

## Planetary Nebulae in the Magellanic Clouds: Probing Stellar Evolution and Populations

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**Abstract.** This review contains: (1) the scientific motivations for studying Planetary Nebulae in the Magellanic Clouds; (2) a review of this field of study, from the origins to the most recent results, focusing on the papers that have been published since the last IAU Symposium on Planetary Nebulae; (3) a review of the Hubble contribution to the field, from the early results to our own Magellanic Cloud Planetary Nebula program.

### 1. Introduction

Planetary Nebulae (PNs) are the relics of intermediate-mass star evolution, and they are important probes of stellar evolution, stellar Populations, and cosmic recycling. PNs have been observed in most galaxies (the Milky Way, the Local Group galaxies, and distant galaxies up to 10 Mpc) and in the medium between galaxies, thus they also probe evolution and Populations in relation to their environment.

The success of the studies of Galactic PNs is based on their proximity. The details of the observations typically surpass the details of stellar and hydrodynamic models. Yet, the distance scale of Galactic PNs is uncertain to such a degree that the meaning of the comparison between observations and theory is hindered. By the same token, statistical studies of PN populations in the Galaxy suffer for the observational bias against the detection of Galactic disk PNs, and for the patchy interstellar extinction. Thus, while it is certainly wise to cherish the level of detail offered by Galactic PN observations, we should also consider studying PNs in other galaxies, to approach the final phases of intermediate star evolution in a quantitative, statistical way.

PNs in the Magellanic Clouds (LMC, SMC), hundreds of low-extinction planetaries at uniformly known distances, are a real bounty for the stellar evolution scientist. Moreover, the composition gradients between the LMC, the SMC, and the Galaxy make studying MC PNs essential to understand the effects of environment metallicity on their evolution. Finally, understanding how stellar evolution operates in very low metallicity ambients, such as the SMC, is a useful step toward the understanding of stellar Populations in distant galaxies.

In essence, I believe that the MCs are ideal laboratories to shed light on the still many unsolved issues of Planetary Nebula formation and evolution. Together with the detailed studies of individual PNs in the Galaxy, the compar-

ison of large and homogeneous samples of the observed properties of LMC and SMC PNs with the correct evolutionary models will enormously improve our knowledge of the evolution of intermediate-mass stars, their stellar and nebular remnants, their origin, and their interaction with the environment.

## 2. Magellanic Cloud Planetary Nebulae: a field in evolution

### 2.1. Pioneers in the field

PN studies in the MCs are relatively recent. The first discovery paper of MC PNs (Lindsay 1955) contains the spectroscopic identification of 17 SMC PNs. Very rapidly, studies of MC PN samples became common, and their importance evident (e.g., Aller 1961; Westerlund 1964). Ground based observation of MC PN suffer from the fact that they are point sources, thus the contributions of nebular and stellar radiation are superimposed. Attempts to measure the central stars magnitudes were hampered by the difficulties in separating stellar and nebular contributions (e.g., Webster 1969).

From stellar evolution theory, we expect that some heavy elements (argon, neon, sulfur) are not processed by stars in the mass range of the PN progenitors, thus the abundances of these elements are the signature of the chemical mix of the environment when the stellar progenitors were born. On the other hand, carbon, oxygen and nitrogen are at variation during the evolutionary paths that preceded the PN phases, and their relative abundances probe the nuclear processes within the evolving star, the occurrence of the dredge up processes, and the mass of the progenitors (Iben & Renzini 1983). Since the central stars of MC PNs are not directly observable from the ground, the correct observations and analysis of the nebular chemistry offers best insight of stellar evolution from the nebular properties.

Observations with the IUE, combined with the optical spectral data acquired from the ground, allowed the abundance analysis of MC PNs. Space observations in the UV range was used for the detection of the complete set of carbon lines at various ionization stages, and made the carbon abundance derivation much more reliable. The key results in abundance studies can be found, to name a few, in Peimbert (1984), Boroson & Liebert (1989); Kaler & Jacoby (1991). Optical spectroscopy of large samples of MC PNs have been carried out by Dopita and collaborators (Meatheringham & Dopita 1991ab, Vassiliadis et al. 1992). IUE observations were also used to measure the stellar luminosity beyond the Lyman limit for the central stars, giving an estimate of the total stellar luminosity, and an approximate estimate to the mass (Aller et al. 1987). Several papers on MC PN spectroscopy, abundances, and the connection of nebulae and stellar evolution can be found in the earlier IAU Symposia on Planetary Nebulae (e.g., Westerlund 1968; Feast 1968; Webster 1978), while the most recent, complete review on MC PNs is due to Barlow (1989).

Magellanic Cloud Planetary Nebula spectra are similar, in general, to the well-known Galactic ones. In the MCs, as well as in the Galaxy, PNs have been classified on the basis of their chemical content (see Peimbert 1978, 1997). New stellar models with the MC metallicity were build (Vassiliadis & Wood 1993, 1994) to improve the overall knowledge of the origin of the MC PNs.

## 2.2. MC PN science since the last IAU Symposium

Magellanic Cloud PNs become even more relevant in the recent years. Since the last IAU Symposium on Planetary Nebulae, more than 70 papers related to MC PNs have been published, of the 363 papers ever published in this field<sup>11</sup>. The most notable recent results are in two major areas: The catalogs and emission line surveys, and the nebular-stellar evolution connection.

To date, 277 LMC PNs (Leisy et al. 1997) and 55 SMC PNs (Meyssonnier & Azzopardi 1993) are known. The total number of MC PNs have more than doubled from the last count by Barlow (1989). In the last few years, several emission line surveys have been completed, or are near completion (e.g., UKST survey: Morgan 1998, Parker & Phillips 1998; UM/CTIO survey: Smith et al. 1996). Future analysis of these surveys is essential for the future health of MC PN research. We expect that the PN counts in the MCs will increase significantly, improving the statistics of these studies. For example, Murphy & Bessel (2000) found 107 new SMC PN candidates, their PN status remains to be confirmed with spectroscopy. One important aspect of these surveys is the discovery of fainter PNs, that contributes to increasing the reliability of the faint end of the MC PN luminosity function (see Jacoby, this volume), and to enlarge the pool of known evolved PNs.

Related to the populations of MC PNs is the 2MASS survey (Egan, Van Dyk, & Price 2001). The importance of this multi-wavelength infrared survey to LMC PNs is related to the spatial distribution of the different types of AGB stars. Egan et al. showed that low mass AGB stars occupy the whole of the LMC projected volume, while the higher mass, younger Population, AGB stars populate preferentially the LMC bar. Chemical and morphological studies of large LMC PN samples should take these distributions into account, to relate the PN populations in the LMC to their immediate evolutionary progenitors.

Studies of the chemical content of MC PNs have been active in the last five years as well. On the observational side, Leisy & Dennefeld (1996), Costa, de Freitas Pacheco, & Idiart (2000), and Idiart & Costa (this volume) have produced new chemical abundances for several MC PNs from optical and UV observations, enriching the databases for studies on the dredge-up of post-AGB stars and on the ISM enrichment in galaxies. On the theoretical side, van den Hoek & Groenewegen (1997) calculated new chemical yields of the enrichment of the interstellar medium from synthetic evolution of intermediate-mass stars. With models from a wide range of initial masses and metallicities, including the MC metallicities, van den Hoek & Groenewegen (1997) confirm that the yields of nitrogen and carbon change abruptly for masses higher than about 4 solar masses, independent on initial composition.

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<sup>11</sup>These numbers are derived from an ADS search, and may not be complete

### 3. The Hubble Space Telescope contribution to the field

#### 3.1. Early Hubble observations of Magellanic Cloud Planetary Nebulae

Extended studies of Galactic PNs have shown that PN morphology is intimately related to the mass and evolution of their central stars, to their stellar progenitors, and to the nebular chemistry (e.g., Machado, this volume). Morphology appears then to be an essential PN property, to be studied statistically, and to be compared case by case to the nebular and the stellar properties. In the case of the LMC and the SMC, morphological studies became possible with the use of the cameras on board the Hubble Space Telescope. Hubble observations have also the capability of spatially separate the image of the nebula and that of the central star, making direct stellar analysis possible.

The early narrow-band images of MC PNs were obtained before the first Hubble servicing mission (i.e., before the installation of COSTAR on Hubble) with the *Faint Object Camera* (Blades et al. 1992). Other images by Blades et al. have later been published by Stanghellini et al. (1999), where the quality of the pre-COSTAR images was validated through their comparison with post-COSTAR images of the same objects. These papers have made available 15 MC PN images usable for statistical and morphological studies, while another 15 LMC PNs have been observed with the *Planetary Camera 1* by Dopita et al. (Dopita et al. 1996; Vassiliadis et al. 1998a). Finally, an additional ten *Wide Field and Planetary Camera 2* narrow-band images of LMC PNs are available in the Hubble Data Archive (program 6407, PI: Mike Dopita).

The UV and optical spectroscopic capability of Hubble have been employed to greatly improve the quality of the spectrophotometric calibration of SMC and LMC PNs. Among the many papers that have been published based on Hubble spectroscopy (e.g., Vassiliadis et al. 1998b, Dopita et al. 1997ab), two results from Dopita et al. are worth noting: first, it is shown that there are different populations of PNs within the LMC, and that it is possible to discern these populations on the basis of their alpha-element abundance (see Fig. 3 in Dopita et al. 1997b). Second, by relating the expansion of the LMC PNs to the central star position on the HR diagram, it is inferred that several central stars of LMC PNs sustain their evolution via helium-burning, rather than hydrogen-burning. Even if the latter result is hindered by the obvious uncertainties on the location of the stars in the HR diagram (the stars were not directly observed in these narrow-band images, and their location on the HR diagram was inferred from nebular analysis), they are still important as they hint to a possible dichotomy of PN populations in the LMC.

#### 3.2. Our program, based on Hubble data, and the future

Statistical studies of MC PNs and their central stars need an homogeneous, large imaging databases to achieve significance. In the past two years, a project with HST was implemented by myself and my collaborators, with the aim of obtaining morphology, nebular physics, and stellar parameters, for all the known PNs in the MCs. The scientific rationale is to derive a complete description of formation and evolution of PNs according to their environment, based on the confrontation

of the HST and ancillary ground-based data with the stellar and hydrodynamic models of PN evolution.

The observing strategy invokes slitless spectroscopy with the *Space Telescope Imaging Spectrograph* (STIS), coupled with STIS broad-band imagery. This technique provides pseudo narrow-band images in the major emission lines (e.g., H-alpha, H-beta, [O III] 5007 Å, [N II] 6584 Å, [S II] 6716-6731 Å), suitable to derive the size, the ionization stage, the gas density, the extinction, and the morphology of the nebulae, plus broad-band images to determine the magnitude of the central stars. The observations, performed in snapshot mode, gather morphological and stellar information in less than one orbit for each MC PN, making it a cost-effective HST program.

The data analysis plan is at an early stage, yet we have already obtained important results from the samples of MC PNs, to add to the value of the sheer quantity and quality of the images collected so far. The major results from the observations and analysis can be summarized as follows:

1. PNs in the Clouds have substantially the same morphologies than Galactic PNs: Symmetric (Round and Elliptical) and Asymmetric (Bipolar, Bipolar Core, and Pointsymmetric) PNs were observed. There is a larger fraction of Asymmetric to Symmetric PNs in the LMC than in the Galaxy; since most Asymmetric Galactic PNs are Galactic disk objects, the result may simply disclose the selection effects that play against the detection of Galactic disk PNs. The fraction of Symmetric to Asymmetric PNs in the LMC is different than that of the SMC, indicating different mixes of PN populations across galaxies.
2. The surface brightness of the LMC PNs in the light of [O III] 5007 Å, correlates with the photometric radii of the nebulae, as shown in Figure 1. The photometric radius of a PN roughly traces the rate of its dynamic evolution (velocities of PNs are within a very narrow range, see Shaw et al. 2001), therefore the relation of Figure 1 can be used to constraint the hydrodynamic models. In fact, preliminary models show a similar surface brightness decline in PN evolution (Villaver et al. in preparation). In Figure 1 the symbols indicate the PN morphology, as listed in the legend. We infer that Asymmetric PNs have a more rapid dynamic evolution than Round PNs. The distribution of the SMC PNs on the plane of Figure according to morphological type is similar to that, shown, of LMC PNs. We do not plot the SMC PNs in Figure 1, since their calibrated surface brightness are yet to be measured from the Hubble spectra.
3. We found that asymmetric PNs are neon and sulfur rich, compared to Round and Elliptical PNs, in the LMC (Stanghellini et al., 2000). This result is broadly consistent with the predictions of stellar evolution if the progenitors of Asymmetric PNs have on average larger masses than the progenitors of Symmetric PNs, independent on assumptions, or relation to, a possible stellar multiplicity of the progenitors. This result is also in broad agreement with the findings in Galactic PNs that bipolar Planetary Nebulae have more massive central stars (e.g., Stanghellini, Corradi, & Schwarz 1993), and bears on the question of formation mechanisms for asymmetric PNs, specifically, that the genesis of PNs structure should

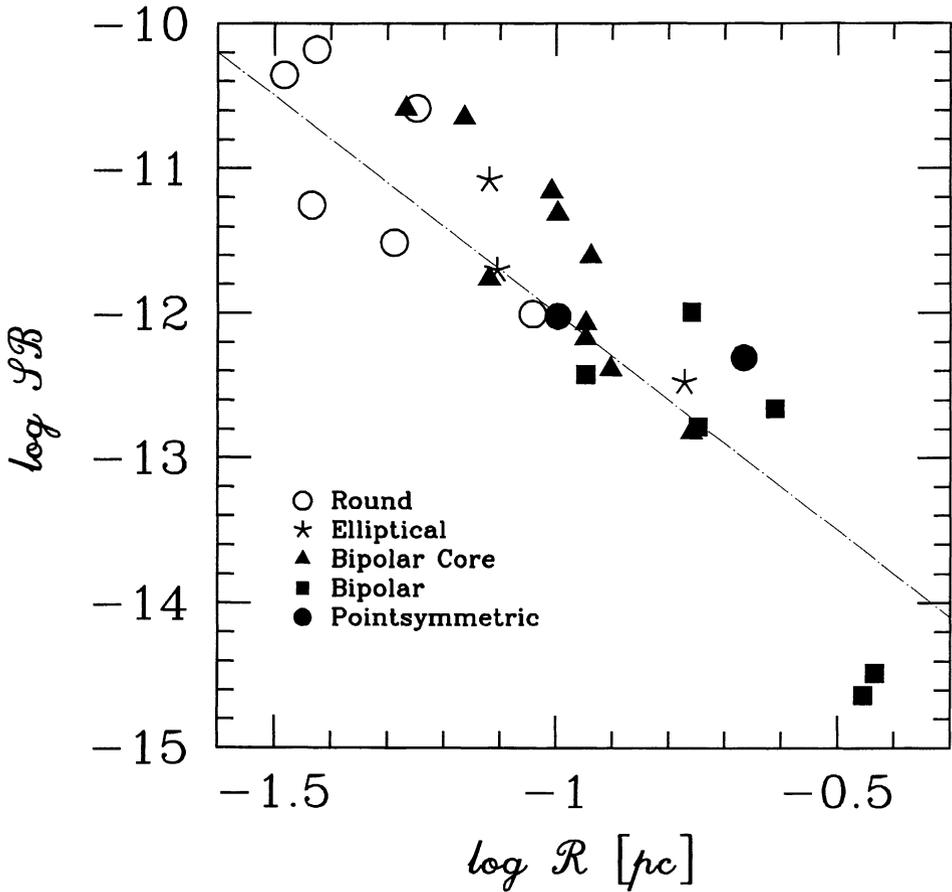


Figure 1. The [O III] 5007 logarithmic surface brightness versus the logarithmic (physical) photometric radii, for LMC Planetary Nebulae. The thin line represents a rough fit to the data,  $SB \propto R^{-3}$

relate strongly to the Population type, and by inference the mass, of the progenitor star, and less strongly on whether the central star is a member of a close binary system.

An important product of our program is the prepared data set, available within the HST Data Archive. The observations, images, analysis, publications, and other useful links for PN science can be found at:

<http://archive.stsci.edu/hst/mcpn/>

In the future, we plan to further exploit the data that we are collecting. One of our aims is the determination of the central star photometry, and the direct calculation of the stellar luminosity. By deriving the effective temperature via Zanstra analysis, or with the analysis of the stellar spectra, we will be able to locate the central stars in the  $\log L$ - $\log T_{\text{eff}}$  plane. The comparison of these locations with the evolutionary tracks will lead to the determination of the central star's masses. The stellar properties will then be related to the nebular ones, to disclose all the possible relation between stars and nebulae, with the aim of finding direction toward the understanding of PN formation and evolution. The stellar properties will also be studied with the UV STIS slitless spectra that we are presently acquiring. The stellar data will constraint the detailed hydrodynamic models, that we will build specifically for MC PNs to compare them to the Hubble images. Optical and ultraviolet spectra will be used to determine the PN abundances, with the aim of confirming our results on LMC PN progenitors.

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