CARBON ABUNDANCE IN SMALL MAGELLANIC CLOUD PLANETARY NEBULAE THROUGH ADVANCED CAMERA FOR SURVEYS PRISM SPECTROSCOPY: CONSTRAINING STELLAR EVOLUTION AT LOW METALLICITY

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ABSTRACT

We perform near ultraviolet ACS prism spectroscopy of 11 Small Magellanic Cloud (SMC) planetary nebulae (PNe) with the main aim of deriving the abundance of carbon. The analysis of the ACS spectra provides reliable atomic carbon abundances for all but a couple of our targets; ionic C^2+ abundances are calculated for all target PNe. With the present paper we more than double the number of SMC PNe with known carbon abundances, providing a good database to study the elemental evolution in low- and intermediate-mass stars at low metallicity. We study carbon abundances of Magellanic Cloud PNe in the framework of stellar evolution models and the elemental yields. Constraining SMC and LMC stellar evolutionary models is now possible with the present data, through the comparison of the final yields calculated and the CNO abundances observed. We found that SMC PNe are almost exclusively carbon rich, and that for the most part they have not undergone the hot bottom burning phase, contrary to about half of the studied LMC PNe. The yields from stellar evolutionary models with LMC and SMC metallicities broadly agree with the observations. In particular, evolutionary yields for M turno < 3.5 M⊙ well encompass the abundances of round and elliptical PNe in the SMC. We found that the carbon emission lines are major coolants for SMC PNe, more so than in their LMC counterparts, indicating that metallicity has an effect on the physics of PNe, as predicted by Stanghellini et al..

Key words: planetary nebulae: general – stars: abundances – stars: evolution – ultraviolet: ISM

Online-only material: color figures

1. INTRODUCTION

Planetary nebulae (PNe) have been studied for decades, and through those efforts an understanding has come of the final phases of stellar evolution of stars with masses in the ~1–8 M⊙ range (also called the low- and intermediate-mass stars or LIMS). Planetary nebulae are ejected toward the end of the LIMS evolution, during the final thermal pulses on the asymptotic giant branch (TP-AGB); thus they are ideal probes to test the ISM enrichment from these stars in a quantitative way. The scientific importance from studying PNe in the Magellanic Clouds (LMC and SMC) can be very simply summarized: LMC and SMC PNe are absolute probes of stellar evolutionary models and the elemental yields. Constraining SMC and LMC stellar evolutionary models is now possible with the present data, through the comparison of the final yields calculated and the CNO abundances observed. We found that SMC PNe are almost exclusively carbon rich, and that for the most part they have not undergone the hot bottom burning phase, contrary to about half of the studied LMC PNe. The yields from stellar evolutionary models with LMC and SMC metallicities broadly agree with the observations. In particular, evolutionary yields for M turno < 3.5 M⊙ well encompass the abundances of round and elliptical PNe in the SMC. We found that the carbon emission lines are major coolants for SMC PNe, more so than in their LMC counterparts, indicating that metallicity has an effect on the physics of PNe, as predicted by Stanghellini et al.

The second convective dredge-up (for M turno, the turnoff mass, larger than ~ 3 M⊙) occurs at the onset of the AGB phase, when the H-burning shell is temporarily extinguished. This process carries 4He, 13C, and 14N-rich material to the stellar surface.

During the TP-AGB phase, the envelope is able to dredge-up material after each thermal pulse, carrying 4He, 12C, and other relatively light s-process elements to the surface. This process is called the third dredge-up.

For M turno > 3–5 M⊙ (exact mass depends on metallicity; Marigo 2001), an additional process is thought to occur that affects the chemical composition: the so-called hot bottom burning (HBB) that processes most of the carbon into nitrogen, occurring during the quiescent interpulse periods between thermal pulses.

The key to assessing the above predictions is to measure the abundances of the processed elements, particularly C, N, and O. Carbon and nitrogen enrichment depends on the progenitor mass, yielding to a direct connection between observed progenitor mass (i.e., population) and chemical content. By measuring the C and N abundances in PNe, one can at once validate key elements of stellar evolution theory and measure the contribution of LIMS to the enrichment of the ISM. While O and N abundance analysis is straightforward to do with PNe, owing to their bright optical emission lines, the carbon analysis requires satellite UV spectroscopy.
In our earlier study of LMC PN abundances (Stanghellini et al. 2005), we have shown that PN morphology is a surprisingly useful indicator of the progenitor stellar evolution and population. We used a subsample of LMC PNe images available from the Hubble Space Telescope (HST)\(^5\) and measured the carbon abundances with STIS (Space Telescope Imaging Spectrograph) spectroscopic analysis. We found that nitrogen enhancement is correlated with asymmetry. These results are consistent with the predictions of stellar evolution only if the progenitors of asymmetric PNe have on average larger masses than the progenitors of symmetric PNe. Our results are the first of the kind for extragalactic PNe, and are thus not biased by the large selection effects that limit the observation of PNe in the Galactic disk.

Owing to the smaller metal abundance in the SMC than in the LMC, it is very important to extend the LMC study to the SMC. Carbon abundance determination in SMC PNe would probe the carbon abundances with STIS (Space Telescope Imaging Spectrograph) spectroscopic analysis. We found that nitrogen abundance determination in SMC PNe (Section 3), and a discussion of our results in the framework on PN evolution and populations (Section 4). The conclusions are given in Section 5.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Observations

We observed 11 SMC PNe using the Advanced Camera for Surveys (ACS) prisms PR130L in the Solar Blind Channel (SBC) and PR200L in the High Resolution Channel (HRC). Our aim is to detect the C iv λ1550, the C iii] λ1909, and the C ii] λ2326 nebular emission lines to determine the ion abundances of the carbon ions that are excited in the PN regime.

We select our targets from the SMC PNe that have been previously observed by us with the STIS (Stanghellini et al. 2003; Shaw et al. 2006). With this selection we guarantee that their morphology, size, optical extinction, and optical fluxes to be observed with the observing configuration within a few orbits (total Hβ fluxes larger than \(2.5 \times 10^{-14} \text{[erg cm}^{-2} \text{s}^{-1}]\)). In addition, our selected targets have angular sizes smaller than \(\lesssim 0.5\) in order to prevent blending of emission lines in the slitless spectroscopy. The targets are listed in Table 1 together with the observing log. Of these, a few have been observed before with the STIS, but none has a sound carbon abundance determination.

The SBC detector is a 1024 \(\times\) 1024 solar-blind CsI Multi-Anode Microchannel Array (MAMA), with \(\sim 0.034 \times 0.030\) pixels, and a nominal 35\(\prime\) \(\times\) 31\(\prime\) field of view. The HRC detector is a 1024 \(\times\) 1024 STe CCD with \(\sim 0.028 \times 0.025\) pixels, covering a nominal 29\(\prime\) \(\times\) 26\(\prime\) field of view. The wavelength range of SBC/PR130L is \(\sim 1200–2000\) Å and the useful wavelength range of HRC/PR200L is \(\sim 1800–4000\) Å. The wavelength scale of the prisms is nonlinear, with spectral resolution decreasing toward longer wavelengths. For PR130L, the dispersion varies from about 2 Å/pixel\(^{-1}\) at the blue end (\(R \sim 300\)), to \(\sim 10\) Å/pixel\(^{-1}\) at 1600 Å (\(R \sim 80\) and 30 Å/pixel\(^{-1}\) at the red end (\(R \sim 30\) at 2000 Å). For PR200L, the dispersion varies from about 6 Å/pixel\(^{-1}\) at the blue end (\(R \sim 150\)), to \(\sim 20\) Å/pixel\(^{-1}\) at 2500 Å (\(R \sim 60\)) and \(\sim 200\) Å/pixel\(^{-1}\) at 4000 Å (\(R \sim 10\); Larsen et al. 2006; Larsen 2006).

For each target, the HRC observations consist of a direct image through a broadband filter (F330W) and two exposures through the prism (PR200L) in order to perform rejection of cosmic rays. Similarly, the SBC observations consist of a direct image through F165LP and one exposure of PR130L, unless cosmic rays. Similarly, the SBC observations consist of a direct image through F165LP and one exposure of PR130L, unless...
2.2. Data Analysis

The pipeline calibration of our data provided bias-subtracted, dark-corrected, and flat-corrected spectral images, as processed with CALACS (Pavlovsky et al. 2004). We used MultiDrizzle and aXe to combine the images, correct for geometric distortion, and to identify any bad pixels in the spectrum. The bad pixels were excluded from the analysis of our flux-calibrated one-dimensional spectra.

The position, size, and magnitude of the extracting sources were identified and determined using the direct images SBC/F165LP and HRC/F330W via analysis with SExtractor (Bertin & Arnouts 1996). The position of the extracting sources on the direct images has then been projected on the prism images for spectral extraction.

The spectral extraction was done with the aXe software (Kümmel et al. 2005) in PyRAF. For prism slitless spectroscopy, the trace and wavelength solutions include spatial variations across the HRC and SBC detectors. The wavelength and flux calibrations are provided by the ST-ECF group in the configuration files for the aXe software. Two white dwarf standards were used to determine the flux calibration for both HRC and SBC prisms. The HRC/PR200L wavelength calibration has been secured with observations of the LMC PN SMP-79 and a quasar with both STIS and the ACS prism (Larsen et al. 2006). The calibration of the SBC/PR130L prism was determined using two quasars (Larsen 2006).

Background subtraction was performed during spectral extraction. To remove the sky background, a local background is estimated by interpolating between the adjacent pixels on either side of the target spectrum, outside the extracting area. The optimal weighting algorithm was chosen to enhance the signal-to-noise ratio (S/N) of the extracted spectra. The algorithm assigns lower weights to pixels that contain only a small fraction of the target flux, due to the larger distance from the spectral trace.

Faint objects near the targets were identified by position and size and then their contribution to the flux was subtracted in the extracted spectra. The contaminating flux from all other sources was estimated with a Gaussian emission model by using the sizes and magnitudes derived from the direct image. This contamination flux was then subtracted when extracting the target spectrum.

The tabular wavelength and the flux of the final extracted spectrum were then read using task tprint and converted to one-dimensional spectrum using the task rspecext. We averaged the multiple exposures using task acombine. The final reduced spectra of the 11 PNe are shown in Figures 1–11. The nebular line fluxes have been measured by integrating the area above the continuum using the IRAF task ap1ot with the d or w options.

In Table 2 we give the complete spectral analysis of our targets, including the identification wavelength (Column 2), the line ID (Column 3), and the measured flux as a fraction of $F_{\text{H}_\beta}$ (Column 4), where the $F_{\text{H}_\beta}$ fluxes are from the HST analysis of Stanghellini et al. (2003) and Shaw et al. (2006). It is worth noting that the emission around $\lambda 1650$ could well be a blend of He ii $\lambda 1640$ and O iii $\lambda 1663$ (the latter corresponding to the 1661/66 Å doublet). For those low-excitation PNe whose optical spectra do not show the $\lambda 4686$ emission line (SMP 18, SMP 20, SMP 24), it is safe to assume that the emission is due to O iii. In the other cases, we identify the emission as a blend. We do not calculate abundances of elements other than carbon in this paper, so we do not present here a detailed analysis of the other emission lines.

Typical uncertainties in the emission line fluxes are $\sim$5% in the bright lines. We have examined data quality flags of each exposure and noticed that a few of the PR200L frames have some saturated pixels at the red end of their spectra. This is caused by red pile-up, due to the low dispersion in the red wavelengths. In general, the saturated pixels do not affect the measured fluxes. Only in two PNe, SMP 15 and SMP 18, the saturated pixels affect the C iii $\lambda 2326$ emission line and, therefore, these are listed as lower limits.

Furthermore, in some cases the spectra are affected by bad pixels. For SMP 24, the two-dimensional PR130L spectrum falls into an area of bad pixels, as indicated in the data quality file. If we exclude the bad pixels when extracting this spectrum, we end up with a very marred one-dimensional spectrum; thus, the C iv $\lambda 1550$ line measurement is not reliable for this nebula even if there seems to be a feature at the appropriate wavelength. The PR200L spectrum looks much better, but the extension shows a dip on the C iii $\lambda 1909$ line, affecting the measured flux at an estimated level of 15% level. For SMP 16, the bad pixels in the

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6 PyRAF is a product of the Space Telescope Science Institute, which is operated by AURA for NASA.
PR200L frame affect the measured fluxes of the C\textsc{iv} $\lambda$2326 and C\textsc{iii} $\lambda$1909 lines at an estimated level of 25%. Finally, in the case of SMP 18, the C\textsc{ii} $\lambda$2326 flux might be affected at the 15% level. In the case of SMP 25, a prominent N\textsc{iv} $\lambda$1485 is seen in the spectrum, but we do not give its flux in our tables since there are few columns of bad pixels in the 1425–1525 Å range for this PN.

Ultraviolet prism spectroscopy performed with the ACS has often not been acquired in the past and the analysis modes used in this paper are unique. In order to have a sanity check of our...
calibration and spectral extraction, we compare the ACS prism HRC/PR200L spectrum of SMP 79, a PN in the LMC, with the corresponding spectrum observed with STIS spectroscopy. The prism spectrum was extracted in the same way as for our SMC PN targets. We measured the flux of C III] λ1909 to compare with the flux measured from the STIS spectrum. In the HST archive there are a total of 24 prism exposures of SMP 79 taken at 12 different positions of the CCD. We extracted the spectrum from...
each exposure and measured the C\textsc{iii}] flux in each spectrum. The average flux is \((9.3 \pm 0.4) \times 10^{-13} \text{ [erg cm}^{-2} \text{ s}^{-1}]\), compared with the flux \(9.4 \times 10^{-13} \text{ [erg cm}^{-2} \text{ s}^{-1}]\) measured from the STIS spectrum. A contaminating source happened to lie just at the spectral trace of C\textsc{ii}] \(\lambda 2326\), so we did not attempt to compare this emission line with the one from STIS for LMC SMP 79. Errors in our flux measurements are \(\sim 5\%\) except the specific cases listed above, as marked in Table 2.
2.3. Extinction Correction

The flux measurements need to be corrected both for Galactic foreground extinction and for the SMC extinction proper. The relation between observed and dereddened fluxes, scaled to H\(\beta\), can be written as

\[
\frac{I_\lambda}{I_\beta} = \frac{F_\lambda}{F_\beta} 10^{c f_\lambda},
\]

(1)

where \(c\) is the target-dependent logarithmic extinction at H\(\beta\) and \(f_\lambda\) is the reddening function at wavelength \(\lambda\). Since the Galaxy and the SMC have different extinction curves in the UV (Hutchings \& Giasson 2001), we need to correct separately for each contribution. We can write

\[
cf_\lambda = cG f_\lambda, G + c_{SMC} f_\lambda, SMC,
\]

(2)

where the suffixes “G” and “SMC” refer to the Galactic foreground and intrinsic SMC extinction, respectively.

To evaluate the Galactic foreground extinction, we used the Galactic H \(\text{i}\) foreground column density map constructed by Bot et al. (2004) from data of the Parkes H \(\text{i}\) Survey of the Magellanic System (Brüns et al. 2005). The column density was obtained by integrating the emission from –60 to +50 km s\(^{-1}\), outside the SMC velocities. The Galactic color excess map is calculated using \(N(H \text{i})/E_{B-V} = 5.8 \times 10^{21}\) [atoms cm\(^{-2}\) mag\(^{-1}\)] (Bohlin et al. 1978; Savage \& Mathis 1979). Figure 12 shows the Galactic foreground color excess map, superimposed to the Digital Sky Survey\(^7\) image of SMC. The target-specific foreground Galactic extinction constant, \(c_G = 1.47 E_{B-V}\), was estimated from Figure 13 for each target.

The constant \(c_G\) is then used to correct the fluxes for foreground Galactic extinction using the extinction function \(f_{\lambda, G}\) provided by Cardelli et al. (1989):

\[
\left(\frac{I_\lambda}{I_\beta}\right)_0 = \frac{F_\lambda}{F_\beta} 10^{cG f_{\lambda, G}}.
\]

(3)

\(7\) The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions.

In order to correct for the SMC extinction, we estimate the optical extinction constant as

\[
c_{SMC} = 2.875 \log \frac{(H\alpha/H\beta)_0}{2.85},
\]

(4)

where \(H\alpha/H\beta)_0\) is the flux ratio corrected for Galactic foreground. We then correct the flux ratios for SMC extinction from

\[
\frac{I_\lambda}{I_\beta} = \left(\frac{I_\lambda}{I_\beta}\right)_0 10^{c_{SMC} f_{\lambda, SMC}},
\]

(5)

where the SMC the extinction function is from Prevot et al. (1984). In Table 2 we list the Galactic (Column 5) and SMC (Column 6) extinction constants, as calculated above, and the final corrected intensity ratios (Column 7). Note that the line extinction estimated in the foreground overestimates the total line extinction in a few cases; thus, the SMC extinction has been assumed to be zero.

2.4. Comparison with Previous Observations

While none of the observed targets had observations in the literature that allowed carbon abundance determination, several have UV spectra taken in comparable wavelength ranges, and limited comparison could be made among data sets. Let us examine these cases.

**SMP 6:** The FOS spectrum published by Vassiliadis et al. (1996) is deemed to be inadequate for precise flux measurements (see also SMP 28 below); thus, we do not compare their fluxes with ours, although we do observe the same bright emission lines.

**SMP 15:** A low S/N IUE spectrum of this SMC PN, also known as N 43, has been acquired by Aller et al. (1987). The only emission line available in the 1200–1910 \(\text{Å}\) wavelength window is C \(\text{iii}\) \(\lambda 1909\), with \(F_{\lambda} = 7 \times 10^{-13}\) [erg cm\(^{-2}\) s\(^{-1}\)], which is within \(\sim 10\%\) of our measurement.

**SMP 20:** Similar to SMP 15, the only emission line measured by Aller et al. (1987) on the IUE spectrum of this SMC PN, also known as N 54, is C \(\text{iii}\) \(\lambda 1909\), with \(F_{\lambda} = 7 \times 10^{-13}\) [erg cm\(^{-2}\) s\(^{-1}\)], which is also within \(\sim 10\%\) of our measurement.

**SMP 28:** The UV spectrum of this SMC PN shortward of the C \(\text{iii}\) \(\lambda 1909\) line is available from Meatheringham et al. (1990). Meatheringham et al. (1990) give flux values and quote the flux
is an FOS spectrum of this PN (Vassiliadis et al. 1996) whose error to better than 15% for brightest lines. By comparing the flux of the bright emission lines that we have in common, O \textsc{iv} \ λ1404, N \textsc{iv} \ λ 1487, He \textsc{ii} \ λ1640, and N \textsc{iii} \ λ1755, we found that they agree to better than the quoted errors for the two bluer lines, but the agreement gets worse for the redder lines measured in our PR130L spectrum. In addition to the \textit{IUE} spectrum, there is an FOS spectrum of this PN (Vassiliadis et al. 1996) whose fluxes are very uncertain, deemed to be systematically off by the authors. For this reason, we will not compare our results with the FOS fluxes. We can use the FOS spectrum as presented by Vassiliadis et al. (1996) to confirm that they also observe the C \textsc{iii} \ λ1909 emission line, contrary to what is derived from the \textit{IUE} spectrum. Furthermore, the emission that we observe at 1553 Å is more likely to be associated with C \textsc{iv} than with Ne \textsc{v}, as suggested by Meatheringham et al. (1990). In summary, the statement that this PN is very carbon poor might not be correct in the light of our observations.

Finally, Idiart et al. (2007) used the \textit{IUE} final archived spectra to measure the λ1909 line for several of the PNe in our sample. The λ1909 intensities by Idiart et al. (2007) carry much larger uncertainties than ours, due to the low S/N of the \textit{IUE} spectra. All intensities agree with our data within the uncertainties, except for SMP 6, SMP 13, and SMP 18, where the \textit{IUE} spectra are noisy and the errors quoted by Idiart et al. (2007) are very large. The \textit{IUE} spectra would not provide the C \textsc{iv} nor the [C \textsc{ii}] fluxes; thus, their use to abundance analysis can only establish lower limits to the atomic abundances.

The comparison of the SMP 28 PR130L spectrum with that of Meatheringham et al. (1990) gives us confidence that the C \textsc{iv} line flux that we measured is accurate. Overall, we do not have errors larger than 5%–10% in this part of the spectrum. Furthermore, the comparison of the C \textsc{iii} \ λ1909 emission lines of our PR200L observations with those by Aller et al. (1987) confirms that we have reliable measurements for all the carbon lines.
3. ABUNDANCE ANALYSIS

The ionic abundances of C⁺/H⁺ and C2⁺/H⁺ were computed using the nebular package in STSDAS (Shaw & Dufour 1995; Shaw et al. 1998). We used the line intensities of Table 2, and $T_e$ and $N_e$ derived from the diagnostic lines measured by R. A. Shaw et al. (2009, in preparation, hereafter SEA), if available, otherwise we used the plasma diagnostics by Leisy & Dennefeld (2006, hereafter LD06). In Table 3, we present the plasma diagnostics used in this paper; Columns (2)–(4) give respectively the low- and high-excitation $T_e$ and the $N_e$ used, Column (5) lists the references for the spectral lines used to calculate the diagnostics, and Column (6) gives the excitation class (EC) of the nebulae, which have been estimated according to Morgan (1984).

The C3⁺/H⁺ abundances must be derived from recombination lines, and we did so on the basis of approximate relations from (Aller 1984, Equation (5.40)). The ionic abundances for carbon are listed in Table 4, where Columns (2)–(4) give respectively the C⁺, C2⁺, and C3⁺ abundances in terms of hydrogen.

It is worth noting that, at our spectral resolution, the λ2326 emission line could have a [O III] component from the λ2321 emission. We calculate the volume emissivities for C⁺ and O2⁺, the latter from the optical emission lines, for all PNe of high excitation. We still calculate the correction and implement the correction, as in LD96, but this has a marginal effect on the final carbon abundances for these PNe. We also calculated the ICfs to account for the unseen C⁺⁺ emission in the medium-to-high-excitation PNe. For planetary nebulae SMP 25, SMP 26, and SMP 28, showing He2⁺ emission and not N4⁺ lines, we use Equation (A20) of KB94. The ionic helium abundances needed in these cases were calculated with the line intensities from LD06, the prescription of Benjamin et al. (1999), and the plasma diagnostics of Table 3.

The final ICfs are listed in column (5) of Table 4, and the corrected abundances expressed in terms of $A(C) = \log(C/H) + 12$ are given in Column (6), together with a conservative estimate of their uncertainties.

The larger factor of uncertainty for the total carbon abundances is the uncertainty in the electron temperature. The errors listed in Table 4 include the propagation of the uncertainty in the $T_e$ for all ions, if the plasma diagnostics were available in SEA. For the other nebulae, we estimate similar errors in the $T_e$ and propagate the errors, as given in Table 4, unless there are other, larger uncertainties, as discussed below.

As reported in Table 2 the C2⁺ fluxes of SMP 15 and SMP 18 are lower limits; we estimate that the total carbon abundances calculated for these two PNe might be underestimated by $\sim 5\%$.

Finally, while most of the emission lines intensities have errors $\sim 5\%$, they go up to 15% and 25% respectively in SMP 24 and SMP 16. These errors are propagated through the carbon abundance analysis.

In order to calculate the total carbon abundances, we follow the discussion of Kingsburgh & Barlow (1994), which was also used by LD06. For low-excitation PNe where the C⁺, C2⁺, and C3⁺ abundances are available, the total carbon abundance can be calculated simply by summing the ionic contribution. This is the case of SMP 13, SMP 15, SMP 16, SMP 18, and SMP 20, whose spectra do not show He II emission; thus, correction for C4⁺ would be unnecessary. This is also the case of SMP 6, whose emission around 1640–1663 Å should be almost entirely due to the [O III] component, given the PN low optical excitation.

Next, we need to calculate the ionization correction factors (ICFs) for the unseen ionization stages. We correct for the unseen C⁺ faces in SMP 8, SMP 24, SMP 25, SMP 26, and SMP 28 with Equations (A11) and (A13) (KB94). The ionic oxygen abundances used to obtain these ICFs have been calculated using the oxygen emission lines in SEA (SMP 8) and LD06, the plasma diagnostics of Table 3, and the nebular routines. As it turns out, no correction is needed for SMP 8. In SMP 25, SMP 26, and SMP 28 we do not see the C⁺⁺ emission probably due to their high excitation. We still calculate the correction and implement the correction, as in LD96, but this has a marginal effect on the final carbon abundances for these PNe. We also calculated the ICFS to account for the unseen C⁺⁺ emission in the medium-to-high-excitation PNe. For planetary nebulae SMP 25, SMP 26, and SMP 28, showing He2⁺ emission and not N4⁺ lines, we use Equation (A20) of KB94. The ionic helium abundances needed in these cases were calculated with the line intensities from LD06, the prescription of Benjamin et al. (1999), and the plasma diagnostics of Table 3.

The final ICFS are listed in column (5) of Table 4, and the corrected abundances expressed in terms of $A(C) = \log(C/H) + 12$ are given in Column (6), together with a conservative estimate of their uncertainties.

The larger factor of uncertainty for the total carbon abundances is the uncertainty in the electron temperature. The errors listed in Table 4 include the propagation of the uncertainty in the $T_e$ for all ions, if the plasma diagnostics were available in SEA. For the other nebulae, we estimate similar errors in the $T_e$ and propagate the errors, as given in Table 4, unless there are other, larger uncertainties, as discussed below.

As reported in Table 2 the C2⁺ fluxes of SMP 15 and SMP 18 are lower limits; we estimate that the total carbon abundances calculated for these two PNe might be underestimated by $\sim 5\%$.

Finally, while most of the emission lines intensities have errors $\sim 5\%$, they go up to 15% and 25% respectively in SMP 24 and SMP 16. These errors are propagated through the carbon abundance analysis.

### Table 3

| Name | $T_e$ | $T_e$ | $N_e$ | Ref | EC |
|------|------|------|------|-----|----|
| SMP 6 | 15600 | 14400 | 11400 | LD06 | 4 |
| SMP 8 | ... | 13700 | 11700 | SEA | 2–3 |
| SMP 13 | ... | 12800 | 13800 | SEA | 4 |
| SMP 15 | 16200 | 12000 | 9000 | LD06 | 2–4 |
| SMP 16 | ... | 11800 | 5000 | LD06 | 0 |
| SMP 18 | ... | 11860 | 800 | 3590 | SEA | 0.5 |
| SMP 20 | ... | 13820 | 11010 | SEA | 1–2 |
| SMP 24 | ... | 11620 | 1050 | 2780 | SEA | 1–2 |
| SMP 25 | ... | 21100 | 9800 | LD06 | 6–7 |
| SMP 26 | ... | 18000 | 3000 | LD06 | 8 |
| SMP 28 | ... | 19200 | 20700 | LD06 | 8 |

**Notes.**

* Temperature for low-excitation ions.
  b Adopted by authors in reference.

### Table 4

| Name | C⁺/H⁺ | C2⁺/H⁺ | C3⁺/H⁺ | ICF(C) | A(C) |
|------|-------|--------|--------|--------|------|
| SMP 6 | 1.016×10⁻⁵ | 1.917×10⁻⁴ | 2.184×10⁻⁵ | 1.0 | 8.35⁺⁰⁻⁰³ |
| SMP 8 | ... | 9.596×10⁻⁵ | 3.631×10⁻⁵ | 1.0 | 8.12⁻⁰⁻¹⁰ |
| SMP 13 | ... | 4.753×10⁻⁴ | 3.445×10⁻⁵ | 1.0 | 8.73⁻⁰⁻⁰⁵ |
| SMP 15 | ≥8.489×10⁻⁶ | 1.621×10⁻⁴ | 1.379×10⁻⁵ | 1.0 | 8.26⁻⁰⁻⁰⁶ |
| SMP 16 | ≥7.357×10⁻⁵ | 7.761×10⁻⁵ | 4.403×10⁻⁶ | 1.0 | 8.19⁻⁰⁻⁰⁸ |
| SMP 18 | ≥6.422×10⁻⁵ | 1.377×10⁻⁴ | 7.047×10⁻⁷ | 1.0 | 8.31⁻⁰⁻²⁰ |
| SMP 20 | ≥2.694×10⁻⁵ | 1.492×10⁻⁴ | 1.283×10⁻⁶ | 1.0 | 8.25⁻⁰⁻²² |
| SMP 24 | ... | 1.485×10⁻⁴ | ... | 1.02 | 8.18⁻⁰⁻²⁵ |
| SMP 25 | ... | 1.626×10⁻⁶ | 1.602×10⁻⁶ | 1.58 | 6.64⁻⁰⁻⁰⁷ |
| SMP 26 | ... | 1.349×10⁻⁴ | 6.497×10⁻⁵ | 1.45 | 8.46⁻⁰⁻⁰⁵ |
| SMP 28 | ... | 4.255×10⁻⁶ | 2.525×10⁻⁶ | 1.34 | 6.96⁻⁰⁻⁰³ |
By considering the sample of this paper and the other carbon abundances in the literature, including only those who consider all the present excitation levels (Aller et al. 1987; LD06), we found that \((C/H)_{\text{SMC}} = (3.75 \pm 3.64) \times 10^{-4}\). This is \(\sim 1.5\) times higher than the same average for the LMC \((C/H)_{\text{LMC}} = (2.49 \pm 2.18) \times 10^{-4}\); Stanghellini et al. 2005).

4. MAGELLANIC CLOUD PNe AND THE STELLAR EVOLUTION MODELS

Carbon, the fourth most abundant element in the universe (Clayton 2003, p. 326), is vigorously produced in LIMS; thus, it probes their evolution. The \(\alpha\)-elements (oxygen, neon, argon, and sulfur), on the other hand, are produced by nucleosynthesis of Type II supernova and provide information about the original composition of the PN progenitor at the time of birth. Oxygen may be brought up to the LIMS surface by the third dredge-up and its abundance should be used cautiously in this capacity.

We use the SMC PN carbon abundances determined in this paper and those available in the literature and relate them to the abundance of the \(\alpha\)-elements to assess the models of stellar evolution and the theoretical yields. In order to compare populations of different metallicity, we also include in the plots the results from our study of carbon abundances in the LMC PNe (Stanghellini et al. 2005). The abundances of N, O, and Ne for LMC PNe used here are from Aller et al. (1987) and Leisy & Dennefeld (1996, 2006). Corresponding values of N, O, and Ne in SMC PNe come from Leisy & Dennefeld (1996) and SEA.

In Figure 13, we show the carbon versus oxygen abundances of PNe in the SMC (filled symbols) and the LMC (open symbols). Their morphologies are indicated by symbols of various shapes. Small symbols are used for PNe of unknown morphologies, i.e., not yet observed with HST or, in a couple of cases, where the morphological class was too uncertain to be assigned. Abundances are in the usual scale of \(A(X) = \log(X/H) + 12\). The PNe separate into two groups: the first group are those with \(C/O < 1\) (below the line), whose shapes are almost exclusively bipolar or bipolar core (BC), as already noted by Stanghellini et al. (2007); these PNe are associated with relatively young stellar populations, such as the disk of the Milky Way. The second group are those with \(C/O > 1\), corresponding to the less massive progenitors. Most of the SMC PNe lie in the \(C/O > 1\) part of this plot.

The predominance of C-rich PNe in the SMC is consistent with the theoretical expectation that the third dredge-up is predicted to be favored at lower metallicity, i.e., to occur in stars of lower masses and with a higher efficiency (e.g., Karakas et al. 2002; Stancliffe et al. 2005). Carbon is converted to nitrogen by HBB. HBB is likely active only in relatively high-mass AGB stars \((M_{\text{AGB}} \sim 3.5–5 M_\odot\), depending on metallicity) with very deep convection and hot cores (Marigo 2001). Star formation has been far more active in the gas-rich LMC than in the gas-depleted SMC. Possibly, many of the PNe that have formed in the LMC have higher average masses than those in the SMC, affecting the fraction of high-end mass LIMS that will go through the HBB phase. That is, the segregation of PNe with bipolar and BC symmetric below the \(C = O\) line is fully consistent with model calculations. It is worth recalling, in fact, that Villaver et al. (2004) found a lack of intermediate-mass central stars in the SMC, present in the LMC.

SMC SMP 22 and SMC SMP 25 are two exceptions to this scenario. They are the two morphologically unclassified SMC PNe in the lower left of the plot: low metallicity (LD06) and \(C/O < 1\). Not much is known about SMP 22. SMP 25 is quite unique among SMC PNe. It is the only PN in the SMC where oxygen-rich dust has been detected (Stanghellini et al. 2007), while all other SMC PNe observed with Spitzer/IRS have carbon-rich dust. Furthermore, the central star of SMP 25 is much more massive \((M \sim 0.82 M_\odot\); Villaver et al. 2004 than the typical central in Magellanic Cloud PNe (Villaver et al. 2007), and it is located in the eastern region of the SMC facing the LMC, a region that contains younger and more metal-rich clusters (Crowl et al. 2001) and where Dopita et al. (1985) found the kinematically younger PNe to be concentrated. SMP 25 may have undergone recent HBB activity.

In Figure 14, where we show the relation between \(C/O\) and the neon abundance, we confirm the carbon-abundance segregation of SMP PNe. There is no evidence that neon’s abundance has been modified in any way, nor that the \(C/O\) ratio is modified differently in the SMC than in the LMC, depending on the initial neon.

The log(\(O/N\)) versus log(\(C/N\)) plot (Figure 15) also shows some obvious and interesting groupings of data. The segregation of bipolar nebulae on the left side of the plotted line is expected, of course, since Figures 13 and 15 are not entirely independent. However, it is clear that the bipolar PNe that exhibit \(O > C\) also have \(N > C\): that is, they are “N rich.” Symbiotic stars and novae stars (not shown; Nussbaumer et al. 1988) are also found in the same region. On the other hand, all of the samples with \(C/O > 1\) from Figure 13 are also nitrogen poor; that is, \(N < O\) and \(N < C\). Most of the SMC PNe fall into the latter group, of course. Carbon stars (not shown; Nussbaumer et al. 1988) are also found in this region.

Carbon stars probably have not undergone any HBB processing. We can compare the data in Figure 15 with the yields from models of stellar evolution. We limit our comparison to the final yields calculated by Marigo (2001) to avoid overcrowding of the plot. The yields by van den Hoek & Groenewegen (1997) or Karakas & Lattanzio (2001) would look very similar to the ones by Marigo (2001) in this plot. We indicate the yields from LIMS evolution with starred symbols: the four-pointed stars correspond \(Z = 0.008\), while the six-pointed stars are for \(Z = 0.004\),
and few model points. be at (0.61; 0.88) in this plot, but it is not marked to avoid overlap with a target and few model points.

(A color version of this figure is available in the online journal.)

Figure 15. Distribution of SMC and LMC PNe on the log(C/N) – log(O/N) plane. Symbols for data are used as in Figure 13. The starred symbols represent the yields from stellar evolution by Marigo (2001), where the four-point stars are for the LMC and six-point stars are for the SMC PNe. Within the same set of models, different points indicate different initial mass, and the smaller symbols represent the yields from the evolution of $M_{\text{ini}} < M_{\text{min}}$. The sun locus would be at (0.61; 0.88) in this plot, but it is not marked to avoid overlap with a target and few model points.

Figure 16. SMC and LMC PN abundance sum of C, N, and O vs. carbon abundance. Symbols used are same as in Figure 13.

and we used smaller symbols for stars with progenitor masses too low to have undergone the HBB ($M_{\text{HBB}}^\text{min} \sim 3.5$ and $4.0 M_\odot$ for the SMC and the LMC models, respectively, as in Marigo 2001). The abundance ratios measured for round and elliptical PNe correspond very well with the final yields predicted for the evolution of the lower mass end of LIMS in both the SMC and the LMC. Similarly, the massive models are in good agreement with the abundance ratios of C, N, and O in the PNe in the LMC with bipolar and BC morphologies. These results are extremely satisfying verifications of difficult model predictions. In Figure 16, we plot the sum of carbon, oxygen, and nitrogen abundances versus carbon of LMC and SMC PNe. Figure 16 is a classical diagram for assessing the efficiency of CNO cycling. The CNO abundance would be preserved if these elements were only acting as catalysts, while carbon enhancement via third dredge-up is clearly present in the SMC PNe.

Based on a study of LMC and SMC optical lines, Stanghellini et al. (2003) found that the observed intensity ratio $I_{\lambda 5007}/I_{\lambda 1909}$ seems to increase with metallicity. The photoionization models of Stanghellini et al. (2003) show that metallicity impacts the relative emission line strength of the major coolants and that the UV carbon emission lines have a significant effect in cooling PNe with low metallicities. Now that we have observations of carbon emission lines in both SMC and LMC PNe, we can assess the validity of those models. In Figure 17, we plot the histogram of the $I_{\lambda 5007}/I_{\lambda 1909}$ line intensity ratio for the SMC (the thick line) and the LMC (the thin, shaded histogram) PNe. The distributions, which have been normalized for the number of PNe in each sample, appear to be different at very low and very high intensity ratios, indicating that the carbon emission line is a very important coolant for most SMC PNe. We calculate that the average line intensity ratio is 6.23 and 2.36, respectively, for the LMC and SMC PNe, and the median values of $I_{\lambda 5007}/I_{\lambda 1909}$ are $3.34 \pm 2.98$ and $1.83 \pm 0.83$ for the LMC and the SMC PNe, respectively, marking a sharp difference in the dominant cooling agents at different metallicities. The carbon $\lambda 1909$ line is a much more efficient coolant, with respect to the $\lambda 5007$ line, in the SMC than the LMC PNe. The C IV line can also be an important coolant in the low-metallicity, highly ionized PNe.

Figure 17. Cooling of SMC and LMC PNe through the major emission lines. The $I_{\lambda 5007}/I_{\lambda 1909}$ histogram is shown for the SMC (the heavy line) and the LMC (the light shaded histogram) PNe. Note the very different distributions for $I_{\lambda 5007}/I_{\lambda 1909} < 1$ and $> 6$.

5. CONCLUSIONS

The present paper provides a database of 11 SMC PNe whose carbon abundance has been accurately derived through prism spectroscopy with the ACS/HST. The number of reliable SMC PNe with well measured carbon abundances has doubled, finally allowing statistically useful analysis of carbon production and CNO cycling in PNe at the very low metallicity in the progenitors of SMC PNe.

By comparing the abundances of SMC and LMC PNe, we found that most observed SMC PNe are carbon rich, except in a couple of unusual cases, SMP 22 and SMP 25, where there is indication that the progenitors underwent the HBB process. This seems to indicate that most SMC PNe derive from low-mass ($M_{\odot} < 3.5 M_\odot$) and low-metallicity progenitors. By comparison, the LMC has a much varied PN population, where both carbon-rich and carbon-depleted PNe are present, indicating a larger range of PN progenitor mass and metallicity, including several PNe whose progenitors could be in the 3–5 $M_\odot$ mass range. While a larger SMC PN sample would improve the impact of these findings, it is worth recalling that both LMC and SMC samples were selected homogeneously, and that with the present observations we have increased the statistical significance of the SMC PN sample to almost the same level of confidence as the LMC sample (Shaw et al. 2006).
The CNO abundances in Magellanic Cloud PNe can now be used to test the predictions of models of stellar evolution. We found that the data agree impressively with the final yields from Marigo (2001) models, calculated for both the SMC and LMC metallicities. In particular, the yields calculated for turnoff mass $<3.5$, and 4.0, $M_\odot$ seem to reproduce PN abundances of round and elliptical PNe in the SMC and the LMC, respectively. Yields from the more massive LIMS encompass well the bipolar PNe abundances. If we accept the model results, then the production of carbon through the CNO cycle in the SMC PNe shows that most SMC PN progenitors are in the low-mass end of the LIMS mass range, while the LMC PNe could have progenitors in the whole LIMS range. In some cases, extra mixing or other processes that were not included in the current models are needed to justify the observed CNO abundances.

Compared with the SMC, the LMC has been a site of recent or ongoing star formation and heavy-element enrichment. One of the most important results of our study is that the average abundance of carbon in SMC PNe is $\sim 1.5$ times higher than the average carbon measured in LMC PNe. Using the Magellanic Cloud sample of PNe with determined carbon abundances and whose IRS/Spitzer spectra allow a determination of the dust chemistry (Stanghellini et al. 2007), we find that \( \langle C/H \rangle = (4.69 \pm 3.33) \times 10^{-5} \) for Magellanic Cloud PNe with carbon-rich dust. This is $\sim 35$ times greater than the same ratio for PN with oxygen-rich dust, \( \langle C/H \rangle = (1.35 \pm 0.88) \times 10^{-5} \), confirming a strong correlation between dust and gas chemistry.

The present observations also show that the high-excitation carbon emission lines are major or dominant coolants in the low-metallicity SMC PNe, as predicted by Stanghellini et al. (2003), much more so than in LMC PNe, where the $\lambda$1909 line intensity is typically a small fraction of the $\lambda$5007 line strength.

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