds using *Spitzer* data. These results have been obtained on the basis of high-resolution spectroscopic observations in the infrared, and are in principle more accurate compared with the abundances of our present sample, since the uncertainties in the electron temperatures do not affect the infrared lines, the interstellar extinction effects are smaller, and the use of the often uncertain ionization correction factors is greatly reduced (cf. Bernard-Salas et al. 2008). A comparison of the Ne/H and S/H abundances from

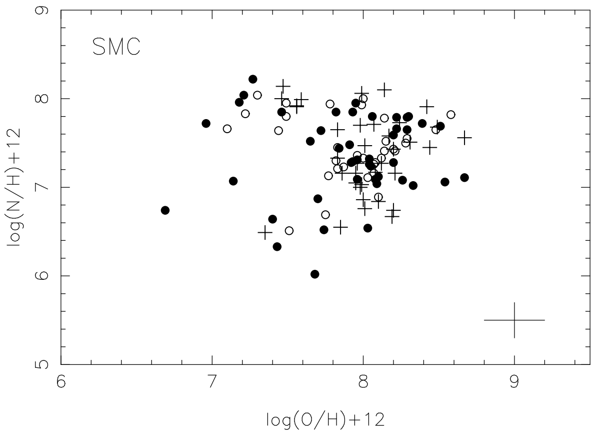

Fig. 15. Distance-independent correlation of N/H × O/H for the SMC. Symbols are as in Figure 8.

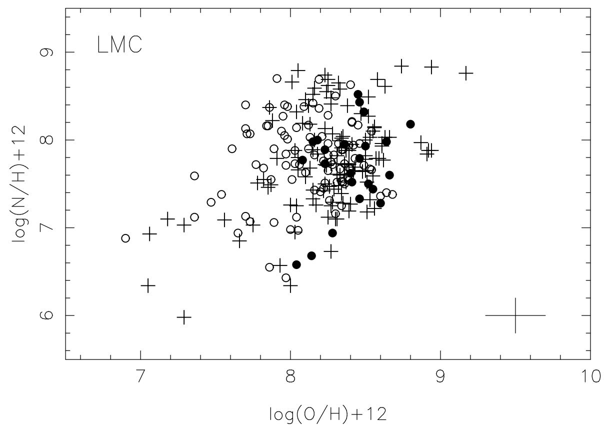

Fig. 16. The same as Figure 15, for the LMC.

this source and those by the IAG/USP group is shown in Figure 14, where the adopted uncertainties are also shown. There are eleven objects in common, which is a small but representative sample. In the figure, the circles refer to Ne/H and the triangles to S/H for the SMC, while the crosses are S/H data for PN in the LMC.

It can be seen that the Ne/H abundances show a very good agreement with the infrared data, while for S/H there is a tedency for our values to be larger than those by Bernard-Salas et al. (2008). Although the differences are not very large except for a few nebulae, it may be suggested that the S/H data presented here should be considered as upper limits. Inspecting Figures 12 and 13, that would be expected especially for those nebulae having lower oxygen abundances, which would explain the scatter diagram observed in Figure 12. In Bernard-Salas et al. (2008), a similar comparison of the *Spitzer* S/H abundances with data by Leisy & Dennefeld (2006) was presented, and it was shown that the latter are also systematically larger than the infrared results. This was interpreted by Bernard-Salas et al. (2008) as due to the fact that the ionization correction factors used by Leisy & Dennefeld (2006) overestimated the contribution of the S^{+3} ion to the total sulfur abundances. In fact, several of the S/H values for Magellanic Cloud PN in Leisy & Dennefeld (2006) are flagged as upper limits. While commenting on the large dispersion of their log S/H *vs* log O/H plot, the authors stress that the sulfur abundances are affected by several problems, such as the lack of [SIV] or [SIII] lines, blending with oxygen lines, and innacuracies in the adopted electron temperatures. By considering only the nebulae for which the sulfur data are more reliable, Leisy & Dennefeld (2006) obtain a somewhat reduced dispersion on the log S/H *vs* log O/H plane, but it is still concluded that the sulfur abundances are not satisfactory metallicity indicators for Magellanic Cloud planetary nebulae.

A discussion of the sulfur abundance problem in PN was recently given by Henry, Kwitter, & Balick (2004) and Henry et al. (2006). These authors identified a so-called “sulfur anomaly”, or the lack of agreement of the S/H ratio in PN with corresponding data from HII regions and other objects. From an analysis of the abundances in Milky Way planetary nebulae, HII regions and blue compact galaxies, it was suggested that the origin of the “sulfur anomaly” is probably linked to the presence of S^{+3} ions, which would affect the total sulfur abundances, at least in some nebulae. According to this view, the abundances of at least some of the galactic PN are underestimated, in the sense that the measured S/H ratio is lower than expected on the basis of the derived O/H abundances. If this explanation is valid for Magellanic Cloud PN, it would probably affect those objects with higher O/H ratios, so it is an alternative to the previous suggestion based on the comparison of optical abundances with infrared data.

However, other factors may play a role, such as the weakness of the sulfur lines, the assumptions leading to the ionization correction factors, etc. so this problem deserves further investigation.

3.6. *Abundance correlations: elements produced by the progenitor stars*

Considering now the elements that are produced during the evolution of the PN progenitor stars, namely, He and N, Figures 15 and 16 show the derived correlations of N/H and O/H for the SMC and LMC, respectively. As expected, a positive correlation is observed, which is especially evident in the

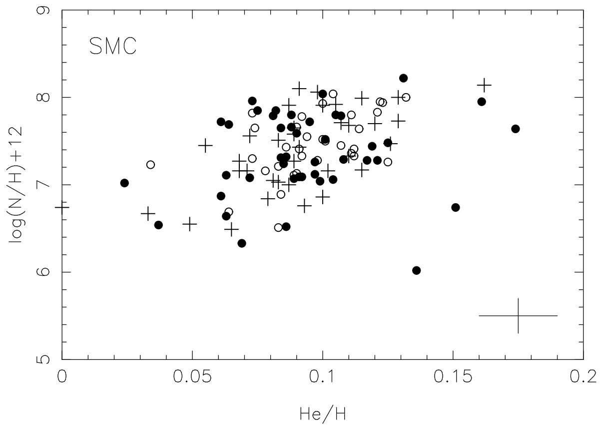

Fig. 17. Distance-independent correlation of N/H *vs* He/H for the SMC. Symbols are as in Figure 8.

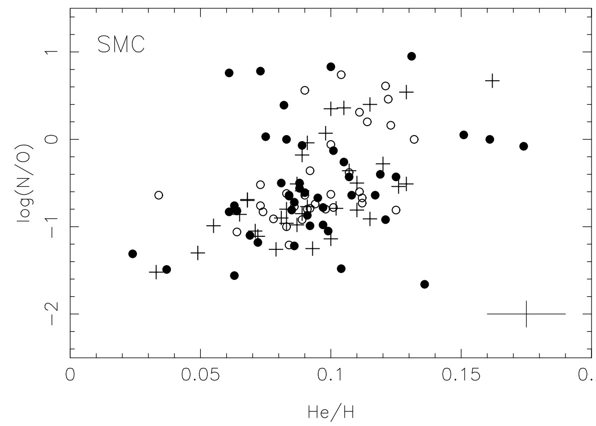

Fig. 19. Distance-independent correlation of N/O *vs* He/H for the SMC. Symbols are as in Figure 8.

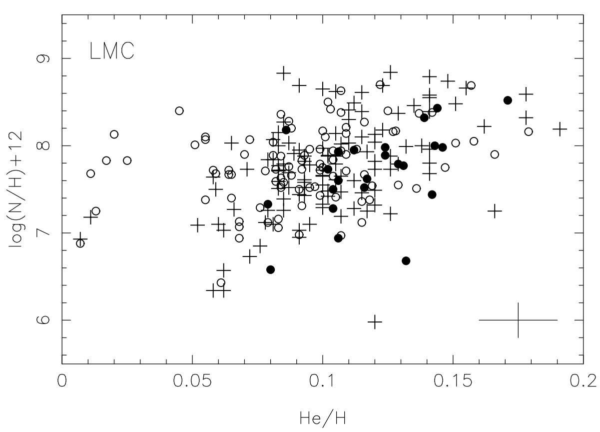

Fig. 18. The same as Figure 17, for the LMC.

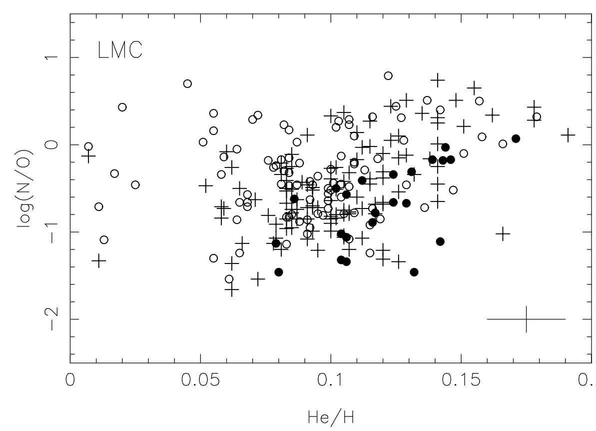

Fig. 20. The same as Figure 19, for the LMC.

case of the LMC, but the dispersion of the data is larger than in the case of Ne and Ar. This is due to the fact that the PN display both the original N present at the formation of the star and the contamination dredged up at the AGB branch of the stellar evolution. In other words, the N/H ratio measured in PN shows some contamination, or enrichment, in comparison with the original abundances in the progenitor star.

An estimate of the nitrogen enrichment from the PN progenitor stars can be made by comparing the average N/H abundances of Table 1 with those of HII regions. The Orion value given in the table is similar to the PN abundances for the 3 samples considered, but HII regions in the lower metallicity Magellanic Clouds have accordingly lower nitrogen abundances. As an example, for 30 Doradus, the brightest HII region in the LMC, Peimbert (2003) estimates $\epsilon(\mathrm{N}) = 7.05$ based on echelle spectrophotometry, assuming no temperature fluctuations ($t^2 = 0.00$). Comparing this result with the data of Table 1, an average enrichment of about 0.6–0.7 dex is obtained for the N/H ratio. Concerning HII regions in the SMC, Relaño, Peimbert, & Beckman (2002) estimate $\epsilon(\mathrm{N}) = 6.81$ for NGC 346 on the basis of photoionization models, which implies an enrichment of 0.5–0.6 dex for the PN samples listed in Table 1. These enrichment factors may be affected by the chemical evolution of the host galaxy, which includes the average increase of the metallicity as the galaxy evolves, but it is interesting that similar factors are obtained both for the LMC and SMC. The quoted values for 30 Dor and NGC 346 are included at the bottom of Table 1, as representative of HII in the Magellanic Clouds.

Figures 17 and 18 show the N/H abundances as a function of the He/H ratio, while Figures 19 and 20 are the corresponding plots for N/O as a function of He/H. As pointed out in the literature (cf. Kwok 2000), these ratios present enhancements rel-

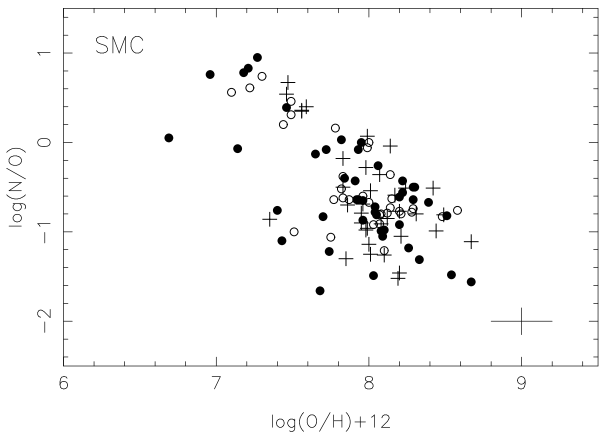

Fig. 21. Distance-independent correlation of N/O *vs* O/H for the SMC. Symbols are as in Figure 8.

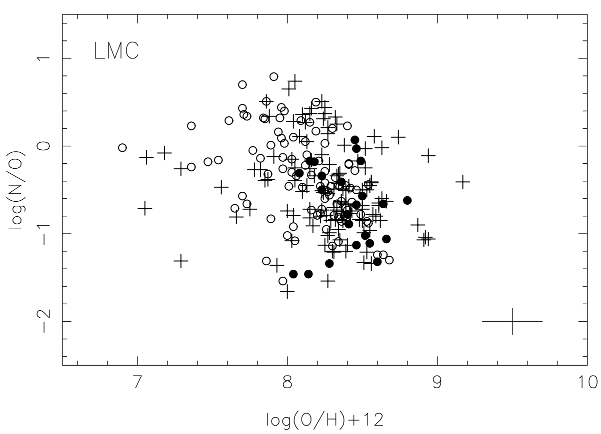

Fig. 22. The same as Figure 21, for the LMC.

ative to the average interstellar values. The dispersion is again large, but a positive correlation can also be observed, as expected, since the same processes that increase the nitrogen abundances in PN also affect the He/H ratio. A plot similar to Figures 19 and 20 was presented by Shaw (2006), in an effort to separate PN of different morphologies. In the LMC, some objects in the sample by Stasińska et al. (1998) have very low He abundances while the N/O ratio is normal, suggesting that neutral helium may be present in these objects. As pointed out by Maciel et al. (2006a), the N/O *vs* He/H ratios in the Magellanic Clouds support the correlation observed in the Milky Way, but the N/O ratio is comparatively lower. The O/H ratio corresponding to the SMC is also lower, which can be interpreted as an evidence that the lower metallicity environment in the SMC leads to a smaller fraction of Type I PN, which are formed by the more massive stars in the Intermediate Mass Star bracket (cf. Stanghellini et al. 2003).

Finally, Figures 21 and 22 show the N/O ratios as a function of the O/H abundances. The conversion of oxygen into nitrogen by the ON cycling in the PN progenitor stars has been suggested in the literature as an explanation for the anticorrelation between N/O and O/H in planetary nebulae (cf. Costa et al. 2000; Stasińska et al. 1998; Perinotto et al. 2006). This relation is approximately valid on the basis of PN data in several galaxies of the Local Group, as discussed by Richer & McCall (2006). From Figures 21 and 22, we conclude that the Magellanic Cloud data support such anticorrelation, particularly in the case of the SMC. As discussed by Maciel et al. (2006a) the Milky Way data define a mild anticorrelation, especially in the case of $\epsilon(\mathrm{O}) = \log(\mathrm{O/H}) + 12 > 8.0$, which is better defined by the SMC/LMC.

This work was partly supported by FAPESP and CNPq.

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