# PLANETARY NEBULAE IN THE MAGELLANIC CLOUDS

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## ABSTRACT

The identification and masses of Magellanic Cloud planetary nebulae are discussed. The masses are shown to be uncertain and should not be directly compared to values for galactic planetaries.

The kinematics suggest that the planetary nebulae belong to a younger rather than an older population. Abundance analyses show the Magellanic Cloud planetaries to be deficient in most elements, but the abundances of helium and carbon are comparable to values found for galactic planetaries.

## 1. INTRODUCTION

The Magellanic Clouds are the nearest galaxies in which a large number of planetary nebulae can be studied in detail. Only in the Clouds can all the planetary nebulae be identified and a significant number of planetaries at a known distance be spatially resolved. These aspects of the Magellanic Cloud planetary nebulae have been exploited to improve our estimates of the number of planetaries in our Galaxy and also to provide values for their shell masses.

The chemical composition of planetary nebulae in the Clouds provides a contrast to abundances derived from the more recently formed HII regions, thereby indicating the importance of planetary nebulae in the chemical evolution of these galaxies. Coupled with an understanding of the kinematics, a clearer view of the history of the Clouds may emerge. Recent efforts have been directed towards determining the chemical abundances using linear optical and UV detectors. These observations provide reliable results and a better understanding of the role of planetary nebulae in the Magellanic Clouds and the Galaxy.

Table 1 lists some of the properties of the Magellanic Clouds which are relevant to the study of their planetary nebulae.

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Table 1.

Properties of the Magellanic Clouds

| | SMC | | LMC | |
|---|---|---|---|---|
| distance, kpc. | 62-69 | | 46-57 | |
| Angular size, deg. | 6 | | 10 | |
| Mass, $M_\odot$ | $1.6 \times 10^9$ | (1,2) | $6.0 \times 10^9$ | (2) |
| $M_{HI}$, $M_\odot$ | $0.5 \times 10^9$ | (2) | $0.5 \times 10^9$ | (3) |
| $M_V$ | -16.7 | (4) | -18.7 | (4) |
| $V_R$, $Km\text{-}s^{-1}$ | 161 | (5) | 278 | (5) |
| Dominant Age, yrs. | $3 \times 10^9$ | (6) | $4 \times 10^9$ | (7) |

References:

(1) Tully et al (1978)

(2) Hindmann (1967)

(3) McGee and Milton (1966)

(4) Allen (1973)

(5) Lin and Lynden-Bell (1982)

(6) Hawkins and Brück (1982)

(7) Stryker (1981)

## 2. IDENTIFICATIONS OF PLANETARY NEBULAE

### 2.1. Surveys

At the distance of the Magellanic Clouds, even the largest planetary nebulae are nearly stellar, having diameters less than about 3 arcsec. The morphology technique used for identifying galactic planetaries is therefore not generally applicable to the Cloud planetaries, so secondary techniques must be used. These other methods rely on the basic property that planetary nebulae are bright emission-line sources but have very weak continua. To discriminate from other emission-line objects such as Be stars, it is important to consider the [OIII] λ5007 line which is generally strong in planetaries but not in emission-line stars. Exclusive use of the [OIII] line, however, can select against finding low excitation planetary nebulae and an alternative line, perhaps [OII] λ3727, can be employed to identify this class of planetary. Some estimate of the continuum intensity is also necessary to provide a means to reject compact HII regions and certain emission-line stars; large scale direct plates are particularly useful to determine diameters to further discriminate against HII regions.

Thus the criteria used to identify planetary nebulae in the Clouds require that candidates have: (1) stellar or nearly stellar diameters, (2) strong emission lines, including [OIII], and (3) little or no continuum.

The two instrumental methods which have been used to survey the Clouds are the objective prism and the on-line/off-line techniques. The objective prism method has the advantage of allowing identifications with a single plate while simultaneously providing spectral information on the excitation and the continuum intensity. It is, however, subject to crowding confusion in dense stellar fields such as the bar region of the LMC where spectra from the multitudes of stars overlap.

The on-line/off-line technique allows identification of fainter objects in very dense fields, while providing plate material suitable for determining accurate positions. It has the disadvantage of requiring two plates per field and a relatively tedious blinking procedure to locate candidates. Both methods have been used successfully, although the objective prism technique has been the most popular.

Planetary nebula surveys in the SMC have been reported by Lindsay (1955,1956,1961), Koelbloed (1956), Henize and Westerlund (1963), Sanduleak, MacConnell, and Phillip (1978), Jacoby (1980), and Sanduleak and Pesch (1981). Koelbloed's identifications are unfortunately irrecoverable because no positions or finding charts were published. Lindsay's objects have been sifted by Henize and Westerlund, and later by Sanduleak, MacConnell, and Phillip to exclude compact HII regions and variable emission-line stars. The list given by Sanduleak, MacConnell and Phillip is probably the most reliable set of planetary nebula identifications in the Clouds and includes finding charts for 28 SMC objects.

Jacoby's survey includes very faint planetaries with the goal of measuring the luminosity function for planetary nebulae in the bars of the SMC and LMC. He identified 19 new SMC planetaries, some of which are 3 magnitudes fainter than previous limits. Also included is the first spatially resolved planetary in an external galaxy, having a diameter of approximately 2.8 arcsec.

Sanduleak and Pesch obtained very deep objective prism plates in which the SMC Bar is nearly saturated due to crowding of overlapping spectra. They identify 6 planetary nebula candidates; two of these (numbers 30 and 31) fall in regions included on my plates. They are just visible at the plate limit, but number 31 is brighter on the off-line plate. Number 30 is extremely faint in [OIII] and probably would not normally be identified as a planetary on objective prism plates. These two objects may be late-type stars with strong absorption bands, or possibly variable stars. Although the possibility that they are very low excitation planetary nebulae cannot be ruled out from the [OIII] plates alone, the criterion used by Sanduleak and Pesch requiring their candidates to have strong [OIII] emission appears to be at odds with the direct plates. For now, these two objects should be considered uncertain.

Surveys of the LMC have been reported by Westerlund and Rodgers (1959), Lindsay and Mullan (1963), Westerlund and Smith (1964), Sanduleak, MacConnell and Phillip (1978), Fehrenbach, Duflot and Acker (1978), Webster (1978), and Jacoby (1980). Again the objects found by Westerlund and Rodgers and Lindsay and Mullan were later re-examined by Westerlund and Smith and Sanduleak, MacConnell and Phillip to reject compact HII regions. Fehrenbach, Duflot and Acker also compared previous identifications to their plate material and noted possible spectral inconsistencies plus one new identification.

Sanduleak, MacConnell and Phillip provide coordinates good to 1 arcmin for 102 LMC planetaries with reliable identifications. Of these, 41 finding charts are published by Westerlund and Smith, so locating the remaining 61 objects may be difficult due to the imprecise positions currently available. Gull (1982) reports improved positions for the bright SMC and LMC planetaries, but these are not yet generally available.

Jacoby's survey identified 34 faint planetary nebulae in the LMC bar which are used to determine the LMC planetary nebula luminosity function. Included in the list are 8 extended planetaries having seeing-corrected diameters between 0.56 and 3.75 arcsec. This survey is the only LMC survey using the on-line/off-line technique, which is especially appropriate in the crowded regions in the LMC bar. Webster (1978) reported examining deep objective prism plates of the LMC bar to test for crowding confusion, but no details are available, other than the conclusion that few bright planetaries would be masked by the stellar spectra. Planetaries much fainter than the limits of the surveys up to that time would probably be considerably more difficult to identify on objective prism plates.

To date, there are a total of 51 planetary nebulae known in the SMC and 137 in the LMC as a result of these surveys.

## 2.2. The Number of Planetaries in the Clouds

Although current technology in astronomical instrumentation is adequate to identify and, therefore, to count nearly all the planetary nebulae in the Magellanic Clouds, the required observations have not been undertaken. Until such data is obtained, we can only estimate the total number of nebulae based on the numbers already known.

Henize and Westerlund (1963) first estimated the number of planetaries in the SMC to be 300 based on the 30 objects known at that time. The factor of 10 is derived from an estimate of the fractional lifetime represented by the luminosity limits of the observed sample. Westerlund and Smith (1964) argued similarly for 450 planetaries in the LMC based on 45 objects. But not all the objects in those samples are true planetaries, nor are those samples spatially complete. The survey by Sanduleak, MacConnell and Phillip (1978) would suggest 280 and 1020 planetaries based on 28 and 102 objects in the SMC and LMC, respectively, again using the lifetime factor of 10.

An alternative approach was taken by Jacoby (1980) who sampled selected regions in the bars of the Clouds to determine the number ratio of faint (3 to 6 magnitudes below the brightest) to bright (0 to 3 magnitudes below the brightest) planetary nebulae in those regions. He then scaled that ratio to the entire galaxy. Because his sample did not include planetaries with luminosities comparable to the faintest identifiable galactic planetary nebulae, a correction was required to account for luminosity incompleteness. This factor was obtained by examining the number ratio of very faint planetaries (6 to 8 magnitudes below the most luminous) to all brighter planetaries in the solar neighborhood. The ratio was found to be about 2. Despite the usual cautions concerning the distances to galactic planetaries, the above ratio is identical to that obtained by extrapolating a theoretical luminosity function beyond the observational limit. Additional corrections were included to account for obscuration by dust, spatial incompleteness of the brighter surveys, and crowding in the LMC bar. Jacoby finds the total estimated number of planetary nebulae in the SMC and LMC to be 285 and 996, respectively, in surprisingly good agreement with the result obtained by scaling the numbers given by Sanduleak et al by the lifetime factor of 10. This is not completely coincidental because the observed luminosity function (see Section 2.4.) agrees rather well with the theoretical one used by Henize and Westerlund (1963) to derive the lifetime factor.

One expects that for galaxies of similar age, composition, and initial stellar mass function, the planetary nebula birthrates per unit star would also be similar. We can compare the birthrates in the two Clouds by dividing the number of nebulae by the mass of the stellar component of each galaxy. The masses listed in Table 1 must be reduced by the HI mass, since the non-stellar components (e.g., neutral hydrogen) do not directly produce planetary nebulae. We then find the mass specific numbers of planetary nebulae to be $2.6 \times 10^{-7} PN/M_\odot$ in the SMC and $1.8 \times 10^{-7} PN/M_\odot$ in the LMC. These numbers suggest either an overabundance of planetaries in the SMC or an underabundance in the LMC.

Jacoby suggests using the visual luminosity specific number rather than the mass specific number due to difficulties in measuring the masses of galaxies. For the Clouds, he finds $7 \times 10^{-7} PN/L_\odot$ in the SMC and $4 \times 10^{-7} PN/L_\odot$ in the LMC, again indicating a greater population of planetaries in the SMC. This argues that the basic assumptions are incorrect -- either the age, initial mass function, or composition is different in the SMC. The metallicity is known to be deficient compared to the LMC while the age is thought to be comparable (see Section 4). The initial mass function is yet to be determined.

We can, nevertheless, apply the above specific numbers to the mass and luminosity of our Galaxy to obtain 23,000 to 34,000 planetaries from the mass specific numbers. Using the preferred indicator, the luminosity specific numbers, we obtain 6,000 to 10,000 planetaries.

## 2.3. Shell Masses

Due to the uncertainties in the galactic distance scale, shell masses for planetary nebulae have been subject to some debate. The hope of exploiting the Magellanic Cloud nebulae, whose distances are reasonably well known, to determine shell masses, has proven to be no easier because the nebulae are, in general, spatially unresolved. Therefore, assumptions and indirect methods have been employed, resulting in a range of derived shell masses comparable to the range seen for shell masses derived for galactic planetary nebulae.

Seaton (1968) took advantage of the fact that the nebula shell attains maximum Hβ luminosity and maximum surface brightness simultaneously. By equating the maximum Hβ flux from the Magellanic Cloud planetaries to the maximum Hβ surface brightness of galactic planetaries and solving for the radii of the brightest galactic planetaries, the distances and shell masses can be readily computed. Seaton thus finds the average shell mass to be $0.17M_\odot$. His basic assumptions include: (1) $T_e$=8,000°K; (2) there are no relevant differences between Magellanic Cloud and galactic planetaries; and (3) the nebulae are optically thin at maximum Hβ flux; that is, the entire shell is ionized.

The above assumed temperature is systematically too low by about 4,000 degrees (Aller et al 1981), due to lower metal abundances than in galactic planetaries. This results in an Hβ emissivity which is systematically too high for the Cloud objects and leads to an underestimate of the shell mass by about 40 percent. This effect is partially offset by the expected higher masses of the average LMC population which is somewhat younger than that in the Galaxy (Butcher 1977, Stryker 1981).

The greatest source of uncertainty in Seaton's approach is the assumption that the nebula shells are brightest when fully ionized. This assumption derives from an evolutionary track for a brightening central star, but this effect has become difficult to support (Paczynski 1971, Pottasch et al 1978, Renzini 1979). In the situation where the central star does not increase in luminosity, the nebula will have its greatest surface brightness when it is very small, due to the very high electron density, and it will monotonically fade throughout its lifetime. Until the radius has expanded to about 0.1 to 0.2pc, the nebula is not yet fully ionized. This effect has been dramatically demonstrated by the mass-radius "relation" given by Pottasch (1980) in which the derived nebula mass (in solar masses) follows the approximate relation $7r_{pc}^{1.8}$. This suggests that for an unresolved nebula in the LMC (diameter less than 1 arcsec, $r<0.13$pc), the maximum derived mass will be less than $0.5M_\odot$, even considering the significant scatter in the mass-radius relation.

Webster (1969a) performed a similar analysis and the same reservations apply. Note that Webster gives hydrogen masses, not total shell masses, of about $0.11M_\odot$ for 4 galactic planetary nebulae. This corresponds to a total shell mass of about $0.16M_\odot$. Although this value is higher than $0.09M_\odot$ calculated from the mass-radius relation for these nebulae which have radii of about 0.09pc, the dispersion about the relation at this radius extends to $0.19M_\odot$ (see Pottasch 1980, Figure 2).

On the other hand, one of the four planetaries, NGC 7662, is a well-known triple shell planetary having a maximum radius of 67 arcsec (Kaler 1974). The existence of ionized material at this radius, corresponding to 0.8pc suggests that ionizing radiation escapes the central nebula. This implies an optically thin nebula, at least in certain directions.

Webster also derived upper limits to 3 Magellanic Cloud planetaries which span the range of the brightest to the faintest identified at that time. The total masses, derived by assuming a radius of 2 arcsec (0.27pc), range from 2.0 to $0.7M_\odot$. The lower value is more likely to be correct because the brighter objects would be much smaller than 1 arcsec in radius. The smaller value is also probably too high because such planetaries would be easily resolved on plates taken during good seeing conditions, yet this has not been reported.

Pottasch (1980) derives total masses for 3 SMC planetaries based on a density dependent method. Because the distance to the SMC is known, a priori, the method is not strongly dependent on density as is Seaton's (1966) method for galactic planetaries. Pottasch finds the masses to be about $0.35M_\odot$.

Webster (1976) uses a method similar to Pottasch to derive similar results, but cautions that inhomogeneities in the nebulae can lead to measured forbidden line densities which are inappropriate to the mass calculation.

Jacoby (1980) was able to spatially resolve 9 faint planetary nebulae in the Clouds to obtain diameters directly for the first time. The availability of physical diameters, distances, and fluxes allows a complete solution of the inverted Shklovskii method:

$$M(M_\odot) = 2.65 \times 10^{-6} \quad [d^5(\mathrm{pc})\, r^3\,(\mathrm{arcsec})\, F(\mathrm{H}\alpha)\varepsilon]^{1/2}$$

where ε is the filling factor, usually about 0.6. Unfortunately, the uncertainties in the individual parameters are non-negligible. In particular, the measured diameters are, in some cases, unreliable due to the convolution of seeing effects and inadequate definition of the nebula edge. Furthermore, the so-called known distances to the Clouds are accurate to perhaps 15 percent (van den Bergh 1975). An additional distance uncertainty is the position of the nebulae within the Cloud, which may affect the distance by up to 4 percent. These factors result in an uncertainty in the derived masses of 50 percent due to the impreciseness of the distance alone! For the 9 objects, the masses are calculated to range from 0.02 to $0.8M_\odot$ thereby spanning the usual quoted values for planetary nebula shells. The conclusion to be drawn is that the Magellanic Cloud planetary nebulae can provide a set of objects at a nearly uniform distance, but the distance is subject to sufficient uncertainty that the derived masses may not be directly applicable to our Galaxy.

Other factors which must be considered when generalizing the properties of the Cloud planetaries to our Galaxy are: (1) there is a compositional difference, and hence a systematic difference in electron temperatures and possibly in central star properties; (2) the progenitor stars in the Clouds are drawn from a somewhat younger stellar population due to a recent (3-5 billion years ago) burst of star information; (3) the likelihood that the brightest and best observed nebulae are not yet fully ionized.

## 2.4. The Luminosity Function

The planetary nebula luminosity function serves several purposes: (1) it provides an observational constraint on models of the combined evolution of nebular shells plus central stars; (2) it is a check on the distances to the Magellanic Clouds and other Local Group galaxies by direct comparison; (3) it provides a means of extrapolating the observed number of planetary nebulae from a luminosity-limited sample to the total number of planetaries in a galaxy. Also, Svestka (1962) used the luminosity function to infer that the brightest of Lindsay's (1961) and Koelbloed's (1956) identifications in the SMC were not likely to be true planetary nebulae, as the luminosity function exhibited an excess of overly bright objects when compared to the planetary nebulae in our Galaxy.

There have been few attempts to measure the luminosity function for galactic planetary nebulae because of the uncertainties in the distance determination. Those for the SMC published by Lindsay (1961) and Koelbloed (1956) were contaminated by HII regions and difficult to interpret. Henize and Westerlund (1963) suggested a simple model of an expanding sphere and deduced the luminosity function based on the relative lifetimes of such a nebula as it expanded to fainter magnitudes.

By extending the identifications of Magellanic Cloud planetary nebulae over a 6 magnitude range, Jacoby (1980) was able to directly measure the luminosity function. The overall shape of the curve is adequately represented by the simple expanding sphere model, although the model underestimates the number of bright planetaries. Pottasch (1982) has compared the luminosity function obtained by Jacoby with that derived from a set of galactic planetary nebulae for which he feels the distances are reasonably accurate. The agreement is generally good, but there are proportionately more faint than bright planetaries in the Galactic sample. Tentatively, this disparity can be attributed to the small number of bright planetaries in both authors' samples.

Using the luminosity function from the Clouds, Jacoby extrapolates the available surveys in 8 additional Local Group galaxies to estimate their total numbers of planetary nebulae. He finds the average mass specific number for the Local Group to be $2.1 \pm 1.5 \times 10^{-7} \mathrm{PN}/M_{\odot}$ while the visual luminosity specific number is $6.1 \pm 2.2 \times 10^{-7} \mathrm{PN}/L_{\odot}$. The relatively smaller dispersion about the luminosity specific number suggests it is a better indicator of the planetary nebulae population in a galaxy. Applying this value to our galaxy, along with the absolute visual luminosity of -20.6 (de Vaucouleurs and Pence 1978), a total number of 9100 ± 3300 planetary nebulae is estimated.

## 3. KINEMATICS OF PLANETARY NEBULAE IN THE CLOUDS

Until very recently extensive velocity data for the older stellar components in the Clouds were available only from planetary nebulae. Freeman, Illingworth, and Oemler (1982) have combined their results for the LMC globular cluster system with those of Ford (1970) and Searle and Smith (1982) to obtain velocities for 59 clusters. The younger blue clusters are found to behave similarly to the HI and HII components while the older red clusters lie in a disklike system but have different rotational parameters. Furthermore, there was no kinematical evidence for an old halo population.

Planetary nebulae are usually associated with an old disk component. We would like to test this association in the LMC by comparing the velocity information for the planetary nebulae with the kinematic solutions for the young and old populations. Interpretation of such a comparison is very difficult because we expect planetaries to form from progenitors of varying ages, especially in the LMC where a major burst of star information occurred 3-5 billion years ago (Butcher 1977, Stryker 1981).

Feast (1968) found that the brightest planetaries exhibited a dispersion of 15 km-s$^{-1}$ about the HII region kinematic solution, and Smith and Weedman (1972) found a similar result for a spatial subset of the planetaries. In contrast, Webster (1969b) found the dispersion of the planetaries to be only 8.2 km-s$^{-1}$ about the rotation curve defined by the planetaries themselves.

Freeman, Illingworth, and Oemler compare their results for the blue and red clusters with the velocities for the 35 LMC planetaries taken from the table of Feitzinger and Weiss (1979) which is derived from the measurements by Feast, Webster, and Smith and Weedman. They find that the planetary nebulae generally follow the kinematic solution for the young population derived from HI and HII data, but with significant scatter. This is attributed to a wide range of ages for planetary nebula progenitors and to deviations in the velocity field which are evident in the HI data. A third consideration is inaccurate velocities for planetaries with asymmetric shells as reported by Smith and Weedman.

It would be best to be able to preselect the planetaries which exhibit properties of younger objects, perhaps excessive nitrogen and helium abundances indicative of dredge-up in the late evolution of higher mass progenitors (Kaler, Iben, and Becker 1978). A subset of young LMC planetaries would be expected to follow the HI solution very closely and have a velocity dispersion comparable to the HII region dispersion of 7.5 km-s$^{-1}$ (Smith and Weedman 1971).

Unfortunately, abundances are available for too few objects to allow compositional sorting. Three planetaries have characteristics indicating high helium abundances -- WS 7 (Osmer 1976), WS 9 and WS 38 (Webster 1976). [Note: The prefix WS refers to the catalogue of Westerlund and Smith (1964)]. Of these, no velocity is available for WS 9, and WS 7 has a velocity affected by an asymmetric shell. Using Smith and Weedman's velocity for WS 7, it falls only 2 km-s$^{-1}$ above the HI solution; but, WS 38 falls about 23 km-s$^{-1}$ above the solution. Clearly more abundance data are needed to assess the population separation.

Interpretation of the situation will still be complicated even if a single population is considered. Feitzinger and Schmidt-Kaler (1982) find evidence for a double structure in the HI rotation curve which is especially evident in the southern part of the LMC. A suggestion of this effect was found by Smith and Weedman (1972) from the planetary nebula velocity dispersion which increases dramatically in the south. Thus, the measured velocity dispersion may not be indicative of the z-motions of the planetary nebulae in a simple circular motion velocity field, but rather of the deviations of that field from circularity.

One final point regarding LMC objects should be mentioned. Feitzinger, Isserstedt, and Schmidt-Kaler (1977) and Lin and Lynden-Bell (1982) report evidence for a transverse velocity of approximately 250 km-s$^{-1}$ in the plane of the sky for the LMC. Due to its large angular size, an apparent radial velocity gradient on the order of 30 km-s$^{-1}$ is introduced across the face of the LMC. None of the analyses discussed here include this effect.

Velocities for 12 SMC planetaries are currently available. Data on more SMC planetaries are of particular interest due to the anomalous grouping found by Feast and also by Webster. The SMC planetaries segregate into two velocity groups differing by about 40 km-s$^{-1}$, but with no apparent spatial preference. Recent HI observations by McGee and Newton (1982) reveal 4 radial velocity groups at 115, 134, 167, and 192 km-s$^{-1}$. The groups at 134 and 167 km-s$^{-1}$ appear to be the most massive and those authors find that stellar radial velocities tend to clump near these values as well. The 12 planetaries prefer velocities of 112 and 150 km-s$^{-1}$, but no definitive statement can be made with so few objects.

On the other hand, Walker (1982) reports 85 additional velocities for Magellanic Cloud planetary nebulae. Although no details are yet available, the bimodal velocity distribution in the SMC is not seen when more data are considered. This is clearly an area where much more observational work is needed. The identification and velocity measurement of a significant number of planetary nebulae in the SMC should help clarify the kinematics of this galaxy.

## 4. CHEMICAL ABUNDANCES OF MAGELLANIC CLOUD PLANETARY NEBULAE

The first suggestion of low abundances in the Cloud planetary nebulae was based on objective prism spectra of the SMC by Sanduleak, MacConnell, and Hoover (1972). They noted that with the exception of only one planetary in the SMC (N67), none had detectable [NII] lines, implying a general nitrogen deficiency. Webster (1976) has shown that excitation differences between planetary nebulae in the SMC (low excitation) and other galaxies (moderate to high excitation) can invalidate such a comparison, but did find evidence for the low SMC nitrogen abundance when low excitation nebulae are compared.

Osmer (1976) performed the first detailed abundance analysis for Magellanic Cloud planetaries using a photoelectric scanner to observe 3 planetary nebulae in the SMC (N2, N54, N67) and LMC (WS7, WS8, WS40). [Note: The prefix N refers to Henize (1956).] He found general underabundances of oxygen and nitrogen by about a factor of 3 in the Cloud planetaries when compared to Galactic planetaries. He also found evidence for a 50 percent overabundance of helium, but this has since been traced to the uncertainties in his photometry as well as to the inclusion of the anomalous planetary N67. His analysis of the ISM nitrogen enrichment rate indicated that planetary nebulae in the Clouds are an inadequate source by a factor of 10.

Dufour and Killen (1977) reobserved N67 and WS7, and additionally observed WS33 plus 3 SMC HII regions. The results of their image-tube spectra indicate a helium abundance comparable to Galactic planetaries, but N67 does appear enriched. They found very high ratios of N/O in the Cloud planetaries relative to their respective HII regions, while N/H is comparable to Galactic planetaries and O/H is comparable to Cloud HII regions. They also conclude that nitrogen enrichment of the Cloud ISM is provided by sources other than planetary nebulae.

Webster (1976) observed 7 planetary nebulae in the SMC (N2, N5, N38, N43, N44, N70, N87) and the LMC (WS2, WS8, WS9, WS24, WS33, WS38) with a spectracon electronographic camera, an image-tube spectrograph, and a photoelectric photometer. Helium is again found to be comparable to Galactic planetaries while oxygen is a factor of 3 below Galactic bulge planetaries. The O/H ratio is about the same in both Clouds but a factor of 2 higher than in their respective HII regions.

Webster (1978) combined the previously available data with additional spectra from the Robinson-Wampler scanner for 19 planetary nebulae in the Clouds. Among these are 5 "HN" objects which exhibit high excitation, strong [NII] lines, and high helium abundance ( $\frac{He}{H} \simeq 0.14$ ). Although planetary nebulae in this category are found in our Galaxy, they occur somewhat less frequently. Peimbert and Serrano (1980) estimate their frequency at 10 percent as compared with 25 percent in the Clouds, but this may be due to selection effects if they are derived from young progenitors which are more likely to be obscured by interstellar extinction in the plane of the Galaxy. Webster concludes that any derived overabundance of helium in Cloud planetary nebulae is probably due to observing HN objects rather than to an actual effect of the planetaries being in the Clouds.

Aller et al (1981) used the IPCS photon-counting spectrograph to observe 7 SMC planetaries (N2, N5, N43, N44, N54, N70, N87). They find the helium abundance to be comparable to Galactic planetaries but slightly higher than the SMC HII regions. Their results are adequately summarized by the values in Table 2, except for the O/H ratio which is nearly a factor of 2 lower than in the table. This can be directly attributed to the additional 5 planetary nebulae in the sample, as the O/H ratios found by Aller et al agree very well with those of Maran et al for the two objects in common. Aller et al conclude that the SMC planetaries contribute nearly enough nitrogen to enrich the ISM, but that massive stars may also be involved.

Maran et al (1982) used IUE to observe N2 and N5 in the SMC and WS40 in the LMC. The advantage offered by the UV data allowed those authors to measure the carbon abundance in an extragalactic planetary nebulae for the first time. Although their sample is small, they find results which generally agree very well with previous investigators. They conclude that planetary nebulae in the Magellanic Clouds are the dominant source of carbon enrichment of the ISM. Their results are summarized in Table 2. The abundances for the Cloud HII regions are from Dufour, Shields and Talbot (1982), while values for Galactic planetary nebulae are averages.

The general conclusions from Table 2 and the previous discussions are: (1) the abundances in the SMC and LMC planetary nebulae are similar; (2) the helium abundance is comparable for planetaries in the SMC, LMC, and the Galaxy, and perhaps 25 percent enhanced above galactically local HII regions; (3) a class of high helium abundance planetaries exists in all three galaxies; (4) oxygen is underabundant by a factor of 2 relative to galactic planetaries but comparable to local HII regions; (5) nitrogen is underabundant by a factor of 5 relative to Galactic planetaries but overabundant by a factor of 3 to 8 relative to local HII regions; (6) the neon abundance is a factor of 2 below Galactic planetaries but is comparable to local HII regions; (7) the carbon abundance is comparable to Galactic planetaries but is very much enhanced relative to the Cloud HII regions.

Thus the overall picture is one of metal deficiency in the Cloud ISM, with the SMC having slightly lower abundances than the LMC. Although the differences between the SMC and LMC can be attributed to the higher gas content of the SMC (Pagel et al 1978), the Clouds appear to have been chemically enriched only in the last few billion years (Butler, Demarque, and Smith 1982). This pattern is consistent with a burst of star formation having recently occurred in these galaxies (Butcher 1977, Stryker 1981, Hawkins and Brück 1982).

The question of responsibility for ISM enrichment has been considered by Williams (1982). He finds that classical novae are likely to be the dominant source of nitrogen in the Clouds as they return approximately 8 times as much nitrogen to the ISM as do the planetaries. Although non-negligible, the nova contribution to carbon enrichment is lower than that of the planetaries.

Table 2.

Chemical Composition of Magellanic Cloud Planetary Nebulae*

| | SMC PN relative to: | | LMC PN relative to: | | Galactic PN |
|---|---|---|---|---|---|
| | HII regions | Galactic PN | HII regions | Galactic PN | $12 + \text{Log}\ \frac{X}{H}$ |
| He | 1.3 | 1.0 | 1.3 | 1.0 | 11.03 |
| O | 1.9 | 0.5 | 0.9 | 0.5 | 8.51 |
| N | 8.1 | 0.2 | 3.6 | 0.2 | 8.18 |
| Ne | 2.1 | 0.4 | 0.9 | 0.4 | 8.02 |
| C | 38 | 0.8 | 6.3 | 0.7 | 8.85 |

*Original data taken from Maran et al (1982).

The anomalous planetary N67 in the SMC appears to have a high helium and nitrogen abundance. It has an extraordinarily high [OIII] electron temperature of 25,000K (Osmer 1976, Dufour and Killen 1977) which leads to a low calculated oxygen abundance. Webster (1978) suggests that the derived temperature is overestimated due to collisional de-excitation of the λ5007 line. Aller et al (1981) further suggest that N67 is atypical. As such it may prove to be a very interesting object in itself but no generalizations should be based on its properties.

## 5. SUMMARY

We currently know of 51 planetary nebulae in the SMC and 137 in the LMC; estimates for the total numbers are 300 and 1000. The derived shell masses exhibit a range from below $0.1M_\odot$ to $0.8M_\odot$. One should be aware that the nebula shells, particularly for the brighter, denser planetaries, may not be fully ionized so that derived masses will underestimate the total shell mass. Furthermore, the derived masses are uncertain due to the uncertainty in the distances to the Magellanic Clouds.

Kinematically, the LMC planetary nebulae tend to associate with a younger rather than an older stellar population. However, the complicated details of the LMC velocity systems preclude a simple interpretation of the kinematics of the planetaries. Currently available data on the SMC planetaries are still too sparse to provide an understanding of the kinematic situation there.

Improvements in instrumentation, in particular the availability of UV data from IUE, has significantly advanced our knowledge of chemical abundances in the Clouds. Relative to galactic planetaries, the Cloud nebulae are a factor of 2 to 4 underabundant in O, N, and Ne, but have similar helium and carbon abundances. Carbon produced by planetary nebulae is probably the dominant source of ISM carbon enrichment in the Clouds. Nitrogen appears to originate primarily from other sources.

The overall view, based on kinematics and compositions of the various stellar components of the Clouds, is one in which most of the planetary nebulae are derived from progenitors having ages of 3-5 billion years.

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PEIMBERT: Is there a selection effect, towards higher masses and higher luminosities, in the sample studied?

JACOBY: Certainly, the abundance studies concentrate on the most luminous PN, which may also be the most massive. The derived range of masses of the resolved PN indicates that at least a few of those observed are not of high mass origin.

ZUCKERMAN: If the brighter PN in the Clouds have $m_V \approx 16$, as you have indicated, then it might be possible to measure the size of these objects in the [O III] lines using optical interferometric techniques.

BARLOW: With reference to the high mass (0.8 $M_\odot$) obtained for the 3 arcsec diameter PN which you discovered in the SMC, spectra which I took of it at the AAT showed [N II] λ 6584 to be twice as strong as Hα; this result will lower the mass estimate.

SERRANO: The masses that you have derived suggest that many of the PN are of type I and may be expected to have strong [N II] lines. This would mean, in turn, that the masses have been overestimated and cast doubt on the suggestion that there has been a recent burst of star formation in the Clouds. In this context, it is worth noting that Cohen has found an age-metallicity relation which does not support such a burst.

JACOBY: Only half of the masses are determined from Hα fluxes - the rest are based on [O III] fluxes and an estimate of the Hα/[O III] flux ratio. Furthermore, only two of the objects have very high masses. The others may not be type I objects and the masses are likely to be correct.

HENIZE: It was exciting to see a resolved image of a Magellanic Cloud PN. How many have you resolved?

JACOBY: Nine have been resolved, but only one in the SMC (1980, Ap. J. Suppl. 42, 1).

PEIMBERT: The very large carbon abundances of some of these objects probably imply that some O and Ne have been produced by the stars themselves. Therefore it is very important to obtain S/H and Ar/H ratios to compare with the results derived from H II regions.

ALLER: In both the Clouds, we have found that S and Ar have essentially the same abundances as in the ambient interstellar medium.

RENZINI: As both Clouds are full of AGB stars which are also carbon stars it is not surprising that many PN in the Clouds are carbon-rich.