Space Telescope Imaging Spectrograph slitless observations of Small Magellanic Cloud Planetary Nebulae: a study on morphology, emission line intensity, and evolution.  

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ABSTRACT

A sample of 27 Planetary Nebulae (PNs) in the Small Magellanic Clouds (SMC) have been observed with the Hubble Space Telescope Imaging Spectrograph (HST/STIS) to determine their morphology, size, and the spatial variation of the ratios of bright emission lines. The morphologies of SMC PNs are similar to those of LMC and Galactic PNs. However, only a third of the resolved SMC PNs are asymmetric, compared to half in the LMC. The low metallicity environment of the SMC seems to discourage the onset of bipolarity in PNs. We measured the line intensity, average surface brightness (SB), and photometric radius of each nebula in Hα, Hβ, [OIII] λ4959 and 5007, [NII] λ6548 and 6584, [SII] λ6716 and 5731, He I λ6678, and [OI] λ6300 and 6363. We show that the surface brightness to radius relationship is the same as in LMC PNs, indicating its possible use as a distance scale indicator for Galactic PNs. We determine the electron densities and the ionized masses of the nebulae where the [SII] lines were measured accurately, and we find that the SMC PNs are denser than the LMC PNs by a factor of 1.5. The average ionized mass of the SMC PNs is 0.3 M☉. We also found that the median [OIII] /Hβ intensity ratio in the SMC is about half than the corresponding LMC median. We use Cloudy to model the dependence

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of the [O\textsc{iii}] /H\beta ratio on the oxygen abundance. Our models encompass very well the average observed physical quantities. We suggest that the SMC PNs are principally cooled by the carbon lines, making it hard to study their excitation based on the optical lines at our disposal.

Subject headings: Stars: AGB and post-AGB — stars: evolution — planetary nebulae: general — Magellanic Clouds

1. Introduction

To understand the final phases of stellar evolution of intermediate mass stars, one has to study the interplay of the stellar and nebular components. During its lifetime, and especially toward the end of its life, a star of mass between 1 and 8 M\odot experiences extreme mass loss, and nuclear burning episodes followed by the occurrence of the dredge-ups that change the chemical mix of its envelope. A planetary nebula is formed by the ejected envelope of its central star at the tip of the AGB, and it can be shaped in part by a fast wind from the remnant, during its subsequent evolution.

The process of PN formation and evolution has been studied both theoretically and observationally for decades, yet many fundamental questions remain only partially solved. For example, what is the origin of the different morphologies, and what phenomenon, or series of phenomena, decide the final PN morphology? Does progenitor mass alone dictate the dynamic evolution rate and expansion speed? What is the connection between binary star evolution and the physical properties of PNs (chemistry, morphology, etc.)? What is the role of the interstellar medium (ISM) on PN structure? How much is the nebular gas mix contaminated by the interaction with the interstellar medium? To what extent do PNs enrich C, N, and O in the ISM?

A number of studies based on the comparison of PN and stellar properties with models have shed light on some of these and other questions. Even so, observations of planetary nebulae and their central stars are notoriously difficult to compare with adequate theoretical models for a variety of reasons. First, the stellar and nebular components are often observed and analysed separately, yet they are of common origin; the nebula carries, in its chemical composition, the nuclear burning and dredge up history of the stellar progenitor, and its morphology carries the signature of the wind history of its central star. Second, the inferred evolutionary times of the stellar and nebular component within the post-AGB phase are unsynchronized. Although theoretical models have been developed to explain the nuclear evolution of the AGB and post-AGB phases, mass loss rates and geometries of the envelope ejection have not yet been successfully modeled from the stellar viewpoint. Dynamic theoretical models have explained the observed nebular morphology only if ad hoc assumptions are made about the evolution of the central star. Photoionization models are able to predict the strength of optical and UV emission lines that appear during the evolution of PNs, but once again without yielding much insight into the numerous details of morphology, the evolution of the progenitor star.

We believe that only with large samples of well defined, high quality data sets that allow the identification and significance of the crucial nebular and stellar physical parameters can one make steps forward in this field of study. Large amounts of data of high quality will be able to constrain the stellar and nebular models, so that open questions on PN formation and evolution may be addressed.

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In the quest for acquiring the best observational sets for model testing, PNs in the Magellanic Clouds (SMC, LMC) deserve special attention. LMC and SMC PNs have known distances and low field reddening, in contrast with Galactic PNs. Our aim in the last few years has been that of acquiring and analyzing a large sample of LMC and SMC PNs spectra and images, that, together with the data existing in the literature, permits the construction of an ideal data set for model testing, and for comparison with disk and halo Galactic PNs.

The importance of observing and classifying SMC PNs morphology, and discerning the evolutionary stage of their central stars, is multifold. First, the ambient metallicity of the SMC is closer to that of a primordial galaxy than the LMC or the Galaxy are, thus making the SMC an unique astrophysical laboratory to study metal depleted yet resolved stellar populations. Second, by observing a sizable sample of SMC PNs with HST (i.e., resolving their morphology and size) we will be able to study the dependence between morphology and abundances in a low metallicity environment.

The Space Telescope Imaging Spectrograph (STIS) has proven to be a very efficient way to acquire broad band and monochromatic images of PNs smaller than about 2". In two previous papers of this series (Shaw et al. 2001; Stanghellini et al. 2002) we have presented the results from the STIS slitless spectroscopy of the first set of 29 LMC PNs. In this paper, we present the results relative to the observations of 27 SMC PNs (HST program No. 8663). In §2 we discuss the observation strategy and the data analysis of this particular observing set; we include there the rationale for target selection, the data calibration and slitless spectral extraction, the spectral analysis, the photometric radii determinations, and the morphological classification. In §3 we present the scientific results derived from this set of images and spectra, including the discussion of the line intensity, the surface brightness in the different lines, the excitation of the nebulae, and their optical extinction, all discussed across morphological classes. Section 4 discusses the results so far and the future endeavors in this study. The analysis of the central stars of SMC PNs from the images and spectra of the data set of Program 8663 will be discussed in a separate paper.

2. Observations, data calibration, and analysis

2.1. Target selection, and misclassifications

Our list of 55 targets was compiled with the intent to obtain data of all known SMC PNs, with accurate coordinates. Most targets came from the Hα survey catalog by Meyssonier & Azzopardi (1993). The majority of these PNs are bright enough to be observed in snapshot mode (less than 1 HST orbit). We included in the target list three objects that have been previously observed with the Wide Field and Planetary Camera 1, and with the Faint Object Camera. This was done to check the consistency of the morphological classification obtained with archived instruments and the STIS.

Our HST observations were performed in snapshot mode. The targets were selected from the original list by the scheduling specialists at STScI, accordingly to the available observing slots. Typically, shorter exposure (i.e., brighter targets) are favored. The program was completed at the 53% level, which is normal for a successful snapshot proposal. Among the 29 targets observed (Table 1), 27 are the SMC PNs analyzed in this paper. Two (MG 2 and Ma 1796) are misclassified H II regions, whose images and analysis will be published in another paper. As it turned out, faint targets are slightly underrepresented in our sample.
2.2. Observing technique

The observations were acquired with STIS. All observations were made with the CCD detector, in direct imaging (50CCD) and slitless mode. The spatial scale of the CCD is 0.051 arcsec pixel$^{-1}$, corresponding to 0.0144 pc pixel$^{-1}$ at the distance of the SMC. This allows a very good spatial resolution to study PN morphology and size, comparable to what used in ground-based imaging observations of Galactic PNs.

Each imaging observation was split in two, to allow easy cosmic rays removal. The slitless spectra were acquired with the G430M and G750M gratings for most nebulae. Observations with the G430M grating cover the range 4818 Å to 5104 Å at 0.28 Å pixel$^{-1}$, and those with the G750M grating cover the range 6295 Å to 6867 Å at 0.56 Å pixel$^{-1}$. The exposures where planned to have a good signal-to-noise ratio in the [O$\text{iii}$] $\lambda$5007 and H$\alpha$ lines. Several additional lines have been detected in many PNs, including H$\beta$ and [O$\text{iii}$] $\lambda$4959 using G430M, and [O$\text{i}$] $\lambda\lambda$6300, 6363, [S$\text{ii}$] $\lambda\lambda$6312, [N$\text{ii}$] $\lambda\lambda$6548, 6584, He I $\lambda$6678, and [S$\text{ii}$] $\lambda\lambda$6716, 6731 using G750M. In some cases the G430M exposures were skipped, limited by the HST snapshot duration.

The observing log is reported in Table 1, where we list the targets, the observing date, the data set name, the spectral element used in the observations, and the exposure time and number of exposures obtained. Aliases are identified in the table notes. The STIS data were calibrated using the standard pipeline system, as in the LMC data (Shaw et al. 2001).

Figures 1 through 6 show the observed SMC PNs in the three observing modes: left panels show the broad band CCD images; central panels show the H$\alpha$ and [N$\text{ii}$] images; right panels show, when available, the [O$\text{iii}$] 5007 Å images.

2.3. One dimensional spectral extraction, and line intensities

Spectral analysis of the SMC PNs have been performed similarly to that of LMC PNs (Stanghellini et al. 2002). For most PNs observed, the combination of dispersion and spatial scale allows a clear separation of the monochromatic images for all emission lines. Exceptions are J 27, where broad and monochromatic images are at the limit of detectability, and MA 1682, where the [N$\text{ii}$] and H$\alpha$ images may have partial overlap. No images are severely overlapped, thus the one dimensional spectral extraction was adequate for nebular line flux and ratio analysis. We extract the one-dimensional spectra and applied a photometric calibration using the standard STIS calibration pipeline module x1d (McGrath, Busko, & Hodge 1999). We used extraction boxes for the nebulae large enough to encompass all the nebular features, but snug enough as to exclude most of the sky background from the extraction. Sky background regions were selected for each object to avoid stray stellar photons from field stars. The background was then averaged and subtracted.

We measured emission line intensities with IRAF$^3$ splot task, fitting gaussians to individual lines, while estimating the continuum level. In the cases in which the emission lines were notably non gaussian, we estimated the line flux as measured from the area above the continuum.

In Table 2 we report the measured line intensities for the SMC PNs in our sample. Column (1) gives the common names; column (2) gives the logarithmic H$\beta$ intensities, not corrected for extinction, in erg cm$^{-2}$.

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$^3$IRAF is distributed by the National Optical Astronomical Observatory, which is operated by the Association of Universities for research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
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s−1; column (3) lists the logarithmic optical extinction at Hβ (Osterbrock 1989); columns (4) to (14) give the line intensities for each nebula, relative to Hβ =100, not corrected for extinction. Line identification are given at the heads of the columns.

From the analysis of our spectral line measurements, and given the similarities of this data set to the ones analyzed in Stanghellini et al. (2002), we confirm that the errors in the line intensities of Table 2 (δlogF) are (in dex): δlogF < .05 if logF > −12.25; δlogF < .15 if −12.25 > logF > −12.75; δlogF < .2 if −12.75 > logF > −13.5; δlogF < .25 if −13.5 > logF > −14.5; and δlogF < .55 if logF < −14.5.

In Figure 7 we compare the measured line intensities with those available in the literature. We used the data from selected references (Dopita & Meatheringham 1990, 1991a,b; Vassiliadis et al. 1992). Some authors give the intensity corrected for extinction, so before comparison to the present results we un-correct the intensity ratios by using the extinction constant given in the same reference. We have comparisons for several emission lines in MG 8, MG 13, SMP 1, SMP 6, SMP 11, SMP 13, SMP 14, SMP 17, SMP 25, and SMP 26. A comparison of our fluxes to with previous values (Fig. 7) shows a generally good agreement. The correlation coefficient between the two sets of fluxes is 0.994, with RMS scatter of 0.2 dex. Uncertainties in the reference fluxes are typically quoted 20% to 50% for high and low fluxes respectively, while our errors are generally smaller (Stanghellini et al. 2002). The outlying point in Figure 7 corresponds to the [NII] λ 6584 Å flux measurement of target SMP 17. We believe that our measurement is correct, since the reddened [NII] λ 6584 to λ 6548 intensity ratio is 2.1, while the reference does not detect the [NII] λ6548 Å line.

3. Results

3.1. Dimensions and morphology of SMC planetary nebulae

In Table 3, columns 2 and 3, we give the positions of the central stars of the nebulae from the continuum images, where observed. Alternately, we give the geometric center positions of the PNs. Columns (4) and (5) of Table 3 give the photometric radii of the nebulae, measured as described in Stanghellini et al. (1999), and the nebular dimensions, measured from the 10% brightness contour.

Figures 1 through 6 show the SMC PNs images, exhibiting the same range of morphological types to those of LMC and Galactic PNs. The morphological classification used in this paper is the same as that in the other papers of this series (Shaw et al. 2001; Stanghellini et al. 2002): we classify PNs as Round, Elliptical, Bipolar Core, Bipolar, and Pointsymmetric. We distinguish between Round and Elliptical if the axial ratio is larger than unity by at least 10 percent. Bipolarity follows the classic definition (Stanghellini, Corradi, & Schwarz 1993), while bipolar core is defined in Stanghellini et al. (1999). Note that bipolar core PNs of this sample are defined as such only if their BC is apparent above the 10 percent intensity contour. Morphology is based primarily on the Hα images, which differs only rarely from that of the [OIII] λ5007 images (Manchado et al. 1996a). Column (6) of Table 3 gives the morphological classification. In a couple of cases, we use the terminology of Round and Elliptical PNs with inner structures. These structures may be bipolar cores, although we believe that we have the necessary spatial resolution to make the distinction. Question marks indicate that the morphological determination is ambiguous or uncertain. In the following paragraphs, we describe in detail the morphological types of our sample PNs.

- J 4 (E): the field is crowded, making the ID on the clear image a little uncertain. The spectrum is reasonably well exposed, and shows emission in the full set of emission lines. The nebular morphology is elliptical. We detected extremely faint emission in the [OIII] frame up to 1″.42 from the center of
the PN in the spatial direction.

- **J 18 (R):** This PN is round in H\(_\alpha\) and has an elliptical shape in [N\text{II}] . It does not show a bipolar core. The [N\text{II}] \(\lambda6584\) emission is brighter than H\(_\alpha\) .

- **J 23:** This object is apparently spatially unresolved, and its identification on the clear image is difficult. The stellar spectrum shows strong and broad H\(_\alpha\) , and a weaker \(\lambda6584\) [N\text{II}] line. We also detect He I \(\lambda6678\). The H\(_\alpha\) velocity width appears to be about 200-300 km/s, which is broad for a PN. This object could not be a common symbiotic star, it would have a giant companion with an unusually bright H\(_\alpha\) emission line and a faint underlying continuum Boroson & Liebert (1989).

- **J 27 (B?):** This object is roughly box-shaped, and may be the remnant of a bipolar. The nebula is barely detected in the broad-band exposure, at roughly 20 counts/pixel above the background. The spectrum shows faint [N\text{II}] emission, with some hint of H\(_\alpha\) emission. No central star is detected.

- **MA 1682 (B):** This is an extreme bipolar PN, with a prominent central torus seen edge on. The H\(_\alpha\) and [N\text{II}] lines are very strong in the spectrum, and [S\text{II}] is barely detected; no other lines are detected. We don’t have a blue spectrum. The central star (CS) is easily detected in the continuum image.

- **MA 1762 (E(bc)):** This is an elliptical PN, with a bi-nebulous inner core. We detected H\(_\alpha\) and marginally [O\text{I}] \(\lambda6300\). The CS is easily detected in the continuum image, and in the spectrum.

- **MG 8 (E):** This elliptical PN has a very distinct ring structure, with a hint of ansae (or arms) that extend 0.1 ″ along the major axis from the 10% contour. The arm-like structure leads to a pointsymmetric classification, but to be conservative we classify this elliptical, possibly bipolar core. H\(_\alpha\) is very strong, and [N\text{II}] is apparent but weaker, [S\text{II}] is very weak, and we could also detect a trace of the [O\text{I}] \(\lambda6300\) emission. H\(\beta\) is well exposed, and [O\text{III}] is only a bit stronger. The morphology in [O\text{III}] differs in detail from the H\(_\alpha\) and other line morphology, in that the emission comes primarily from a ring that is inside the emission from most other lines. The CS is exceptionally bright in the continuum image; could it be a binary companion to the true CS?

- **MG 13 (E):** This elliptical PN has a very knotty ring structure, and is classified as E(s). H\(_\alpha\) is very strong, but neither [N\text{II}] nor any other line is detected in the G750M spectrum. The CS is easily detected in the continuum image.

- **SMP 1:** Marginally resolved round or elliptical PN with no detected image of the central star. Most emission lines are present, and there may be a trace of He I at 4927 Å as well. The [S\text{II}] lines are marginally detected.

- **SMP 6 (E):** Elliptical PN, the [N\text{II}] morphology is slightly different from that of the other lines, in that it shows a larger elongation.

- **SMP 8 (R):** This Round PN has very strong H\(_\alpha\) and [O\text{III}] emission, with [N\text{II}] and He I at the 1% level, and [S\text{II}] weaker still. [O\text{I}] is marginally detected at 6300 Å. The CS is detected in the continuum image, but there is a significant contribution from the nebular emission.

- **SMP 9 or J 3 (R):** This round PN has a bright hemisphere of emission to the NE, making the whole somewhat asymmetric in appearance. We are not sure that the inner structure clearly discloses a bipolar core, but there is a lot of structure. H\(_\alpha\) and [O\text{III}] are very strong, but [N\text{II}] is fairly weak. The asymmetry is pronounced in the [N\text{II}] lines. [S\text{II}] and He I, are also present but very weak, and [O\text{I}] \(\lambda6300\) may be marginally detected. The CS has been detected in the continuum image.
• SMP 11 or J 8 (B): This complex bipolar PN has a distinct dark band that divides the bright core into two, unequal lobes. This looks very much like a case of a strong bipolar ring, viewed some distance from the plane. A faint bipolar structure is even evident up to 2″ from the center (particularly to the south), but the ribbed, fan-like structure is projected off-center on the sky, and [N\text{II}] $\lambda6548$ is blended with the H$\alpha$ gaussian wing. H$\alpha$ and [O\text{III}] are very strong, but [N\text{II}] $\lambda6584$ is fairly weak; these lines all show the same morphological structures. [S\text{II}] and He I, are also present but very weak, and [O\text{I}] $\lambda6300$ is also detected. The CS is detected in the continuum image, and possibly also in the G750M spectrum.

• SMP 12 (E): Elliptical PN with detected central star. The central emission shows some structure (Es). In the [O\text{III}] image there is a hint of extended lobe to the east.

• SMP 13 or J 11 (R): the appearance of this PN is nearly stellar in the continuum, but appears very mildly elliptical in the ionization lines. We classify it as round, since the ellipticity is below the 10% level. Faint emission in the [O\text{III}] image is detected up to 1.42″ from the geometrical center. H$\alpha$ and [O\text{III}] are very strong, [N\text{II}], He I, and [S\text{II}] are very weak but detected. Also weak are [O\text{I}] $\lambda\lambda6300, 6363$, and [S\text{III}] $\lambda6312$. The CS may be detected in the continuum image.

• SMP 14 (R): This round PN has a distinct structure in the inner core and faint ansae that extend 0.3″ from the 10% contour. H$\alpha$ is very strong, and [N\text{II}] is detected in the spectrum, but is very weak. [S\text{II}] and He I, are also present but weak. [O\text{III}] is quite strong. The CS is easily detected in the continuum image.

• SMP 17 (E): This is an elliptical PN, with a very faint outer halo that is detected in the continuum image, in H$\alpha$, and in [O\text{III}] at the 0.4% contour level, out to about 1.3″. the inner portion is somewhat elliptical in all the observed lines except [N\text{II}], where it is ring-like. the [O\text{III}] emission shows a marginal bipolar core. H$\alpha$ is very strong, and [N\text{II}] is present but very weak. The CS is detected in the continuum image, but there is a significant contribution from the nebular emission.

• SMP 18 or J 19: This small PN with bright H$\alpha$ and [O\text{III}] emission. The [N\text{II}] extension is smaller than in the other lines. It is barely resolved when compared to the broad band images of the stars.

• SMP 19 or J 20 (R): morphologically similar to J 3, the inner parts of this PN are slightly distorted in the [O\text{III}] lines and H$\alpha$. We classify it as R with structures. There is outer emission of 1″ radius.

• SMP 20: This PN is bright but unresolved. H$\alpha$ and [O\text{III}] are very strong, with [N\text{II}] at the 1% level, and He I, [S\text{II}], and [O\text{I}] weaker still. The CS is detected in the continuum image, but there is a significant contribution from the nebular emission. The stellar spectrum shows a feature at about 6577 Å, which is also seen in a few other targets in our sample.

• SMP 22 (B?): This PN has a very interesting box/ring shape, with a possible emission “arm” toward the east, which is very evident in the [N\text{II}] images (could it be part of the ISM?). It is classified as bipolar. There are at least three high emission features within the ring. The line profiles of all lines but H$\alpha$ and H$\beta$ are split, showing the ring morphology.

• SMP 23 or J 26 (E(bc)): Elliptical PN with a bipolar core.

• SMP 24 (E): Elliptical PN in the H$\alpha$ and [O\text{III}] emission lines, it shows some small scale structures in the light of [N\text{II}]. This nebula may have a faint halo.

• SMP 25 (E): Elliptical Planetary nebula with likely broad stellar H$\alpha$ emission line.
• SMP 26 (P): This PN could be pointsymmetric, with two arms that extend from the NE and SW of the center. It is possible that this PN is elliptical with low ionization ansae. Hα is fairly strong, but [NII] is nearly as bright, and shows the arms much more clearly. The line profiles in the 1D spectra are split in all lines except Hα. No CS is detected in the continuum image.

• SMP 27 (R): This is a (very low ellipticity) elliptical PN. There is a hint of structure in the [NII] images only. Hα and [OIII] are very strong, with [NII] at the 1% level, and He I, [SII], and [OII] weaker still. The CS is detected in the continuum image, but there is a significant contribution from the nebular emission.

• SP 34 (R): This is a round PN, with a faint outer halo that is detected in the continuum image and in Hα at the 5% contour level. The inner portion shows significant asymmetry in all the observed lines, in that the western edge is much brighter. Hα is fairly strong, and [NII] is present but much weaker. No CS is detected in the continuum image.

3.2. Targets in common with prior HST programs

We included in our STIS target list three objects that were previously observed with the Planetary Camera 1 and the Faint Object Camera. The rationale to include a few repeat targets from the sample of Stanghellini et al. (1999) was to check the morphological types and dimensions with both methods and to assess the reliability of the pre-COSTAR archival data. All three were observed before the first HST servicing mission, thus the images suffer for the uncorrected spherical aberration of the telescope mirror. In an HST archival study (Stanghellini et al. 1999) it was found that morphology was well determined with the archived instruments, while dimensions of the nebulae with the photometric method were not always reliable because of the possible presence of fainter extended halos around the images.

Since program No. 8366 was a snapshot program, we could not guarantee exactly which targets would be observed for this comparison. In the end, targets SMP 1 (N1), SMP 6 (N6), and SMP 22 (N67) were re-observed with STIS. The first two targets were observed with PC1 earlier, while SMP 22 had been observed with FOC.

SMP 1 and SMP 6 are small nebulae with very uncomplicated structures. The round (E7?) morphology of these two targets was easily seen in the PC1 data set (Vassiliadis et al. 1998). The early photometric radius measured for these two PNs were 0.12″ and 0.152″, respectively for SMP 1 and SMP 6 was close to our measurements of 0.15″ and 0.19″.

The situation of the bipolar planetary nebula SMP 22 is very different. The complete nebular morphology that we see in most emission lines of the STIS spectra, but in particular in the [NII] lines, is not as evident in the FOC image (Stanghellini et al. 1999), Figure 5. Furthermore, we measure a photometric radius of 0.4″, while the radius from the FOC image is almost three times larger. We reanalyzed these measurements, and noted that a radius of 0.4″ already included about 75% of the total flux, but to encircle the 85% of the flux required 1.37″ radius. From the comparison of the old and new SMP 22 images we conclude that the main morphological features of MC PNs are reliable from the pre-COSTAR images, even if the detailed morphology was not resolved. On the other hand, the measurements of the photometric radii are not reliable.
3.3. Statistics of morphological types

From our analysis we can see that SMC PNs are nicely classified using the same morphological scheme as the LMC and Galactic PNs. In order to increase the sample size for statistical purposes, we include in the present sample three additional SMC PNs described and classified in Stanghellini et al. (1999). After eliminating unresolved objects and repeats, we have at our disposal a sample of 30 SMC PNs whose morphology is well determined. This SMC PN sample constitute nearly 50 percent of all known SMC PNs, thus we consider fairly representative at least of the bright PNs. In Table 4 we give the statistics of PN morphology for the SMC sample as compared to the LMC and Galactic samples from Shaw et al. (2001).

The LMC and SMC samples in columns 2 and 3 of Table 4, have been selected in similar ways, and they have similar observational biases (but none of the extreme selection biases that affect Galactic PN samples toward the Galactic plane). While the fraction of round PNs remains more or less the same in the two samples, the fractions of E and BC in the SMC are respectively twice and one-half those of the LMC. The overall frequency of asymmetric PN in the SMC is only sixty-percent that of the LMC. This remarkable results strongly suggests that the difference between the Magellanic Clouds is reflected in their PN populations: something in the environment of the SMC may not be favorable to the formation of bipolar and bipolar core PNs. Alternately, this may be the result of the low metallicity of the SMC, indicating that the production of the higher mass progenitors of PNs in the SMC has long subsided, and that the low percentage of asymmetric PNs in the SMC is due to the lack of recent star formation episodes. This issue will be better framed once we have complete abundance analysis for the PNs analyzed in this paper.

3.4. Surface brightness–radius relation

We plot the surface brightness versus radius relation for SMC (Fig. 8) and SMC and LMC PNs together, using the LMC data from Stanghellini et al. (2002) (Fig. 9). In Figures 8 and 9 the PNs are coded for their morphological types. We exclude from these plots round and elliptical PNs (both SMC and LMC) with inner (and outer) structure, to avoid possible misclassifications (see above). These figures confirm for SMC PNs the trend that we found for LMC PNs: surface brightness in the light of [O\textsc{iii}] $\lambda 5007$, H$\alpha$, H$\beta$, [O\textsc{i}] $\lambda 6300$, [N\textsc{ii}] $\lambda 6584$, and [S\textsc{iii}] $\lambda 6312$ evolves differently for the different morphological types. The surface brightness to radius relation is very tight in all spectral lines, with the exception of the [N\textsc{i}] emission line, where a larger spread is present. From the lower left panels of Figures 8 and 9 we see that the [N\textsc{ii}] spread is more extreme for bipolar PNs. A possible factor is the higher but more varied nitrogen abundances of bipolar and BC PNs.

3.5. The [O\textsc{iii}] $5007$/H$\beta$ distribution

In Figure 10 we plot a histogram of the ratio of reddening-corrected fluxes of the [O\textsc{iii}] $\lambda 5007$ and H$\beta$ lines (hereafter “[O\textsc{iii}] /H$\beta$”) for the PNs of the SMC and the LMC. The median of the SMC distribution is a factor of two lower than for the corresponding LMC distribution. Specifically, our STIS data yield galaxy averages $<\text{[O\textsc{iii}] /H\beta}>_{\text{SMC}} = 5.7 \pm 2.5$ and $<\text{[O\textsc{iii}] /H\beta}>_{\text{LMC}} = 9.4 \pm 3.1$.

To the best of our knowledge this result is free of object selection biases since both sets of targets were chosen in much the same way. The objects with very low [O\textsc{iii}] /H$\beta$ ratios are very low-ionization objects
whose central stars are presumably too cool to form much O$^{++}$. However, the $[\text{OIII}] / \text{H}$β ratio tends to reflect that of the PNs with the brightest [OIII] and Hβ lines. In general we tend to favor targets with hottest central stars: $T_{\text{eff}} \geq 50,000$ K.

The low median value of $[\text{OIII}] / \text{H}$β in the SMC has been noted before, from ground-based measurements (Webster 1975). However, the STIS images allow us to distinguish between small, bright HII regions and PNs. Using the ground-based data from Stasinska, Richer, & McCall (1998) we derive substantially the same result: $<[\text{OIII}] / \text{H}$β $>$SMC = 4.0 ± 2.8 and $<[\text{OIII}] / \text{H}$β $>$LMC = 9.2 ± 4.2. For reference, the $[\text{OIII}] / \text{H}$β ratio for Galactic PNs is of the order of 15.

The $[\text{OIII}] / \text{H}$β emissivity ratio is physically scaled linearly with the O/H abundance and the fractional ionization of O$^{++}$. Also it depends exponentially on the local electron excitation temperature, $T_e$(O$^{++}$) since electron collisions on the high-energy tail of the free energy distribution excite the transition. Of course, $T_e$(O$^{++}$) depends on O/H and O$^{++}$/O as well. So interpreting the differences between the $[\text{OIII}] / \text{H}$β ratios of the SMC and the LMC is best done using ionization models.

We used the ionization model Cloudy (Ferland 1996) to understand the systematic trends in the behavior of $[\text{OIII}] / \text{H}$β for the SMC, LMC and the Galaxy. We adopted a gas density of 1000 cm$^{-3}$ and standard chemical abundances for the three environments. Galactic abundances for the PNs of the Galaxy are those adopted in the Paris meeting (1985; see Table 7 in the Hazy manual, Ferland 1996). We used LMC average abundances of PNs quoted in Stanghellini, et al. (2000) and SMC average abundances from Stasinska, Richer, & McCall (1998) except for the C/H ratio which comes from Leisy & Dennefeld (1996), where we had selected from their Table 3 only the low-error data. The stellar ionizing spectrum is assumed to be a blackbody with temperatures and luminosities from the H-burning evolutionary tracks for the appropriate galaxian population by Vassiliadis & Wood (1994). Our model parameters are summarized in Table 5.

The predictions of $[\text{OIII}] / \text{H}$β from Cloudy models are shown in Figure 11 for the SMC, LMC, and Galactic PNs. The outcomes of the Cloudy models are rather insensitive to the adopted stellar properties and the assumed density (e.g., Fig. 12). But they are very sensitive to the adopted abundance ratios, especially the oxygen abundance. The model values of $[\text{OIII}] / \text{H}$β are shown as a function of stellar temperature over the range of temperatures encountered by a star of mass $= 2$ M$\odot$, as it evolves from the AGB tip to its maximum post-AGB temperature. At stellar temperatures in excess of $\sim 10^5$ K the $[\text{OIII}] / \text{H}$β ratio is in rough agreement with the present observations (see also Garnett & Dinerstein (1989, 1988)). It is worth noting that the Galactic models presented here are not to be compared directly with the known observed $[\text{OIII}] / \text{H}$β distribution, without accounting for selection effects that hamper Galactic PN statistics. We should clarify that the results of Figure 11 are valid for the input abundances. If, for example, we chose to use as input the average oxygen abundance for SMC ONs from Leisy & Dennefeld (1996) instead of that of Stasinska, Richer, & McCall (1998), the $[\text{OIII}]$ over H$\beta$ emission line would be as high as 7.2.

The cooling processes that determine $T_e$(O$^{++}$) in the SMC, LMC and Galactic PNs are noteworthy. In the Galaxy the primary coolants of PNs with hot central stars are the optical forbidden lines of [OIII] $\lambda$5007 and other lines of O$^+$ and O$^{++}$. However, in environments in which O/H is as low as in the SMC, the primary coolants may become ultraviolet intercombination lines of C$^+$ and C$^{++}$. It will be interesting to confirm these predictions with future UV observations.

Before reaching conclusions and further speculation, let us explore the weight of our assumptions. One is that these models have constant hydrogen density, which is arbitrarily assumed equal to 1000 cm$^{-3}$. By running Cloudy for a constant density model, the outer radius is determined by the Stroemgen sphere. This makes our models larger as stellar temperature increases, reaching a maximum and then decline with the
[O\textsc{iii}] λ5007/H\textbeta intensity ratio. But in order to compare the radii of our models with our data we should make a model for each nebula with the correct radius (i.e., assuming a density profile that reproduces that PN, for example, as determined in hydrodynamic calculations). This will be done in detail in a future paper. For now, let us examine what a difference in the average hydrogen density will make in the [O\textsc{iii}] 5007 flux ratio. In Figure 12 we plot the [O\textsc{iii}] /H\textbeta ratio against the oxygen abundance for the early and the hottest models in the SMC (triangles), LMC (squares), and the Galaxy (circles). The early models correspond to models 1, 6, and 11 of Table 5, with log N\textsubscript{H}=3 cm\textsuperscript{-3}. The hot models have been calculated for log N\textsubscript{H}=2.5, 3, and 3.5 cm\textsuperscript{-3}. We see that varying the density does not affect very much the studied intensity ratio, especially for the low oxygen models. The different hot SMC models in Figure 12 are all within δ I(5007)/I(H\textbeta )=1, and their outer radii are 0.11, 0.25, and 0.55 parsecs for log N\textsubscript{H}=3.5, 3, and 2.5 cm\textsuperscript{-3} respectively.

All models described in this paper have filling factor (ε) equal to unity. Changing the value of the filling factor will also change the outer radius of the nebular models. For example, the hot Galactic model (with log N\textsubscript{H}=3) with ε=0.5 has an outer radius about 1.3 times larger than the model with ε=1. We find that the [O\textsc{iii}] λ5007/H\textbeta intensity ratio with the different radius and filling factor is 95% the ratio in the unity filling factor model, thus the filling factor assumption is not very important the discussion of the [O\textsc{iii}] 5007 line intensity with respect to H\textbeta .

Oxygen is usually the major coolant in the oxygen abundant PNs. But what other coolants play a role? In Figure 13 we show the intensity of the line relative to H\textbeta for the major coolants in the SMC, LMC, and Galactic PNs, versus the oxygen abundance. The intensities are from the hottest models for each galaxian mix. Cloudy predicts that although the 5007 Å line is the major coolant for the Galactic and LMC PNs, in the SMC PNs the [C\textsc{iv}] λ1548 line is the major coolant. Other carbon lines are also important coolant in the SMC PNs, while the [O\textsc{iii}] λ4959 and [O\textsc{i}] λ3727 lines are significant mostly for the Galactic models. Clearly, more detailed models and observations of [C\textsc{iv}] λ1909 and [C\textsc{iv}] λ1550 are essential to confirm these predictions, but the interpretation is plausible and consistent with the available data.

In Stanghellini et al. (2002) we used the I[O\textsc{iii}] (5007+4959) / H\alpha ratio to trace the nebular excitation, and by inference the stellar temperature, of the LMC PNs. We can not perform the same analysis here, since it is clear from Figure 11 that the [O\textsc{iii}] /H\textbeta ratio versus temperature relation is very non-monotonic.

### 3.6. Electron densities and ionized masses

Table 6 lists nebular densities determined from strong [S\textsc{ii}] λλ6716,6731 lines for eight SMC PNs (this paper) and twelve LMC PNs (Stanghellini et al. 2002). We assumed T\textsubscript{e}=10\textsuperscript{4} K for these estimates. However, the derived densities are extremely insensitive to T\textsubscript{e} (Osterbrock 1989). We find that \langle N\textsubscript{e} \rangle_{\text{SMC}}=3.45, whereas \langle N\textsubscript{e} \rangle_{\text{LMC}}=3.28, a factor 1.5 different. Given the small sample size, a factor of 1.5 is not likely to be very significant. Furthermore, there is no discernible trend of N\textsubscript{e} with morphological type in SMC or LMC PNs. Moreover, nebulae with bright [S\textsc{ii}] lines are strongly biased to those of generally high fluxes or surface brightness, or low ionization. These selection biases render trends in N\textsubscript{e} of limited significance.

In addition we estimate masses of PNs in the LMC and SMC using the method of Boffi & Stanghellini (1994). The average ionized mass of the eight SMC PNs, 0.3 M\odot, is slightly larger than that of LMC PNs, 0.2 M\odot. Given the uncertainty in the data, and the small data sample, we do not believe that the mass discrepancy between SMC and LMC PNs is significant. Also, we fail to see any obvious trend between nebular mass and morphological type.
4. Summary and conclusions

A sample of 27 SMC PNs have been observed in imaging a slitless mode with HST/STIS to examine their morphology, shape, and fluxes, and to study their evolution. This morphological sample is the first sizable set of SMC PNs, and represents almost half of the known SMC PNs. The images and spectra have the same high quality and resolution as our LMC sample. We present the broad images and monochromatic images in the major emission lines, and determine that morphology is easily recognized in most emission lines. We find that the ratio of symmetric to asymmetric PNs is remarkably different in the SMC and the LMC. Specifically, bipolar PNs are much rarer in the SMC than the LMC (or the Galaxy). This new result has significant implications for the relation between stellar population and PN morphology. It is well known from Galactic and LMC PN studies that PN morphology correlates with the mass of the progenitor stars. In particular, bipolar PNs evolve from relatively massive (≥1.5 M⊙) progenitors. Thus the low incidence of bipolar PNs in the SMC probably reflects the low formation rate of these stars in the past ≥5 Gyr. This is in accord with other studies of star formation rates in the LMC and the SMC. Alternately, or in addition, the low metallicity of the SMC may inhibit wind collimation somehow.

We also present the measurement of the optical line intensities. We find that the surface brightness declines with radii in most emission lines, adding value to the possible calibration of the surface brightness-nebular radius correlation seen in the LMC. Ionized masses and electron densities were calculated where the [SII] doublet intensity was available. The resulting ionized masses do not seem to have a relation to the morphology, as already found in the LMC PNs.

The [OIII]/Hβ ratio of Magellanic Cloud PNs has been studied in detail. The factor of two difference between the LMC and SMC PNs were modeled with Cloudy. We find that the cooling models strongly depend on the oxygen content, and that the brightest parts of the [OIII] 5007/Hβ luminosity function shifts between SMC and LMC PNs. We also find a relation between the brightest [OIII] 5007/Hβ PNs and their morphology, that is different for each Magellanic Cloud population.

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Fig. 1.— STIS images of the LMC PNs J 4, J 18, J 23, and J 27 with a logarithm intensity scale. From left to right, we show for each PN the broad band image, the [N\text{II}] – H\alpha section of the G750M spectrum, and the [O\text{III}] 5007 image of the G430M spectrum, when available.

Fig. 2.— Same as in Figure 1, but for MA 1682, MA 1762, MG 8, and MG 13.

Fig. 3.— Same as in Figure 1, but for SMP 1, SMP 6, SMP 8, SMP 9, and SMP 11.

Fig. 4.— Same as in Figure 1, but for SMP 12, SMP 13, SMP 14, SMP 17, and SMP 18.

Fig. 5.— Same as in Figure 1, but for SMP 19, SMP 20, SMP 22, SMP 23, and SMP 24.

Fig. 6.— Same as in Figure 1, but for SMP 25, SMP 26, SMP 27, SP 34.
Fig. 7.— Comparison of the measured line intensity ratios with those in the literature, in logarithmic scale.
Fig. 8.— Surface brightness decline for the multiwavelength images of the PNs in our STIS survey. Emission lines in which the SB is derived are indicated in the panels. Symbols indicate morphological types: open circles=round, filled circles=pointsymmetric, stars=elliptical, filled triangles=bipolar core, filled squares=bipolar (and quadrupolar) planetary nebulae. The photometric radii are measured from the [OIII] \textlambda 5007 images, where available.
Fig. 9.— Same as in Figure 8, but for SMC and LMC PNs together (see text).
Fig. 10.— Distribution of the [O\textsc{iii}] $\lambda$5007 over H$\beta$ intensity ratios in the SMC (thick histogram) and LMC (shaded histogram) PNs.

Fig. 11.— The [O\textsc{iii}] $\lambda$5007 over H$\beta$ intensity ratios for SMC (triangles), LMC (squares) and Galactic (circles) models. Temperatures reflect the evolution from the AGB to the maximum central star temperature in the evolutionary tracks of SMC, LMCm and Galactic post-AGB stars.
Fig. 12.— The \([\text{O} \text{iii}] \lambda5007\) over H\(\beta\) intensity ratios versus the oxygen abundances for SMC, LMC, and Galactic PNs. Symbols as in Figure 11. PN models have constant density. We plot one cool model, and a group of hot models, for each galaxy. The three hot models represent three mean densities, see text.

Fig. 13.— Intensity ratios of the major PN coolants over H\(\beta\), versus oxygen abundances. The coolant is indicated in the right hand side of the plot.
Table 1. Observing Log for SMC Planetary Nebulae

| Nebula | Date       | Data Set | Disperser | $T_{Exp}$ (s) | $N_{Exp}$ |
|--------|------------|----------|-----------|---------------|-----------|
| J 4    | 2000 Aug 18| O65S03030| G430M     | 840           | 2         |
|        |            | O65S03020| G750M     | 890           | 2         |
| J 18   | 2000 Oct 3 | O65S08020| G750M     | 2100          | 2         |
|        |            | O65S08010| MHRVIS    | 300           | 2         |
| J 23   | 2000 Aug 8 | O65S12020| G750M     | 2100          | 2         |
|        |            | O65S12010| MHRVIS    | 300           | 2         |
| J 27   | 2000 Oct 10| O65S16020| G750M     | 2100          | 2         |
|        |            | O65S16010| MHRVIS    | 300           | 2         |
| MA 1682| 2000 Nov 5 | O65S24020| G750M     | 2100          | 2         |
|        |            | O65S24010| MHRVIS    | 300           | 2         |
| MA 1762| 2000 Aug 19| O65S25020| G750M     | 2100          | 2         |
|        |            | O65S25010| MHRVIS    | 300           | 2         |
| MA 1796| 2000 Sep 27| O65S26040| G430M     | 200           | 2         |
|        |            | O65S26020| G750M     | 100           | 2         |
|        |            | O65S26030| G750M     | 400           | 2         |
|        |            | O65S26010| MHRVIS    | 120           | 2         |
|        |            | O65S26KGQ| MHRVIS    | 15            | 2         |
| MG 2   | 2000 Nov 7 | O65S28030| G430M     | 800           | 2         |
|        |            | O65S28020| G750M     | 1300          | 2         |
|        |            | O65S28010| MHRVIS    | 300           | 2         |
| MG 8   | 2000 Nov 7 | O65S34030| G430M     | 1200          | 2         |
|        |            | O65S34020| G750M     | 620           | 2         |
|        |            | O65S34010| MHRVIS    | 120           | 2         |
| MG 13  | 2000 Sep 28| O65S39020| G750M     | 2100          | 2         |
|        |            | O65S39010| MHRVIS    | 300           | 2         |
| SMP 1  | 2001 Feb 6 | O65S40030| G430M     | 360           | 2         |
|        |            | O65S40020| G750M     | 170           | 2         |
|        |            | O65S40010| MHRVIS    | 120           | 2         |
| SMP 4  | 2001 Jan 9 | O65S41030| G430M     | 460           | 2         |
|        |            | O65S41020| G750M     | 230           | 2         |
|        |            | O65S41010| MHRVIS    | 120           | 2         |
| SMP 6  | 2001 Mar 9 | O65S42030| G430M     | 280           | 2         |
|        |            | O65S42020| G750M     | 190           | 2         |
| SMP 8  | 2001 Jan 23| O65S43030| G430M     | 320           | 2         |
|        |            | O65S43020| G750M     | 160           | 2         |
|        |            | O65S43010| MHRVIS    | 120           | 2         |
|        |            | O65S43KGQ| MHRVIS    | 15            | 1         |
| SMP 9a | 2000 Nov 20| O65S02030| G430M     | 1100          | 2         |
|        |            | O65S02020| G750M     | 790           | 2         |
|        |            | O65S02010| MHRVIS    | 300           | 2         |
| SMP 11a| 2000 Sep 6 | O65S05040| G430M     | 200           | 2         |
|        |            | O65S05020| G750M     | 60            | 2         |
|        |            | O65S05030| G750M     | 300           | 2         |
|        |            | O65S05010| MHRVIS    | 120           | 2         |
|        |            | O65S05LBQ| MHRVIS    | 15            | 1         |
| SMP 12 | 2000 Oct 14| O65S44030| G430M     | 650           | 2         |
|        |            | O65S44020| G750M     | 810           | 2         |
|        |            | O65S44010| MHRVIS    | 300           | 2         |
| SMP 13a| 2000 Nov 20| O65S06040| G430M     | 52            | 2         |
|        |            | O65S06020| G750M     | 36            | 2         |
|        |            | O65S06030| G750M     | 180           | 2         |
|        |            | O65S06010| MHRVIS    | 120           | 2         |
|        |            | O65S06CHQ| MHRVIS    | 15            | 1         |
| SMP 14 | 2000 Sep 17| O65S45030| G430M     | 540           | 2         |
|        |            | O65S45020| G750M     | 290           | 2         |
|        |            | O65S45010| MHRVIS    | 120           | 2         |
| Nebula | Date       | Data Set | Disperser | $T_{Exp}$ (s) | $N_{Exp}$ |
|--------|------------|----------|-----------|--------------|----------|
| SMP 17 | 2001 Jan 16| O65S47040| G430M     | 160          | 2        |
|        |            | O65S47020| G750M     | 100          | 2        |
|        |            | O65S47030| G750M     | 100          | 2        |
|        |            | O65S47010| MIRVIS    | 120          | 2        |
|        |            | O65S47FXQ| MIRVIS    | 15           | 1        |
| SMP 18$^a$ | 2001 May 16| O65S09040| G430M     | 160          | 2        |
|        |            | O65S09020| G750M     | 42           | 2        |
|        |            | O65S09030| G750M     | 210          | 2        |
|        |            | O65S09010| MIRVIS    | 120          | 2        |
|        |            | O65S09JHQ| MIRVIS    | 15           | 1        |
| SMP 19$^a$ | 2000 Oct 14| O65S10030| G430M     | 330          | 2        |
|        |            | O65S10020| G750M     | 260          | 2        |
|        |            | O65S10010| MIRVIS    | 120          | 2        |
| SMP 20 | 2001 Jan 21| O65S48040| G430M     | 160          | 2        |
|        |            | O65S48020| G750M     | 80           | 2        |
|        |            | O65S48030| G750M     | 320          | 2        |
|        |            | O65S48010| MIRVIS    | 120          | 2        |
|        |            | O65S48YXQ| MIRVIS    | 15           | 1        |
| SMP 22 | 2000 Oct 14| O65S49030| G430M     | 840          | 2        |
|        |            | O65S49020| G750M     | 200          | 2        |
|        |            | O65S49010| MIRVIS    | 120          | 2        |
| SMP 23$^a$ | 2000 Oct 14| O65S15030| G430M     | 230          | 2        |
|        |            | O65S15020| G750M     | 380          | 2        |
|        |            | O65S15010| MIRVIS    | 120          | 2        |
| SMP 24 | 2001 Mar 9 | O65S50030| G430M     | 500          | 2        |
|        |            | O65S50020| G750M     | 150          | 2        |
|        |            | O65S50010| MIRVIS    | 120          | 2        |
| SMP 25 | 2001 Mar 5 | O65S51030| G430M     | 920          | 2        |
|        |            | O65S51020| G750M     | 460          | 2        |
|        |            | O65S51010| MIRVIS    | 120          | 2        |
| SMP 26 | 2000 Sep 28| O65S52030| G430M     | 1200         | 2        |
|        |            | O65S52020| G750M     | 900          | 2        |
|        |            | O65S52010| MIRVIS    | 300          | 2        |
| SMP 27 | 2001 Jan 19| O65S53040| G430M     | 160          | 2        |
|        |            | O65S53020| G750M     | 80           | 2        |
|        |            | O65S53030| G750M     | 360          | 2        |
|        |            | O65S53010| MIRVIS    | 120          | 2        |
|        |            | O65S53QHQ| MIRVIS    | 15           | 1        |
| SP 34  | 2000 Oct 14| O65S55030| G430M     | 1000         | 2        |
|        |            | O65S55020| G750M     | 500          | 2        |
|        |            | O65S55010| MIRVIS    | 300          | 2        |

$^a$SMP 9=J 3; SMP 11=J 8; SMP 13=J 11; SMP 18=J 19; SMP 19=J 20; SMP 23=J 26
Table 2. Relative Emission Line Intensities of SMC Planetary Nebulae

| Nebula | $F(H\beta)$ | c | [Oii] | [Oiii] | [Oi] | [Sii] | [Siii] | [Oi] | [Nii] | Ha | [Ni] | He I | [Si] | [Si] |
|--------|-------------|---|-------|-------|------|-------|-------|------|------|-----|------|------|-----|-----|
|        | (4861)      |   | (4959)| (5007)| (6300)| 6312  | 6363  | (6548)| (6563)| 6584| 6678 | 6654 | (6716)| (6731) |
| J 4    | −13.55      | 0.168| 159.1| 480.4 | 5.1  | 3.8   | 2.5   | 28.9 | 326.3| 102.5| 1.9  | 1.6  | 3.0  |
| J 18   | −13.90\(^a\) | 1.736| 0.168| 159.1| 480.4 | 5.1  | 3.8   | 2.5   | 28.9 | 326.3| 102.5| 1.9  | 1.6  | 3.0  |
| J 23   | −13.19\(^b\) | 100  | 1.736| 0.168| 159.1| 5.1  | 3.8   | 2.5   | 28.9 | 326.3| 102.5| 1.9  | 1.6  | 3.0  |
| J 27   | −14.05\(^a\) | 1.736| 0.168| 159.1| 480.4 | 5.1  | 3.8   | 2.5   | 28.9 | 326.3| 102.5| 1.9  | 1.6  | 3.0  |
| MA 1682| −14.17\(^b\) | 100  | 0.7829| 1.736| 0.168| 5.1  | 3.8   | 2.5   | 28.9 | 326.3| 102.5| 1.9  | 1.6  | 3.0  |
| MG 8   | −13.27      | 0.133| 41.4  | 126.5 | 2.0  | 1.6   | 22.9  | 317.2| 98.3 | 4.7  | 5.3  | 22.0 |
| MG 13  | −13.10\(^b\) | 100  | 1.736| 0.168| 159.1| 5.1  | 3.8   | 2.5   | 28.9 | 326.3| 102.5| 1.9  | 1.6  | 3.0  |
| SMP 1  | −12.85      | 0.287| 85.0  | 262.1 | 2.0  | 0.9   | 0.7   | 8.9  | 359.3| 25.7 | 4.3  | 0.3  | 0.7  |
| SMP 6  | −12.80      | 0.385| 267.7 | 791.1 | 7.0  | 1.9   | 1.6   | 13.7 | 388.6| 44.5 | 5.3  | 0.8  | 1.6  |
| SMP 8  | −12.81      | 0.026| 198.7 | 592.3 | 1.7  | 0.9   | 0.7   | 8.9  | 359.3| 25.7 | 4.3  | 0.3  | 0.7  |
| SMP 9  | −13.46      | 0.070| 318.8 | 959.4 | 1.4  | 1.6   | 1.3   | 1.3  | 291.0| 2.5  | 3.6  | 1.0  | 1.6  |
| SMP 11 | −13.13      | 0.352| 110.9 | 351.4 | 5.0  |      | 10.0  | 378.6| 28.5 | 3.9  | 3.3  | 8.0  |
| SMP 12 | −13.59      | 0.056| 203.5 | 613.3 |      | 2.9   | 332.0 | 8.8   | 3.9  | 0.8  | 1.3  |      |      |
| SMP 13 | −12.59      | 0.190| 277.3 | 828.1 | 2.8  | 0.8   | 1.0   | 2.9  | 332.0| 8.8   | 3.9  | 0.8  | 1.3  |
| SMP 14 | −13.04      | 0.069| 311.1 | 928.8 | 2.6  | 1.1   | 1.0   | 4.4  | 301.2| 2.5   | 3.6  | 1.0  | 1.8  |
| SMP 17 | −12.55      | 0.064| 294.0 | 893.2 | 2.8  | 0.3   | 1.2   | 3.7  | 300.0| 7.6   | 4.0  | 1.1  | 0.5  |
| SMP 18 | −12.66      | 0.122| 105.0 | 309.0 | 1.3  | 0.7   | 0.4   | 7.3  | 314.5| 24.0  | 3.6  | 0.4  | 0.7  |
| SMP 19 | −13.04      | 0.161| 282.4 | 847.2 | 4.0  | 1.2   | 0.9   | 3.4  | 324.5| 7.7   | 2.4  | 1.5  | 2.2  |
| SMP 20 | −12.47      | 0.019| 143.8 | 434.9 |      | 1.0   | 280.8 | 2.8   | 3.9  |      |      |      |      |
| SMP 22 | −12.94      | 0.165| 99.1  | 298.2 | 14.8 |      | 5.6   | 87.7 | 325.4| 250.6| 2.9  | 9.8  | 14.3 |
| SMP 23 | −13.18      | 0.101| 271.5 | 828.1 |      |      |      |      |      |      |      |      |      |
| SMP 24 | −12.66      | 0.047| 137.9 | 420.1 | 1.9  | 0.9   | 6.2   | 295.9| 18.8 | 4.0  | 2.1  | 2.5  |
| SMP 25 | −13.28      | 0.100| 108.8 | 328.2 | 3.2  | 1.6   | 15.8  | 309.0| 47.6 | 5.6  | 1.3  | 1.9  |
| SMP 26 | −13.58      | 0.253| 205.0 | 613.0 | 19.7 | 5.2   | 111.1 | 349.4| 327.2| 2.0  | 14.8 | 17.7 |
| SMP 27 | −13.51      | 0.040| 188.8 | 580.1 | 1.4  | 0.5   | 1.8   | 294.2| 5.2  | 3.8  | 0.2  | 0.6  |
| SP 34  | −13.67      | 0.163| 162.8 | 488.4 | 12.7 |      | 22.4  | 19.0 | 325.1| 55.8 | 14.3 | 14.6 |

\(^a\)The Hβ flux is not available for this target. We give the Hα flux instead. All line ratios are calculated with respect to \(F_{H\alpha} = 100\) for this PN.

\(^b\)This measurement include the Hα and [Nii] blended fluxes.
Table 3. Positions, Dimensions and Morphologies of SMC Planetary Nebulae

| Nebula   | R. A. (J2000) | Dec. (J2000) | R\textsubscript{phot} (arcsec) | Dimensions (arcsec) | Morphological Classification | Notes |
|----------|---------------|--------------|-------------------------------|-------------------|-----------------------------|-------|
| J 4      | 0^h 45^m 27.30 s | -73^d 42' 15.7'' | 0.32 0.27 | E | Possible ansae. |
| J 18\*   | 0 51 43.39 s | -73 00 54.1  | 0.17 0.14 | R? | Elongated in [Ni]. |
| J 23\*   | 0 55 30.52 s | -72 50 21.3  | 0.38 ... | ... | Broad H\alpha emission; unresolved. |
| J 27\*   | 0 59 43.48 s | -72 57 17.9  | ... 2.5 1.7 | B? | Very low surface brightness. |
| MA 1682\*| 1 09 03.52 s | -72 29 05.2  | 0.83 2.86 x 2.17 | B | |
| MA 1762\*| 1 12 40.28 s | -72 53 46.4  | 0.71 1.45 x 1.26 | E(bc) | |
| MG 8     | 0 56 19.59 s | -72 06 58.5  | 0.48 1.39 x 1.28 | E | Inner structure. |
| MG 13\*  | 1 13 10.33 s | -72 57 03.2  | 1.55 1.22 x 1.09 | E | Inner structure. |
| SMP 1    | 0 23 58.67 s | -73 38 03.8  | 0.15 ... | ... | Unresolved. |
| SMP 6    | 0 41 25.72 s | -73 47 06.2  | 0.19 ... | ... | E |
| SMP 8    | 0 43 25.17 s | -72 38 18.9  | 0.23 0.41 x 0.38 | R | |
| SMP 9    | 0 45 20.66 s | -73 24 10.5  | 0.55 1.20 | R | Inner structure. |
| SMP 11   | 0 48 36.61 s | -72 58 00.1  | 0.99 0.78 x 0.66 | B | Possible inner ring. |
| SMP 12   | 0 49 21.00 s | -73 52 58.0  | 0.37 0.78 x 0.51 | E | |
| SMP 13   | 0 40 51.71 s | -73 44 21.3  | 0.19 0.20 | R | |
| SMP 14   | 0 50 34.99 s | -73 42 57.9  | 0.42 0.83 | R | Ansae and/or inner structure. |
| SMP 17   | 0 51 56.41 s | -71 24 44.6  | 0.25 0.50 | E | Faint detached 1.5' halo; inner ring in [Ni]. |
| SMP 18   | 0 51 57.97 s | -73 20 30.1  | 0.15 0.14 | ... | Unresolved. |
| SMP 19   | 0 53 11.14 s | -72 45 07.5  | 0.30 0.59 | R | Outer structure. |
| SMP 20   | 0 56 05.39 s | -70 19 24.7  | 0.15 0.20 x 0.23 | ... | Unresolved. |
| SMP 22   | 0 58 37.44 s | -71 35 49.1  | 0.40 0.71 x 0.54 | B? | Possible ansae. |
| SMP 23   | 0 58 42.14 s | -72 56 59.6  | 0.30 0.66 x 0.60 | E(bc) | |
| SMP 24   | 0 59 16.09 s | -72 01 59.7  | 0.20 0.38 | E | |
| SMP 25   | 0 50 33.22 s | -70 44 38.4  | 0.19 ... | ... | E |
| SMP 26   | 1 04 17.81 s | -73 21 51.2  | 0.28 0.61 x 0.57 | P | |
| SMP 27   | 1 21 10.67 s | -73 14 35.4  | 0.23 0.45 | R | Attached outer halo. |
| SP 34    | 1 12 10.76 s | -71 26 50.2  | 0.61 0.71 x 0.69 | R | Attached outer halo. |

\*No [Oiii] image available.
Table 4. PN Morphological Types: SMC versus LMC, and Galaxy

| Morphological Classification | SMC (%) | LMC (%) | Galaxy (%) |
|-----------------------------|---------|---------|------------|
| Round (R)                   | 30      | 29      | 23         |
| Elliptical (E)              | 37      | 17      | 49         |
| Bipolar core (BC)           | 17      | 34      | 9          |
| Bipolar (B)<sup>a</sup>     | 13      | 17      | 17         |
| Point-symmetric (P)         | 3       | 3       | 3          |
| Total, Asymmetric<sup>b</sup>| 30      | 51      | 26         |

<sup>a</sup>Includes Quadrupolar PNs

<sup>b</sup>Includes B and BC, but not P
Table 5. Photoionization Models, Input

| Model | log He/H | log C/H | log N/H | log O/H | log $T_{\text{eff}}$ | log $L/L_{\odot}$ |
|-------|---------|---------|---------|---------|----------------------|------------------|
| ---Galactic models--- | | | | | | | |
| 1 | -1.0 | -3.523 | -3.222 | 4.517 | 3.887 |
| 2 | -1.0 | -3.523 | -3.222 | 4.828 | 3.869 |
| 3 | -1.0 | -3.523 | -3.222 | 5.032 | 3.823 |
| 4 | -1.0 | -3.523 | -3.222 | 5.292 | 3.655 |
| 5 | -1.0 | -3.523 | -3.222 | 5.238 | 3.348 |
| ---LMC models--- | | | | | | | |
| 6 | -1.0 | -3.380 | -3.91 | 3.644 | 4.569 | 3.973 |
| 7 | -1.0 | -3.380 | -3.91 | 3.644 | 4.797 | 3.964 |
| 8 | -1.0 | -3.380 | -3.91 | 3.644 | 5.024 | 3.932 |
| 9 | -1.0 | -3.380 | -3.91 | 3.644 | 5.233 | 3.905 |
| 10 | -1.0 | -3.380 | -3.91 | 3.644 | 3.983 | 3.481 |
| ---SMC models--- | | | | | | | |
| 11 | -1.03 | -3.370 | -4.57 | -4.06 | 4.523 | 3.938 |
| 12 | -1.03 | -3.370 | -4.57 | -4.06 | 4.838 | 3.936 |
| 13 | -1.03 | -3.370 | -4.57 | -4.06 | 5.064 | 3.905 |
| 14 | -1.03 | -3.370 | -4.57 | -4.06 | 5.234 | 3.775 |
| 15 | -1.03 | -3.370 | -4.57 | -4.06 | 5.292 | 3.474 |

Table 6. Electron Density and Ionized Mass

| name | log $N_e$ | Mion |
|------|----------|------|
| SMC  | | |
| SMP 13 | 3.6 | 0.40 |
| SMP 14 | 3.6 | 0.10 |
| SMP 18 | 3.6 | 0.28 |
| SMP 19 | 3.4 | 0.21 |
| SMP 22 | 3.4 | 0.28 |
| SMP 24 | 3.1 | 0.86 |
| SMP 25 | 3.4 | 0.10 |
| SMP 26 | 3.1 | 0.15 |
| average | 3.4 | 0.30 |
| LMC  | | |
| SMP 9 | 3.2 | 0.12 |
| SMP 13 | 2.9 | 0.63 |
| SMP 16$^a$ | 2.9 | 0.33 |
| SMP 19 | 3.4 | 0.21 |
| SMP 28 | 3.2 | 0.10 |
| SMP 30$^a$ | 2.9 | 0.16 |
| SMP 46 | 3.4 | 0.05 |
| SMP 53 | 3.5 | 0.26 |
| SMP 71 | 3.6 | 0.17 |
| SMP-80 | 3.2 | 0.14 |
| SMP 95$^a$ | 2.9 | 0.16 |
| SMP 100 | 3.4 | 0.17 |
| average$^b$ | 3.3 | 0.21 |

$^a$Possible overlap of the [Sii] 6716 and 6731 lines, uncertain electron density and ionized mass.

$^b$do not include PNs with uncertain ratios (see $^a$).
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