Carbon Abundances in Compact Galactic Planetary Nebulae: An Ultraviolet Spectroscopic Study with the Space Telescope Imaging Spectrograph (STIS)

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Abstract

We surveyed a sample of compact Galactic planetary nebulae (PNe) with the Space Telescope Imaging Spectrograph on the Hubble Space Telescope (HST) to determine their gas-phase carbon abundances. Carbon abundances in PNe constrain the nature of their asymptotic giant branch (AGB) progenitors, as well as cosmological recycling. We measured the carbon abundances, or the limits thereof, of 11 compact Galactic PNe, notably increasing the sample of Galactic PNe whose carbon abundance based on HST ultraviolet spectra is available. The dust content of most targets has been studied elsewhere from Spitzer spectroscopy; given the compact nature of the nebulae, both UV and IR spectra can be directly compared to study gas- and dust-phase carbon. We found that carbon-poor (C/O < 1) compact Galactic PNe have an oxygen-rich dust type, while their carbon-enhanced counterparts (C/O > 1) have carbon-rich dust, confirming the correlation between gas- and dust-phase carbon content that was known for Magellanic Cloud PNe. Based on models of expected final yields from AGB evolution, we interpret the majority of the carbon-poor PNe in this study as the progeny of ∼1.1–1.2 M⊙ stars that experienced some extra mixing on the red giant branch. They went through the AGB but did not go through the carbon star phase. Most PNe in this group have a bipolar morphology, possibly due to the presence of a subsolar companion. The carbon-enhanced PNe in our sample could be the progeny of stars in the ∼1.5–2.5 M⊙ range, depending on their original metallicity.

Unified Astronomy Thesaurus concepts: Planetary nebulae (1249)

1. Introduction

Planetary nebulae (PNe), the gas and dust remnants of low- and intermediate-mass stars (LIMS; ∼1 < M/M⊙ < 8), are key probes of the chemical evolution in galaxies. Understanding how LIMS evolve is extremely important in astrophysics, since the LIMS population represents most of the stellar mass in galaxies. Most LIMS are believed to go through the asymptotic giant branch (AGB) phase, which prominently contributes to the integrated luminosity of a galaxy (e.g., Maraston 2011). Furthermore, AGB stars and the subsequent PNe are major dust producers. It is thus important to have the best observational data sets to constrain the nucleosynthesis models at various metallicities.

At the end of their lives, LIMS become major producers of C and N. Nucleosynthesis of these elements occurs in the stellar core. Mass loss brings these elements to the interstellar medium after they are dredged up to the stellar surface. The PN abundances of the major elements are typically straightforward to measure by analyzing emission lines. While ground-based telescopes allow the direct observation of most key elements in Local Group PNe, carbon remains elusive, since its major collisionally excited and bright emission lines, C II λ2325–29, C III λ1909, and C IV λ1550, are emitted in the ultraviolet. Carbon recombination lines are emitted in the optical spectrum, and they are much fainter than the collisionally excited lines in the UV; combined with nearby oxygen emission features, they are useful to constrain the C/O ratio (García-Rojas et al. 2018). Yet carbon is an essential element; carbon and its compounds relate to the origin of life in the universe, which makes it fundamental to understand where it forms and how its abundance grows over time. Furthermore, stellar evolution theory predicts that processes defining the final yields of nitrogen and carbon, such as third dredge-up (TDU) and hot bottom burning (HBB), strongly depend on the progenitor mass; thus, carbon concentration in PNe (especially relative to nitrogen) is a signature of the mass range of the progenitor LIMS and, ultimately, their age.

To understand dust formation and evolution in the context of stellar and galactic evolution, Stanghellini et al. (2007) observed dust features in Magellanic Cloud PNe from the Spitzer Space Telescope Infrared Spectrograph (Spitzer/IRS) spectra and gas-phase PN properties from Hubble Space Telescope (HST) imaging and UV spectroscopy and found that nebular gas chemistry, dust composition, and PN morphology are correlated. The IRS spectra carry a wealth of information on the dust continuum and solid-state dust features. Intermediate mass stars in the Magellanic Clouds produce symmetric (i.e., nonbipolar), carbon-rich PNe with carbon-rich dust (CRD) features (such as polycyclic aromatic hydrocarbons, hydrogenated amorphous carbon grains, etc.), while high-mass progenitors produce generally bipolar, nitrogen-rich PNe with
oxygen-rich dust (ORD; e.g., amorphous and crystalline silicates).

We have learned from the Magellanic Cloud PN project that
the simultaneous availability of IRS spectra, narrow- and
broadband HST images, and optical and UV spectra yields
detailed insight into the post-AGB and PN evolution. We need
to build a similar data set for compact Galactic PNe—that
whose maximum angular radii are smaller than ~4"-5"
— to extend the analysis across metallicities. Compact Galactic PNe,
defined and analyzed by Stanghellini et al. (2016), have many
advantages with respect to extended PNe when used as
evolutionary probes. The relevant property that makes compact
PNs compelling in this study is that their spectra, from UV to
optical to IR, can be acquired with just one pointing to include
the whole nebula, which in turn provides plasma diagnostics
and chemical analysis of the PN as a whole. Their compact
shapes allow the study of the dust content with Spitzer/IRS and
other spectroscopy without the problem of aperture correction.
Furthermore, compact Galactic PN spectra, whether UV,
optical, or IR, are analyzed identically in the Galactic samples
and the Magellanic Clouds; thus, the comparative analysis of
the various samples is direct and unambiguous.

A detailed search through the literature disclosed that only a
few Galactic PNe with Spitzer/IRS spectroscopy have reliable
gas-phase carbon abundances (Ventura et al. 2017). We thus
embarked on this spectroscopic study of carbon in compact
Galactic PNe. Our observing goals were to acquire a sizable set of
UV spectra to detect strong UV carbon transitions of PNe
whose Spitzer/IRS spectra were also available and whose
nitrogen, oxygen, and other elemental abundances were
available in the literature; measure their gas-phase carbon
content; and study their correlation with the dust-phase carbon
and, in the context of PN progenitors and their evolution,
compare their surface chemistry with the final surface chemical
abundances of AGB stars, with the final goal of constraining
the mass and metallicity (and age) of the progenitors. The HST
is the only telescope, and the Space Telescope Imaging
Spectrograph (STIS; Kimble et al. 1998; Woodgate et al. 1998)
the best instrument, that can be used to measure carbon
abundances in compact Galactic PNe.

This paper represents the first systematic study of carbon
abundances—from direct observations of UV lines—of
compact Galactic PNe with known dust-phase chemistry. With
this study, we considerably augmented the observational data
with which to constrain AGB evolution in the Galaxy. Prior to
this study, there were only seven Galactic PNe, compact or
otherwise, whose HST UV spectra could be employed to
determine the gas-phase abundance of carbon (Dufour et al.
2015; Henry et al. 2015), in addition to the Henry et al. (2008)
observations of the halo PN DdDm 1 (PN G061.9+41.3). Another
~30 Galactic PNe had been previously observed with the
International Ultraviolet Explorer, providing reliable carbon
abundances mostly for nearby, extended PNe (Ventura et al.
2017, and references therein). Dust- and gas-phase carbon
properties were studied by Delgado-Inglada & Rodríguez
(2014) based on a sample of mostly extended Galactic PNe and
with aperture corrections applied to several targets. Finally, as a
comparison, carbon abundances are available for 11 Small
Magellanic Cloud (SMC) and 24 Large Magellanic Cloud
(LMC) PNe, all from UV emission lines and observed with the
HST (Stanghellini et al. 2005, 2009).

2. Observing Program

2.1. Observations

Our observations were obtained in HST program GO-15211,
which was extended by the mission in program GO-16013,
with observations taking place between 2018 January 5 and
2020 September 20. We selected our targets to be spatially
compact Galactic PNe (with apparent radii \( \theta \leq 5^\prime \)), preferen-
tially already observed in the optical wavelengths with HST
(e.g., program GO-11657), which, in addition to providing their
size and morphology, greatly simplifies target acquisition. We
observed each target with far-UV (FUV) G140L and near-UV
(NUV) G230L spectroscopic configurations with STIS. The
aperture was placed on the center of each nebula to detect the
central stars (CSs) as well. The program is not dissimilar from
the UV HST program targeting LMC PNe (GO-9120), since
PNe in the LMC have similar maximum extensions to our
compact Galactic PNe. Our allocation of 75 targets in Cycles
25 and 26 was only partially fulfilled, as expected in
“snapshot” mode. Because we were primarily interested in
obtaining total fluxes in critical lines of C, in order to facilitate
a direct comparison with ground-based optical observations,
each target was observed with the \( 6^\prime \times 6^\prime \) aperture. As all or
most of the flux from these targets is emitted within about 5"
(Stanghellini et al. 2016), this aperture is nearly equivalent to
slitless spectroscopy and carries the advantage of excluding
bright UV sources in the field that could pose a risk to the
MAMA detectors. This choice comes at the cost of
diminished spectral resolution, which is set primarily by the
angular extent of each target.

Our observing plan specified exposures with both the FUV-
MAMA detector with the low-resolution grating G140L and the
NUV-MAMA with G230L. The observing log is presented in
Table 1. Observations for three targets failed due to instrument
or telescope problems, but they are included in Table 1 (with
zero observing time) for completeness. Also notable is that
PN G286.0-06.5 was observed in both programs.

We planned the exposure times to achieve a signal-to-noise
ratio \((S/N) > 10\) in the brightest emission lines of carbon over
the extent of the target. This is sufficient to obtain good C
abundances, since one or more of the observable ions
\(^{12}\text{C}^+\), \(^{13}\text{C}^+\), and \(^{13}\text{C}^+\) will dominate the emission. The exposure
durations were, however, limited to a maximum of 1200 s to
ensure that both FUV and NUV spectra could be obtained for
each target within a single orbit; single-orbit visits are required
for “snapshot” programs.

All data analyzed for this program are available in the
Mikulski Archive for Space Telescopes at the Space Telescope
Science Institute (STScI). The specific observations we
analyzed can be accessed via 10.17909/t9-n5ef-9894.

2.2. Data Reduction and Spectrum Extraction

We reduced the data through flat-field correction with the
distributed python package stistools, which embodies the
STScI CALSTIS calibration pipeline as a library. Our
observations used an available but unsupported observing
mode, which obligated us to rectify the flattened images and
extract the 1D spectra with custom software. The raw data were
first processed with the CALSTIS task basic2d to perform 2D
image reduction. To initialize the data quality array, basic2d
uses a bad-pixel reference table and performs a bitwise logical
“OR” on the pixels in the initial data quality file. This routine
| PN G | Name | Date       | ObsIDa | Grating | Durationb (s) | Aperture (arcsec) |
|------|------|------------|--------|---------|---------------|------------------|
| 003.9–14.9 | Hb 7 | 2019 May 22 | odk350aq | G140L    | 218           | 2.0              |
| 004.3–02.6 | H 1-53 | 2019 May 23 | odk350hq | G140L    | 218           | 0.25             |
| 006.1+08.3 | M 1-20 | 2018 Jun 6  | odk362kq | G230L    | 0             | …                |
| 011.1+07.0 | Sa 2-237 | 2019 Mar 9 | odk354yq | G140L    | 37            | 0.25             |
| 025.3–04.6 | K 4-8 | 2018 Aug 28 | odk304haq | G140L    | 236           | 1.00             |
| 032.5–03.2 | K 3-20 | 2018 Sep 10 | odk357dbq | G140L    | 1200          | 0.25             |
| 038.4–03.3 | K 3-20 | 2018 Sep 10 | odk358buq | G140L    | 1200          | 0.50             |
| 038.7–03.3 | M 1-69 | 2018 May 28 | odk371dq | G140L    | 152           | 0.25             |
| 042.9–06.9 | NGC 6807 | 2018 Nov 5 | odk371dq | G230L    | 155           | 1.00             |
| 048.5+04.2 | K 4-16 | 2018 Nov 5  | odk308f | G230L    | 17            | 0.25             |
| 053.3+24.0 | Vy 1-2 | 2019 Mar 30 | odk310b | G230L    | 206           | 3.00             |
| 068.7+14.8 | Sp 4-1 | 2018 Aug 6  | odk310q | G140L    | 155           | 1.25             |
| 095.2+00.7 | K 3-62 | 2018 Jul 22 | odk364q | G230L    | 1200          | 0.25             |
| 097.6–02.4 | M 2-50 | 2019 Jul 11 | odk315o | G230L    | 1200          | 0.25             |
| 107.4–02.6 | K 3-87 | 2018 Mar 6  | odk315o | G230L    | 1200          | 0.25             |
| 232.8–04.7 | M 1-11 | 2018 Jun 2  | odk379q | G230L    | 175           | 1.50             |
| 264.4–12.7 | He 2-5 | 2018 Aug 20 | odk321eq | G140L    | 149           | 2.75             |
| 275.3–04.7 | He 2-21 | 2020 Jul 28 | oe7322h | G230L    | 1200          | 2.50             |
| 278.6–06.7 | He 2-26 | 2018 Jan 7  | oe7322h | G230L    | 1200          | 2.50             |
| 281.0–05.6 | IC 2501 | 2018 Mar 3 | odk365q | G230L    | 154           | 5.00             |
| 285.4+01.5 | Pe 1-1 | 2019 Jun 10 | odk324e | G140L    | 1200          | 0.25             |
| 285.4+02.2 | Pe 2-7 | 2019 Feb 2  | odk324e | G140L    | 1200          | 0.25             |
| 286.0–06.5 | He 2-41 | 2019 Feb 2  | odk326y | G140L    | 623           | 2.00             |
| 295.3–09.3 | He 2-62 | 2018 Jan 5  | oe7326h | G230L    | 567           | 623              |
| 309.0+00.8 | He 2-96 | 2018 Jun 15 | oe7326h | G230L    | 567           | 623              |
| 336.9+08.3 | St Wr 4-10 | 2019 Feb 27 | odk337d | G140L    | 0             | …                |
| 340.9–04.6 | Sa 1-5 | 2020 Aug 27 | odk337d | G230L    | 0             | …                |
| 343.4+11.9 | H 1-1 | 2020 Sep 20 | odk345h | G140L    | 0             | …                |
| 351.3+07.6 | H 1-4 | 2019 May 5  | odk345h | G140L    | 842           | 1.00             |
| 355.2–02.5 | H 1-29 | 2019 Jun 17 | odk374f | G230L    | 76            | 1.00             |

Notes.

a Observation identifiers beginning with “odk3” correspond to HST program GO-15211, and those beginning with “oe73” correspond to GO-16013.

b A duration of zero indicates an onboard failure of the exposure.
appropriately combines data quality information from neighboring pixels before performing the OR operation in order to take Doppler smearing and binning into account. The primary cause of dark current in the MAMA detectors is believed to be a phosphorescent glow from impurities in the detector window. In short timescales, the glow varies exponentially with temperature; in a long timescale, the behavior becomes more complex. With basic2d, we subtracted the dark signal using relevant reference files and updated the science data quality files for bad pixels in the dark reference file. Lastly, we used basic2d to correct for pixel-to-pixel and large-scale sensitivity gradients using a p-flat and l-flat reference file, respectively. The p-flats are configuration-dependent (grating, central wavelength, detector, etc.) flat-field images with no large-scale sensitivity variation, and the l-flats are subsampled flat-field images that contain large-scale sensitivity variation across the detector. The basic2d task combines these two types of flat field and then corrects the science image by dividing it with the combined flat-field image. The data quality and error arrays are updated again to account for flat-fielding.

To perform spectral extraction, we need to consider that the spectral trace orientation on the STIS detectors slowly changes over time and is also subject to an offset that is unique to each observation caused by the mode selection mechanism positioning. To rectify this, we use the IRAF task mktrace, which corrects the orientation of the spectral trace, recenter it on a new row, and provides the new center as an output. However, it takes an approximate center as an input. To determine our best approximate center, we fit a 1D Gaussian model to a column with a strong signal from the trace. We also use this Gaussian model to determine approximate box parameters, used in our last extraction step. Although the Gaussian fitting does provide approximate box parameters, we adjust these manually on the actual image.

The x2d task then rectifies the image using bilinear point interpolation. For each point in the rectified output image, there is a corresponding point in the distorted input image, and the four nearest pixels are bilinearly interpolated to determine the value to be assigned to the point in the output image. This mapping from output pixel to input images is done by using the dispersion relation and the spectral trace table generated by mktrace. Pixel number as a function of wavelength is given by the dispersion relation, and the displacement in cross-dispersion direction at each pixel along the dispersion direction is given by the trace table. Appropriate corrections are applied to take binning into account. Lastly, the x2d task converts the counts to surface brightness in erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ arcsec$^{-2}$.

Examples of the 2D spectra are shown in the top and middle panels of Figures 1–4. The 2D spectra clearly show the footprint of the nebular shape as observed in correspondence of the major nebular emission lines. For example, the elliptical (Figures 1–3) versus bipolar (Figure 4) shapes are clearly identified for most individual spectral images. The 2D spectra also show the presence of stellar continua.

After masking the bad pixel in the 2D image, we extract the 1D spectra using our own python routine. We choose a spectral extraction box as large as the largest feature in the 2D spectral image, and we subtract the average background from two regions on either side of the spectral trace. If the PN has been previously observed with the HST cameras—i.e., it has been spatially resolved—we use the measured photometric diameter as a guide to the initial guess for the extraction box size.

The final spectra have been calibrated through the default wavelength calibration, since we did not observe simultaneous comparison arcs. This is not an issue for the UV spectra of Galactic PNe, where the major emission lines are easily recognizable, as we can see in the 2D spectral images. We thus adjusted the zero-point of the wavelength solution of each extracted 1D spectrum based upon the brightest known nebular emission lines.
emission features. Figures 1–4 (bottom panels) also show the extracted 1D spectra of the PNe.

### 3. Analysis

#### 3.1. Emission Line Measurements

The rectified 2D spectrograms and the extracted 1D spectra of the observed PNe have been inspected for features. For the following, we discuss only targets that show at least one nebular emission line with sufficient S/N for the subsequent analysis. We list these PNe in Table 2. Table 2 also gives the ancillary parameters that are relevant for our analysis and includes the distance from the Galactic plane; the He, N, and O atomic abundances; the nebular morphology; and the dust type derived from IRS spectral analysis. All parameters are referenced in the table.

We measured the emission line fluxes with the IRAF task *splot*. The emission line intensities have been measured via Gaussian fit, which is a good model for all of the measured lines. The flux uncertainties given for the emission lines are the random error estimates assuming the Gaussian shape. We checked that this approximation worked for all of the lines used.
for abundance measurements. Naturally, this procedure assumes, as is often the case in spectroscopic analysis, that the continuum level is well identified. If the continuum was mismatched, there would be additional uncertainty, up to about 10%, for the flux lines. All fluxes and their uncertainties derived from the above measurement procedure were scaled to $I_{\text{H}\beta} = 100$. The observed intensities and extinction-corrected fluxes are related by

$$\frac{I_{\lambda}}{I_{\beta}} = \frac{F_{\lambda}}{F_{\beta}} \times 10^c \times 100.$$  \hspace{1cm} (1)

Here $c$ is the logarithmic extinction at $\text{H}\beta$ for each target, and $f_{\lambda}$ is the wavelength-dependent reddening function from

Table 2

| PN G   | $|a_{\text{type}}|^b$ | log(He/H) + 12$^b$ | log(N/H) + 12$^b$ | log(O/H) + 12$^b$ | Morph. | Dust Type$^e$ |
|--------|------------------|------------------|------------------|------------------|-------|---------------|
| 006.1+08.3 | 1.09             | 11.02 ± 0.05     | 7.78 ± 0.08      | 8.56 ± 0.08      | E$^f$ | CRD; aromatic/aliphatic |
| 025.3–04.6 | 0.84             | 11.01 ± 0.03     | 7.79 ± 0.06      | 8.59 ± 0.09      | P$^g$ | ORD; amorphous |
| 042.9–06.9$^f$ | 0.84         | 10.99 ± 0.03     | 8.00 ± 0.24      | 8.57 ± 0.08      | B$^h$ | ORD; crystalline/amorphous |
| 053.3+24.0$^f$ | 3.16            | 11.23 ± 0.05     | 7.90 ± 0.05      | 8.46 ± 0.05      | B$^h$ | N/A |
| 068.7–14.8 | 3.24             | ...              | ...              | 8.29 ± 0.19      | E$^h$ | CRD; aromatic |
| 107.4–02.6 | 0.56             | 11.01 ± 0.05     | ...              | 8.44 ± 0.10      | E$^h$ | CRD; aliphatic |
| 275.3–04.7 | 0.37             | 11.08 ± 0.04     | 7.64 ± 0.09      | 8.52 ± 0.11      | E$^h$ | CRD; aliphatic |
| 278.6–06.7 | 0.45             | 11.00 ± 0.04     | 8.00 ± 0.13      | 8.51 ± 0.10      | E$^h$ | CRD; aliphatic |
| 281.0–05.6 | 0.61             | ...              | 8.16 ± 0.00      | 8.63 ± 0.10      | E$^h$ | CRD; aromatic/aliphatic |
| 286.0–06.5 | 0.76             | 10.99 ± 0.03     | 7.66 ± 0.08      | 8.32 ± 0.07      | B$^h$ | CRD; aliphatic |
| 295.3–09.3 | 1.63             | 11.01 ± 0.03     | 7.87 ± 0.12      | 8.15 ± 0.07      | B$^h$ | ORD; amorphous |
| 351.3+07.6 | 2.90             | ...              | ...              | ...              | BC$^e$ | ORD; amorphous |

Notes:

$^a$ Calculated using the Gaia DR2-calibrated distance scale (Stanghellini et al. 2020), where $d_{\text{scale}}/d_{\text{par}} = 0.95 ± 0.25$. The PN G351.3+07.6 distance was derived directly from the DR2 Gaia parallax.

$^b$ The He, N, and O abundances used in this study are from García-Hernández & Górny (2014), except for PN G042.9–06.9 and PN G275.3–04.7 (Perinotto et al. 2004) and PN G053.3+24.0 (Stanghellini et al. 2006).

$^c$ Dust types are from Stanghellini et al. (2012), except for PN G006.1+08.3 (Perea-Calderón et al. 2009; García-Hernández et al. 2010) and PN G281.0–05.6 (Otsuka et al. 2014).

$^d$ Uncertain morphology based only on UV slitless spectroscopy (this study).

$^e$ Morphology derived from WFC3 imaging through a selection of filters (Stanghellini et al. 2016).

$^f$ May be a halo PN.
Table 3
Relative Emission Line Fluxes

| Wave (Å) | ID   | 006.1–08.3 | 025.3–04.6 | 042.9–06.9 |
|----------|------|------------|------------|------------|
|          |      | $F_A$ | $I_A$ | $F_A$ | $I_A$ | $F_A$ | $I_A$ |
| 1907+09  | C III | 5.08 ± 0.46 | 173.92 ± 15.75 | 10.03 ± 0.96 | 45.65 ± 4.39 | 6.86 ± 0.51 | 23.53 ± 1.76 |
| ~2810    | ?     | 4.57 ± 0.13 | 26.55 ± 0.74 | ... | ... | ... | ... |
|          | log $F_{HI}$ | −11.93 ± 0.01 | −12.44 ± 0.10 | −11.41 ± 0.01 | ... | ... | ... |
|          | $e_{HI}$ | 1.17 ± 0.10 | ... | ... | ... | ... | ... |

Table 4
Relative Emission Line Fluxes

| Wave (Å) | ID   | 053.3–24.0 | 068.7–14.8 | 107.4–02.6 |
|----------|------|------------|------------|------------|
|          |      | $F_A$ | $I_A$ | $F_A$ | $I_A$ | $F_A$ | $I_A$ |
| 1640     | He II | 88.67 ± 0.42 | 101.63 ± 0.48 | ... | ... | ... | ... |
| 1907+09  | C III | 15.39 ± 0.72 | 17.90 ± 0.84 | 197.86 ± 0.67 | 615.87 ± 2.08 | 9.10 ± 0.34 | 396.6 ± 14.86 |
| 2325–29  | C II | 20.74 ± 0.52 | 24.11 ± 0.60 | 38.24 ± 0.70 | 118.48 ± 2.15 | ... | ... |
| 2470     | [O III] | 3.11 ± 0.31 | 3.49 ± 0.34 | ... | ... | ... | ... |
| 3023     | O III | 4.89 ± 0.52 | 5.20 ± 0.55 | ... | ... | ... | ... |
| 3043+47  | O III | 2.09 ± 0.55 | 2.22 ± 0.59 | ... | ... | ... | ... |
|          | log $F_{HI}$ | −11.51 ± 0.01 | −11.95 ± 0.10 | −13.21 ± 0.20 | ... | ... | ... |
|          | $e_{HI}$ | ... | 0.38 ± 0.10 | 1.25 ± 0.10 | ... | ... | ... |

Table 5
Relative Emission Line Fluxes

| Wave (Å) | ID   | 275.3–04.7 | 278.6–06.7 | 281.0–05.6 |
|----------|------|------------|------------|------------|
|          |      | $F_A$ | $I_A$ | $F_A$ | $I_A$ | $F_A$ | $I_A$ |
| 1548+50  | C IV | 134.6 ± 0.44 | 1206.5 ± 3.94 | 33.89 ± 0.28 | 141.51 ± 1.19 | ... | ... |
| 1640     | He II | 48.97 ± 0.42 | 396.5 ± 3.40 | 18.70 ± 0.22 | 73.03 ± 0.87 | ... | ... |
| 1907+09  | C III | 120.1 ± 1.28 | 1139.9 ± 12.15 | 137.67 ± 0.32 | 621.27 ± 1.46 | 54.73 ± 0.47 | 271.20 ± 2.32 |
| 2325     | C II | ... | ... | 16.71 ± 3.31 | 74.97 ± 1.48 | ... | ... |
| 2424     | [Ne IV] | 11.81 ± 0.97 | 88.09 ± 7.23 | ... | ... | ... | ... |
| 2836     | O III | ... | ... | 3.53 ± 0.18 | 7.32 ± 0.37 | ... | ... |
| 3133     | O III | ... | ... | 6.39 ± 0.53 | 11.31 ± 0.94 | ... | ... |
|          | log $F_{HI}$ | −12.15 ± 0.10 | −11.55 ± 0.01 | −10.67 ± 0.01 | ... | ... | ... |
|          | $e_{HI}$ | 0.8034 ± 0.10 | 0.50 ± 0.10 | 0.53 ± 0.05 | ... | ... | ... |

Cardelli et al. (1989). We obtain the final line intensities by using the H$_{β}$ fluxes and extinction constants from Stanghellini et al. (2016), except for PN G001.6+8.3 and PN G281.0–05.6, whose parameters are from Cahn et al. (1992). The measured line fluxes and intensities and the H$_{β}$ fluxes and extinction constants are given in Tables 3–6. More details on individual nebular spectra are given in Section 4.

3.2. Plasma Diagnostics
The electron densities ($N_e$) and temperatures ($T_e$) adopted for the abundance calculation are given in Table 7. Most of the diagnostics have been taken from the literature (cited within the table), since the UV ranges observed in this work do not include any diagnostic lines. When both $T_e$[N II] and $T_e$[O III] were available for the same PN, we used $T_e$[N II] for the C$^+$ abundances and $T_e$[O III] for the C$^{2+}$ and C$^{3+}$ abundance calculation. We always preferentially used the [S II] densities, if available, for a given PN. When the electron density or temperature was not available, we calculated them from published diagnostic line intensities (Acker et al. 1992) using the pyneb package in python (Luridiana et al. 2015). In one case, we could not find plasma diagnostics or diagnostic flux ratios in the literature; thus, we adopted a typical value of $N_e$ to calculate abundances, as noted in Table 7.

3.3. Abundance Analysis
We measured ionic abundances from the line fluxes and ancillary diagnostics with the pyneb package and the atomic data set therein, as also given in Table 8. All ionic abundances are intended in terms of H$^{+}$; thereafter, we use the term “ionic abundance” to mean “ionic abundance ratios to H$^{+}$.” The derived abundances of the carbon ions are presented in Table 9; the ionic abundances of other elements derived from the same UV spectra are in Table 10.

Uncertainties in the line intensity and plasma diagnostics both contribute to the final abundance errors.
We measured the uncertainties in the ionic abundances due to line uncertainties (including reddening correction) with Monte Carlo simulations assuming a Gaussian distribution centered on the measured intensities. The resulting uncertainties are in the 0.001–0.04 dex range for the ionic abundances.

The contributions to the abundance uncertainties from the line ratio are the only ones that we can actually calculate with our data set. On the other hand, by far, the dominant source of uncertainty in PN abundances stems from plasma diagnostics. We adopted electron density and temperature values from the literature, and none of the original references in Table 7 give uncertainties for these parameters. We thus estimate the magnitude of the final abundance uncertainty, as it stems from guessed 5% and 10% uncertainties in both the electron density and temperature. Temperature shifts due to inhomogeneity in the atomic data sets, e.g., Juan de Dios & Rodríguez (2017), are folded into these assumed values.

We found that the electron density uncertainty has no effect on the final ionic abundances. In fact, for all ions and PNe, a 10% uncertainty in the density produces ionic abundance uncertainties in the $1 \times 10^{-3}$–$3 \times 10^{-5}$ dex range.

On the other hand, a 10% uncertainty in $T_e$ propagates into a mean uncertainty of $0.39 \pm 0.03$ dex in the ionic abundances. The assumption of $\Delta T_e \sim 10\%$ is conservative, while a ±5% uncertainty is more realistic and translates into a $0.17 \pm 0.01$ dex uncertainty in the final abundances. The final uncertainties are thus dictated by our guesses of the electron temperature uncertainties. Since these initial guesses translate into abundance uncertainties in such narrow ranges, we will use their averages as final uncertainties.

It is worth noting that a formal analysis would yield to a final C/H abundance uncertainty that is $\sqrt{N}$ times the ion uncertainty adopted, where $N$ is the number of available ions.

We calculated atomic carbon abundances from the ionic values using the scheme by Kingsburgh & Barlow (1994) to correct for unobserved ionization stages. In our spectra, we expect to see the transitions relative to C II, C III, and C IV. In
Table 9

| PN G   | log(C+/H+) | log(C2+/H+) | log(C3+/H+) | ICF(C) | log (C/H) + 12 |
|--------|------------|-------------|-------------|--------|---------------|
| 006.1+08.3 | ... | −3.42 | ... | ... | 8.58* |
| 025.3–04.6  | ... | −4.14 | ... | 1.04  | 7.88 |
| 042.9–06.9  | −4.29 | ... | 1.90 | 7.99 |
| 053.3–24.0  | −4.48 | ... | ... | 7.84b |
| 068.7+14.8  | −3.96 | −3.19 | ... | ... | 8.88 |
| 107.4–02.6  | −3.10 | ... | ... | 8.90a |
| 275.3–04.7  | −3.34 | −3.67 | 1.04 | 8.85 |
| 278.6–06.7  | −4.29 | −3.29 | −4.22 | ... | 8.80 |
| 281.0–05.6  | −3.12 | ... | 1.08 | 8.92 |
| 286.0–06.5  | −4.07 | −3.15 | ... | ... | 8.90 |
| 295.3–09.3  | −4.05 | ... | ... | ... | 7.95a |

Notes.

* The atomic abundance is a lower limit because we could not correct for unseen emission lines.

b The atomic abundance is uncertain (see text).

The section below, where applicable, we describe how the atomic carbon abundance has been derived and which literature data we used to derive the ionization correction factor for carbon (ICF(C)). Both ionic and atomic carbon abundances and the ICFs are listed in Table 9.

4. Individual PNe

4.1. PN G003.9–14.9

The 2D STIS UV spectrograms spatially resolve this PN for the first time (this PN was previously unobserved with HST). We found that an extraction box of 2″ encompasses most of the spectra in both gratings. The nebula has an elliptical shape, although the morphology determination is uncertain on the UV spectra. The G140L image shows a very good spectral trace with high S/N; it shows the C IV emission feature with a P Cygni profile, whose spatial extension indicates its stellar origin. We could not detect He II λ1640 in the G140L spectrum, even if a faint emission feature corresponding to He II λ4686 has been detected in the optical spectrum (Tylenda et al. 1994). The P Cygni feature with emission centered around 1232 Å could be N V λ1239–43, similar to what was observed in the LMC PNe SMP 18 and SMP 25 (Stanghellini et al. 2005). The G230L spectrum does not show emission lines.

4.2. PN G006.1+08.3

A box of 2″ encompasses the nebular UV spectrum of this Galactic bulge, roughly elliptical PN, previously unobserved with HST. This PN had not been previously spatially resolved from the ground (Tylenda et al. 2003). Our STIS program acquired only the G230L spectrum, showing a (likely) C III] emission line at 1890 Å (∆λ ~ 17). Another notable feature at λ ~ 2810 Å is unidentified. We note a strong nebular continuum for λ > 2300 Å. The stellar spectrum is prominent, although an estimate of the CS temperature is problematic, given the lack of the G140L spectrum. We could not find the optical line’s strengths to estimate the ICF to correct for the unobserved C III] line; thus, the atomic carbon abundance in Table 9 is a lower limit thereof.

4.3. PN G025.3–04.6

The STIS G230L spectrum shows nebular continuum emission and a likely emission feature that could be identified as C III] at 1907–09 Å. The G140L spectrum does not show obvious emission lines. The atomic carbon abundance in Table 9 has been derived from C = ICF(C) × C2+. We used the fluxes by García-Hernández & Górny (2014) to derive the oxygen abundances needed to estimate the ICF.

4.4. PN G038.4–3.3

Both STIS spectra of this PN are noisy. We were unable to make unambiguous line identifications.

4.5. PN G042.9–06.9

The only emission feature observed for this PN is in the G230L spectrum, which we interpret to be C III] at 1907–09 Å. We used the optical emission lines from García-Hernández & Górny (2014) to correct for the unseen emission lines via ICF analysis as in PN G025.3–04.6.

4.6. PN G053.3+24.0

The He II feature at 1640 Å in the G140L spectrum is very strong, which is indicative of a medium- to high-excitation PN. The only other feature in the G140L spectrum is a very faint, noisy emission at λ ~ 1243 Å that could be N V. The flux of the emission line identified as C III] at 1907–09 Å in the G230L spectrum corresponds to a very broad feature, which can be used as an upper limit to the emission line flux. We also list in Table 4 a couple of possible O III features, although the wavelengths of the identified lines are not perfect matches to those observed. This is not a low-excitation PN; thus, we did not apply the ICF corrections to measure the atomic carbon...
abundance following Kingsburgh & Barlow’s (1994) prescription.

4.7. PN G068.7+14.8

The C IV emission has a P Cygni profile and is not spatially extended, while the C II] and C III] carbon lines show spatial extension. We infer that the former is of stellar origin. Since the optical 4686 Å emission line has been detected (Tylenda et al. 1994), this could be a medium- to high-excitation PN. We thus derive the abundance without ICF, as in PN G053.3+24.0. The G140L spectrum shows a faint line emission at \( \lambda \sim 1242 \) Å, which could be N V, possibly of stellar origin as well.

4.8. PN G097.6–02.4

Both UV STIS spectra are very noisy, and we were unable to make unambiguous line identifications.

4.9. PN G107.4–02.6

The STIS G140L spectrum is too noisy for line detection, and the C III] emission line is the only line detected in the G230L spectrum. There is no information in the literature about the low-excitation O II lines; thus, we cannot calculate the ICF to get the total carbon abundance. As a result, the carbon abundance in Table 9 is a lower limit thereof. This is a similar case to PN G006.1+08.3.

4.10. PN G232.8–04.7

Both UV STIS spectra are too noisy for line identification.

4.11. PN G264.4–12.7

Both the C IV and N V features in the G140L spectrum have P Cygni profiles, and they both look stellar in origin. The C II] and C III] lines are very faint and extended in the G230L spectrum, and their abundances could not be measured.

4.12. PN G275.3–4.7

The presence of He II in the G140L spectrum indicates a medium- to high-excitation PN. In order to correct for the missing C II] line, we use the optical oxygen lines from the literature (Milingo et al. 2002), from which we estimate ICF (C) = 1.037.

4.13. PN G278.6–06.7

The G140L spectrum is characterized by strong He II and C IV emission lines from the whole volume of the PN, thus indicating a medium- to high-excitation PN, which agrees with the presence of the optical emission line at 4686 Å, corresponding to He II emission (Tylenda et al. 1994). There is a noisy emission line corresponding to N V in the G140L spectrum as well. As clearly seen in Figure 3, the spatial distribution of the C III] and C II] emission shows ionization stratification. The atomic carbon abundance is the sum of the measured ionic abundances.

4.14. PN G281.0–05.6

The C III] line is the only emission line detected in the G230L spectrum and presents itself as a very broad emission. We correct for the undetected C II] emission from the optical oxygen lines in the literature (Milingo et al. 2002), finding ICF(C) = 1.084, which has been used to calculate the total atomic abundance in Table 9. There are P Cygni lines corresponding to N V and C IV in the STIS G140L spectrum. Their extensions indicate that they are probably of stellar origin.

4.15. PN G286.0–06.5

There is a very noisy emission, not measured, that could be He II at 1640 Å. There are N V and C IV emission lines in the G140L spectrum with P Cygni profiles; their extension indicates that they are probably of stellar origin. The atomic carbon abundance has been calculated by the sum of the C II and C III abundances.

4.16. PN G295.3–09.3

In the G140L spectrum, the emission line corresponding to N V has a P Cygni profile, and the emission flux given has a high uncertainty given the shape of the underlying continuum. The identification of the [O III] line is uncertain. The only nebular carbon line detected here is C III]. There are no lower-excitation transition intensities available in the literature for this PN to correct for C II]; thus, the atomic abundance in the table is a lower limit thereof.

4.17. PN G351.3+07.6

Both N V and C IV emission in the G140L spectrum have P Cygni profiles. There are no emission features detected in the G230L spectrum. This is a similar case to PN G003.9–14.9 and PN G264.4–12.7.

5. Comparison between PN Abundances and Stellar Evolutionary Models

In this section, we characterize the observed PN sample in the framework of the stellar evolution of LIMS. The chemical abundances of PNe reveal the nucleosynthesis and mixing processes experienced by the star during the previous evolutionary phases. Before entering the PN stage, stars of masses 0.8 ≤ M/M\(_\odot\) ≤ 8 experience H- and He-shell burning phases while climbing along the AGB (Schwarzschild & Härm 1965; Iben 1975, 1976).

The low-mass threshold (0.8 M\(_\odot\)) is partly dependent on the description of mass loss adopted, as a more efficient mass loss during the red giant branch (RGB) and the phases following the core helium burning favor a rapid loss of the external mantle, which might prevent the star from experiencing the thermal pulses. The high-mass threshold (8 M\(_\odot\)) is sensitive to the assumption of core overshoot during the main sequence, since the core mass at the beginning of the AGB is correlated with the amount of extra mixing assumed during the core H-burning phase.

The high-mass threshold is valid in this context for the solar and slightly subsolar metallicity, and it was determined on the basis of the stellar models used in the present investigation, which adopt a moderate overshoot from the external border of the convective core during the main sequence. If we do not take into account extra mixing, this high-mass threshold would shift to \(\sim 10 M\odot\). The high-mass threshold of AGB evolution also depends on metallicity. The minimum mass for carbon to be ignited in the stellar core also depends on metallicity, and it is M = 8 M\(_\odot\) at solar metallicity, and 7.5 M\(_\odot\) at Z = 3 × 10^{-4},
and even lower at lower metallicities (see, e.g., Dell’Agli et al. 2019).

The AGB evolution is characterized by the gradual expansion and cooling of the external regions of the star, which favor the loss of the entire envelope with high rates of mass loss and the injection into the interstellar medium of gas reprocessed by internal nucleosynthesis (see Herwig 2005, for an exhaustive review).

The surface chemistry during the AGB phase varies due to two main physical processes whose relative importance depends on the mass of the progenitor. Stars with $M < 4 M_\odot$ experience repeated episodes of TDU. These are deep inward penetrations of the surface convection during which the innermost layers of the stellar envelope reach triple-$\alpha$ nucleosynthesis sites; such sites are greatly enriched in $^{12}$C, which is then rapidly transported to the stellar surface, owing to the high efficiency of the convective currents (e.g., Iben & Renzini 1983; Busso et al. 1999).

Repeated TDU events can lead the carbon-to-oxygen number ratio to exceed unity ($C/O > 1$), and the AGB becomes a carbon star. Stars with $M \sim 4 M_\odot$ experience HBB, whose ignition occurs when the temperature of the convective envelope reaches values higher than 30–40 MK, which allows for efficient $^1$H burning via proton capture nucleosynthesis in the most internal regions of the envelope (Renzini & Voli 1981; Blöcker & Schönberner 1991; Sackmann & Boothroyd 1991). This process has the main result of converting carbon into nitrogen in the surface regions, thus preventing the formation of carbon stars and enhancing nitrogen abundances.

The latest generation of AGB models (see Karakas & Lattanzio 2014, for a summary review) are the best to describe the detailed evolution of the chemical variation at the stellar surface. By comparing the chemical pattern measured in the PNe with the chemical abundances predicted for the final stage of the AGB evolution for stars with different masses and metallicities, it is possible to characterize the individual sources in terms of their epoch of formation and initial chemistry (Ventura et al. 2015b, 2016b, 2017).

For model comparison, we use the ATON models (Ventura et al. 1998) at solar ($Z = 0.014$; Ventura et al. 2018) and subsolar ($Z = 0.008, 0.004$; Ventura et al. 2013) metallicities. These models are presently the only ones where the full integration of the equations of stellar structure and the AGB evolution for stars with different masses and metallicities. We find significant dissimilarities for stars that experience the HBB ($M > 3 M_\odot$), both in the evolution of the main physical parameters and in the surface chemistry. The reason is related to the different description of turbulent convection adopted by the various models, particularly in the inner regions of the convective envelope. On the other hand, consistency was found in the low-mass domain, where stars do not experience HBB. All sources analyzed in this paper descend from $M < 2.5 M_\odot$ progenitors; therefore, the conclusions drawn in the present context are substantially independent of the stellar models used.

In Figure 5, we examine the PN carbon abundances in the context of stellar and nebular evolution. In the left panel, we

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**Figure 5.** Left panel: $\log(N/H) + 12$ vs. $\log(C/H) + 12$; right panel: $\log(O/H) + 12$ vs. $\log(C/H) + 12$. In both panels, carbon abundances are from this paper (Table 9), and other abundances are from the literature (Table 2 and references therein). The black symbols represent the abundance groups from our carbon analysis and interpretation, as given in the legend. Open squares are low-carbon PNe, which we interpret as descending from half-solar metallicity stars; filled squares are for enhanced carbon PNe descending from low-metallicity stars; and the crossed square represents PN G053.3+24.0, whose carbon abundance is uncertain. Open circles represent the representative carbon abundance error bars derived from a 5% and 10% uncertainty in the electron temperature, for reference. In both panels, the symbols in color connected by lines represent the final abundances of AGB stars with initial metallicities $Z = 0.014$ (blue squares), 0.008 (red triangles), and 0.004 (green pentagons), calculated from the models. The numbers indicate the initial mass of the model in solar mass. In the left panel, the dashed red arrows point to the final C and N abundances of the 1 (left arrow) and 1.5 (right arrow) $M_\odot$ models if deep mixing in the RGB is taken into account. The yellow area in the left panel highlights the range of final C and N values of the ejecta from stars with mass $1 M_\odot < M < 1.5 M_\odot$ if deep mixing in the RGB is taken into account.
compare data and models in the (C/H)–(N/H) plane, and in the right panel, we compare those in the (C/H)–(O/H) plane. The plotted data (black symbols) refer to the abundances derived in this paper. The error bars shown in the figure give the typical carbon abundance uncertainty in dex if we assume 5% or 10% uncertainties in the electron temperatures. Note that these uncertainties stem from an initial guess, are narrowly distributed, and thus can be used for all of the plotted points. Also note that uncertainties in electron densities, line fluxes, and reddening are too small to make a difference in the plotted bar, as described in Section 3. The model surface chemistries of different initial masses and metallicities are indicated with colored symbols. The models with the same initial metallicity have been connected with lines, and the initial stellar masses are also indicated in the figure.

The ATON models and the chemical loci in Figure 5 do not include the effects of deep mixing during the RGB evolution, which is effective for $M < 2 M_{\odot}$. For these models, the N/H in Figure 5 is the lower limit of the theoretical expectations for stars exposed to deeper mixing while ascending the RGB. Carbon abundances are also affected by the extra mixing in stars with $M \sim 1 M_{\odot}$. In these stars—experiencing only a few, if any, TDU events—the extra mixing has the effect of lowering C/H; thus, the model carbon abundances should be interpreted as upper limits.

In the following discussion, we match the data points and models, assuming that binary interaction with stellar companions is not affecting the evolution and nucleosynthesis of the primary AGB star. This means we assume that the progenitor stars do not evolve through the common-envelope stage; i.e., they are either single stars or members of wide binary stars. We found that PNe with carbon abundances can be sorted into two major groups.

5.1. PNe with Low Carbon Abundances

The PNe PN G025.3–04.6 and PN G042.9–06.9 (open squares in Figure 5), PN G053.3+24.0 (crossed square), and PN G295.3–09.3 (filled square) are characterized by similar low carbon abundances ($\log(C/H)+12 \sim 7.9$) and C/O ratios below unity. The carbon abundance of PN G053.3+24.0 is uncertain. By their carbon abundances, it is unlikely that any of these PNe had progenitors with masses in the $1.5 M_{\odot} \leq M \leq 3 M_{\odot}$ range, since, if that was the case, they would exhibit significantly higher carbon abundances ($\log(C/H)+12 > 8.5$). Furthermore, their nitrogen abundances ($\log(N/H)+12 < 8$) seem to indicate that their progenitors did not go through the HBB process, seemingly excluding high-mass ($>3 M_{\odot}$) progenitors. This scenario is reinforced by their low He abundances ($\log(He/H)+12 < 11.2$; see Table 2), which seem to indicate that their progenitors did not experience a second dredge-up.

From the comparison with models (Figure 5, left panel), the carbon abundances of these PNe would be compatible with those expected in the external layers of $\sim 1 M_{\odot}$ AGB stars with initial half-solar metallicity (red triangles), but the nitrogen abundances measured for these PNe are higher than the final surface abundances of AGB stars with such metallicity and mass.

The effect of extra mixing on the RGB is included in the left panel of Figure 5. To this end, we estimate the differences of the final yields if we include extra mixing for initial masses of 1 and $1.5 M_{\odot}$ following the prescriptions of Lagarde et al. (2019, and references therein). The yellow area of the figure indicates the final surface chemical abundances for progenitors in the $1-1.5 M_{\odot}$ mass range and half-solar metallicity that had experienced extra mixing on the RGB. If we assume that the progenitor mass of the observed low-carbon PNe is in the $\sim 1.1-1.2 M_{\odot}$ range, the extra mixing would make both the carbon and nitrogen abundances compatible with the observations.

Most PNe in the low carbon abundances group (black squares in Figure 5) are compatible with progenitors with half-solar metallicity. The only exception is PN G295.3–09.3 (filled square), which has a lower O abundance. This PN could still derive from a similar evolutionary path to the other PNe in this group, except with a lower-metallicity progenitor. The right panel of Figure 5 shows well the effect of initial metallicity on the O/H abundances, and it is used to resolve the degeneracy between the initial composition and CNO evolutionary effects.

Three of the low-carbon PNe (i.e., all except PN G053.3+24.0) have been observed with Spitzer/IRS; thus, their dust type is known. All three are ORD PNe with an amorphous dust type—PN G042.9–06.9 displays additional weak crystalline silicate features—in agreement with the gas-phase carbon abundances and the observed nebular C/O ratios below unity, thus reinforcing the connection between the gas- to dust-phase chemistry and our initial mass and metallicity interpretation.

The PNe in the low-carbon group are characterized by morphology that departs from symmetry, such as bipolar and point-symmetric. Observational analysis of large PN samples associates asymmetric morphology with high nitrogen abundances and low Galactic latitude, both hinting at younger, more massive progenitors (e.g., Manchado et al. 2000). Interestingly, PNe with low carbon abundances seem to be located away from the Galactic plane (see Table 2), based on their distances and uncertainties calibrated with Gaia parallaxes (Stanghellini et al. 2020), which is incompatible with high-mass progenitors.

From the viewpoint of modeling, bipolar PN morphology has been linked to the presence of binary (sub)stellar companions (e.g., Jones & Boffin 2017; Decin et al. 2020) or to magnetic fields (e.g., García-Segura 1997), although it has been shown that strong deviations from spherical symmetry via the action of magnetic fields generally require a binary companion (e.g., Nordhaus et al. 2007; García-Segura et al. 2014). It appears that the observations for the low-carbon PNe agree with a low-mass progenitor, possibly with a substellar companion.

5.2. PNe with Enhanced Carbon Abundances

The PNe PN G006.1+08.3, PN G278.6–06.7, and PN G281.0–05.6 (open circles in Figure 5); PN G107.4–0.26, PN G275.3–04.7, and PN G286.0–06.5 (filled circles); and PN G068.7+14.8 (not in the figure for lack of ancillary abundances) have enhanced C abundance or a lower limit thereof ($\log(C/H)+12 \geq 8.5$), which is compatible with several TDU episodes in the progenitor star. Following this interpretation, these PNe should have progenitors with masses in the $1.5-3.0 M_{\odot}$ range, which were formed around 0.25–1.5 Gyr ago. To verify this interpretation, we should also consider the N and O abundances available in the literature (see Table 2). Two nebulae, PN G006.1+08.3 and PN G281.0–05.6, have nitrogen and oxygen abundances compatible with masses in the $1.5-3.0 M_{\odot}$ range formed with a half-solar metallicity or slightly higher. A progenitor of $1.5-3.0 M_{\odot}$ and metallicity...
between half-solar and solar is also compatible with PN G278.6-06.7 (note that above 1.5 \(M_\odot\), the effects of extra mixing are marginal; Lagarde et al. 2019). For this PN, a progenitor of a higher mass (\(~3.5\ M_\odot\)) and lower metallicity would also comply with the observed C, N, and O abundances, although its argon abundance would rule it out; the expected argon abundance at \(Z = 0.004\) is 12+log(Ar/H) = 5.65, while the measured abundance is definitively higher (García-Hernández & Görny 2014 measured log(Ar/H)+12 \(~6\)). The N and O abundances of PN G286.0-06.5 and PN G275.3-04.7 are compatible with \(Z = 0.004\) models of masses in the range of 1.5–3.0 \(M_\odot\). The same type of progenitor is plausible for PN G107.4-02.6, even if in this case, the N abundance is not available from the literature.

Three of these PNe have round or elliptical morphology, two have uncertain morphology from the 2D UV spectrograms (no resolved optical imaging available), and one (PN G286.0-06.5) is an elongated bipolar. All PNe in the high-carbon group have CRD, either aromatic or aliphatic (two objects display both dust types), consistent with the gas-phase abundances and showing complete agreement between the dust- and gas-phase carbon.

### 6. Discussion

We determined that several PNe in our sample have C/O < 1. We can infer that their progenitors did not go through the carbon star phase by comparing their chemistry to the stellar AGB models. Objects PN G25.3-4.5, PN G42.9-06.9, and PN G295.3-09.3 seem to have evolved from \(~1\) to \(1.2\ M_\odot\) progenitor stars whose surface C and N abundances are the result of a few TDU events and deep mixing during the RGB, respectively (yellow area in the left panel of Figure 5). All low-carbon PNe have faint spectra, and they are far from the Galactic plane. The latter observable is consistent with the scenario that the progenitors of these low-carbon PNe are low-mass AGB stars that were in binary systems with a substellar body as a companion. Decin et al. (2020) showed that all 14 C/O < 1 AGB stars observed with the Atacama Large Millimeter/submillimeter Array under their ATOMIUM program are aspherical, suggesting that binary interaction may dominate the evolution of low-mass AGB stars with low C/O. It is worth noting that the carbon abundance of PN G053.3+24.0 is uncertain; thus, its classification within this evolutionary group is also uncertain. Note also that its optical morphology (Stanghellini et al. 2016) is rather different from that of the other PNe in this group. The group of PNe that have enhanced carbon abundances could have progenitors with masses in the \(\sim 1.5–2.5\ M_\odot\) range, which were formed around 0.25–1.5 Gyr ago. Unfortunately, all carbon abundances of this group of PNe are either lower limits or uncertain. Nonetheless, their status of carbon-rich PNe is supported by their Spitzer/IRS CRD dust types.

In Figure 6, we plot the log(C/O) versus log(O/H)+12 for the compact Galactic PNe studied here and elsewhere, together with the samples of Magellanic Cloud PNe. In this figure, we included all compact PNe with UV-based carbon abundances published in the literature or studied in this paper. We indicate the PN population by the symbol shape: triangles for the SMC; squares for the LMC; circles for compact Galactic PNe (this study; O, N, and C abundances from Tables 2 and 9); and plus signs, crosses, and asterisks for compact Galactic PNe from, respectively, Dufour et al. (2015), Henry et al. (2000), and Kingsburgh & Barlow (1994). We use the symbol color to indicate the dust status of the PNe from Spitzer/IRS spectroscopy: cyan symbols for featureless dust spectra, red symbols for CRD PNe, blue symbols for ORD PNe, and black symbols for no IRS dust information. Since we selected the Galactic PNe from both this study and the literature based on their apparent sizes (\(\theta < 5\)\(^\prime\)), their diameters are smaller than the Spitzer/IRS aperture; thus, the comparison with the Magellanic Cloud and compact Galactic PNe of the other samples is meaningful, as all spectra include the flux from the whole nebular surface. We found complete segregation of CRD PNe in the C/O > 1 quadrant and ORD PNe in the C/O < 1 quadrant. This occurs independently of stellar or galactic metallicity. Our carbon analysis indicates that the sample studied here has a predominantly supersolar carbon abundance, with median carbon \(\langle C/H\rangle_{\text{med}} = \pm 5.6 \pm 3.5 \times 10^{-5}\). We plot in the figure the fit by Nicholls et al. (2017) derived by interpolating stellar abundances (see references cited therein). The nebular enrichment of carbon is clearly seen for CRD PNe, independent of the studied population, a confirmation of the PN carbon enrichment role (e.g., Henry et al. 2018), with the added value of the correlation with dust composition. It is worth noting that the correspondence between dust and gas abundances—i.e., all CRD PNe have C/O > 1, and all ORD PNe have C/O < 1—is stronger in our study than in the work.
by Delgado-Inglada & Rodríguez (2014), who found a few exceptions to this correspondence, likely due to the mismatch between the Spitzer and other spectral apertures and the inclusion of extended Galactic PNe in their sample.

7. Summary

We selected 75 compact or moderately extended Galactic PNe to be observed with HST/STIS through the G230L and G140L gratings to detect their UV emission lines for carbon abundance measurements. Only 30 of the targets have been observed in two “snapshot” programs, and we measured the carbon abundances of 11 targets. With the support of ancillary data sets, we found a striking correlation between gas-phase (this and other studies of UV-based carbon abundances in compact Galactic PNe) and dust-phase (Spitzer/IRS) carbon abundances; i.e., all CRD PNe studied here have C/O > 1, and all ORD PNe have C/O < 1. By studying these correlations together with those found in Magellanic Cloud PNe, we found that this one-to-one correlation is independent of the initial progenitor’s metallicity. We compared the loci of the C, N, and O abundance patterns on different diagnostic planes for our PN sample with the footprints of the final yields from stellar evolution models. We found that the progenitors of most carbon-poor PNe are likely in the M/M∗ < 1.2 range, with slightly subsolar metallicity. Identifying such old progenitors is useful to calibrate a radial metallicity gradient for old Galactic probes (Stanghellini & Haywood 2018). It is worth noting that, while Gaia distances from parallaxes are not available for all of the CSs of the compact Galactic PNe studied here, statistical distances based on Gaia DR2 parallaxes indicate that the PNe in this group are generally far from the Galactic plane, an additional indication of a very old Galactic population. We also found that the carbon-enhanced PNe in our sample are the likely progeny of carbon stars in the 1.5 < M/M∗ < 3 range. This work presents a limited but important sample of carbon abundances from UV lines in compact Galactic PNe, considerably augments the number of Galactic PNe whose carbon abundances have been measured based on HST spectra, and greatly expands the sample for which gas- and dust-phase carbon can be simultaneously available in compact PNe.

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