THE MAGELLANIC CLOUDS AND PLANETARY NEBULAE

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Abstract. A review of the statistics, emission line intensities, central star fluxes, radial velocities and chemical compositions of PN in the MC is given. From these data a discussion is made of: a) the distance scale, b) the envelope mass, c) the comparison between the observed chemical abundances and those predicted from stellar evolution models and, d) the effect that intermediate mass stars have on the chemical evolution of the MC and our galaxy.

I. INTRODUCTION

The Magellanic Clouds can provide us with a better understanding of PN, for example: a) the distribution of PN across the face of the nebula and their radial velocities can give us an indication of the mass range of the progenitor stars, b) the common distance of MC PN can permit us to derive the [O III]or Hα luminosity function and the mass distribution of their envelopes, c) the very low He, C, N, O abundances from which the progenitors of PN were formed can allow us to study the enrichment produced by stellar evolution and to check the stellar evolution models. Alternatively PN in the MC can tell us something about the star formation rate, the chemical evolution of the MC as a whole and the kinematical history relative to the formation and evolution of the MC. The purpose of this review is to study some of these relations. Previous reviews related to PN in the MC and in the Local Group are those by Webster (1978), Jacoby (1983) and Ford (1983) where several aspects related to MC PN as well as many references that will not be discussed here are presented. Special effort will be made to discuss the effect that intermediate mass stars, IMS, $1 < M/M_{\odot} < 8$ have on the chemical evolution of the MC, some overlap with the review by Dufour (1984) on chemical evolution is anticipated.

II. DISTRIBUTION AND KINEMATICS

Webster (1978), from an objective prism study done with the 1.2 m

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Schmidt and covering the central 36 square degrees of the LMC, found that PN exhibited no concentration either to the Bar or to the regions of active star formation and concluded that the distribution of bright PN, identified up to then, originated from more massive, and consequently younger, stars than the bulk of galactic PN.

Freeman *et al.* (1983) compared the galactocentric velocities from Feitzinger and Weiss (1979) of 35 PN in the LMC with those of the HI/HII rotation curve and with the older cluster rotation curve, derived from objects with ages larger than 10^9 years, and found that PN do appear to show a wide range of kinematical properties; the PN within about 2° of the rotation center follow the HI/HII region rotation curve, as noted by Smith and Weedman (1972), while the outer ones show higher scatter and two of them lie near the older cluster rotation curve. These results are not in contradiction with the conclusions of Webster (1978) and the idea that most IMS become PN. A larger number of high accuracy radial velocity determinations coupled with abundance determinations are needed to be more specific.

III. [O III] LUMINOSITY FUNCTION AND NUMBER OF PN

Jacoby (1980) obtained on-line/off-line filter photographs in [O III] or Hα of four fields in the central regions of each of the clouds using the Cerro Tololo 4m prime-focus camera; from this survey he was able to detect planetary nebulae 250 times fainter than the brightest ones, improving the detection limit by three magnitudes relative to previous surveys. He established an [O III] luminosity function and from it estimated that the total numbers of PN in the SMC and LMC are 285±78 and 996±253 respectively. Previous estimates of the total number of PN are reviewed by Jacoby (1983).

Based on his MC PN luminosity function Jacoby (1980) estimated that, for local group galaxies, the average luminosity specific number is $6.1\pm2.2\times10^{-7}$ PN/$L_\odot$ and the mass specific number is $2.1\pm1.5\times10^{-7}$ PN/$M_\odot$, where the uncertainties are 1 standard deviation values derived from the averaging procedure. From the luminosity specific number he concludes that there are 10000±4000 PN in our Galaxy.

IV. MASS FUNCTION OF THE SHELL, PN DISTANCE SCALE, PN AS STANDARD CANDLES

Jacoby (1980) was able to spatially resolve 9 faint PN in the MC and to obtain diameters for the first time. Under the assumption that the PN are optically thin it follows that

$$M\varepsilon^{-1/2} = K[I(H\alpha)\ d^5\ \phi^3]^{1/2} \quad , \qquad (1)$$

where M is the mass of the shell, ε is the filling factor, K is a constant, I(Hα) is the intrinsic Hα flux, d is the distance to the MC, and ϕ is the angular radius in arcseconds. Jacoby obtained a spread of a

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factor of forty in $M\varepsilon^{-1/2}$ which, under the assumption of a constant ε, implies that there is a spread of shell masses of a factor of 40 as observed in galactic PN. The spread in M might be smaller due to two reasons: a) LMC 18, which is the minimum mass object observed by Jacoby, might be optically thick and its real mass might be consequently higher; b) the filling factor ε might decrease with the size of the PN (e.g., Torres-Peimbert and Peimbert 1977), reducing the mass of the most massive objects which are the largest. To improve our knowledge of this problem spectra of the objects are needed: to establish if they are optically thin and to determine electron densities from forbidden lines to be able to derive a value of ε for each object.

Seaton (1968), under the assumption that the masses of optically thin nebula are the same in the Galaxy and the MC, obtained a distance scale for galactic PN that sometimes is referred as the Seaton-Webster distance scale and that has been widely used by Cahn and Kaler (1971). Seaton made three additional assumptions that can affect the distance scale: a) MC PN have T_e = 8000°K, b) MC PN have N(He)/N(H) = 0.16, and c) that the maximum values of S, the surface brightness, and E, the total Hβ emission, will occur at the time in which PN become optically thin. From recent observations of MC PN it has been found that $\langle T_e \rangle$ = 12000°K and that $\langle$N(He)/N(H)$\rangle$ = 0.11 each of these two effects amount to about 20% in the distance scale but they go in opposite directions and consequently cancel each other; with respect to c) if the number of ionizing photons increases with time E will become maximum when the nebula reaches the transition between optically thick and optically thin, alternatively S might reach its maximum before the PN becomes optically thin since S is proportional to N_e^2 R and even if within the ionized zone R is increasing with time, due to the advance of the ionization front, N_e is diminishing with time due to the PN expansion. Since Seaton compared MC E values with galactic S values, from the previous argument it follows that his distance scale becomes a lower limit to the real distance scale (if the average masses of optically thin PN are the same in the MC and the Galaxy). That the maximum S values are attained by galactic PN before they become optically thin has been argued by Cudworth (1974) and Pottasch (1980). The distance scales by Cudworth (1974) and Weidemann (1977) are 1.5 and 1.3 times larger than the Seaton scale; moreover the estimated total number of PN in the Galaxy also support the larger distance scales (Jacoby 1980; Alloin *et al.* 1976). If the Cudworth distance scale is adopted, and if the comparison between the MC and galactic PN is valid, it follows that when E is maximum S is two times fainter than its maximum value.

PN have been used as standard candles to determine extragalactic distances. Jacoby and Lesser (1980) have been using the intrinsically luminous PN in M31 and the MC to establish distances to galaxies whose Local Group membership is uncertain. Moreover Ford and Jenner (1979, see also Ford 1983) have obtained a preliminary distance to M81 of 2 to 3 Mpc based on 8 PN.

V. CHEMICAL COMPOSITION

Chemical abundance determinations of PN in the MC have been obtained by: Osmer (1976), Webster (1976,1977,1978), Dufour and Killen (1977), Aller *et al.*(1981*a*), Maran *et al.*(1982), Aller and Czyzak (1983), Barlow *et al.* (1983), and Aller (1983). In Table 1 we present some of these determinations as well as those of other objects for comparison. The accuracy of the determinations are typically of: 0.04 dex for He/H, 0.1 dex for O/H, 0.1 dex for N/O and 0.2 dex for C/O at the one sigma level. With the possible exception of O the elements presented in Table 1 are those expected to be affected by stellar evolution of the progenitor star.

PN apparently are produced by stars in the 0.8 to 8 $M_\odot$ mass range (e.g., Peimbert 1978; Torres-Peimbert 1984). Peimbert (1978) based on chemical composition and kinematics divided galactic PN in four types which roughly correspond to the following mass intervals of the progenitor stars: Type I (He-N rich), 2.4-8 $M_\odot$; Type II (intermediate population),1.2-2.4 $M_\odot$; Type III (high velocity), 1-1.2 $M_\odot$; and Type IV (halo), 0.8 to 1.0 $M_\odot$. Those PN whose progenitors have masses larger than 1.4 $M_\odot$ on the main sequence are expected to show abundances very similar to

TABLE 1
Chemical Abundances

Object	He/H[a]	O/H[a]	N/O[b]	C/O[b]	Source
⟨PN LMC⟩	11.07	8.3	-0.8	+0.7	1,2
⟨He-N⟩ LMC	11.23	8.0	+0.4	...	1,3,4
N25 LMC	...	8.3:	-1.8	...	5,6
N97 LMC	11.26	8.4	+0.2	-0.8	4
⟨H II⟩ LMC	10.92	8.34	-1.31	-0.48	7,8,9
⟨PN⟩ SMC	11.02	8.1	-0.8	+0.6	2,10
N67 SMC	11.27	7.7	-0.1	...	3
⟨H II⟩ SMC	10.89	7.89	-1.48	-0.89	8,9,11
PN 6822	11.27	8.1	+0.7	...	12
⟨H II⟩6822	10.92	8.3	-1.7	...	8
Type I PN	11.18	8.6	+0.0	-0.3+0.5	13
Type II PN	11.04	8.7	-0.6	-0.3+0.5	13
Orion	11.00	8.62	-0.97	-0.10	14,15
Sun	...	8.92	-0.93	-0.25	16

a. Given in log N(A)/N(B)+12; b. Given in log N(A)/N(B);
1. Aller 1983; 2. Maran *et al.* 1982; 3. Dufour and Killen 1977; 4. Barlow *et al.* 1983; 5. Webster 1977; 6. Webster 1978; 7. Peimbert and Torres-Peimbert 1974; 8. Lequeux *et al.* 1979; 9. Dufour *et al.* 1982; 10. Aller *et al.* 1981*a*; 11. Peimbert and Torres-Peimbert 1976; 12. Dufour and Talent 1980; 13. Torres-Peimbert 1984; 14. Peimbert and Torres-Peimbert 1977; 15. Torres-Peimbert *et al.* 1980; 16. Lambert 1978.

those of H II regions for elements not affected by their stellar evolution, like Ar and S; those PN with smaller mass progenitors should show underabundances in these elements reflecting the chemical evolution of the interstellar medium from which they formed. Results of investigations of MC PN indicate that the Ne, Ar and S abundances are similar to those of H II regions in their respective galaxy, indicating that their progenitor stars formed relatively recently. From the previous argument it follows that most of the observed objects in the MC seem to be of Types I and II with the possible exception of N25 in the LMC (Webster 1977, 1978), which is 45 arc seconds from the center of the red globular cluster NGC 1852, that might have a progenitor of smaller mass. N67, N97 and N102 are He-N rich objects corresponding to those of Type I.

Stecher *et al.* (1982) have obtained masses of $\sim 1\ M_\odot$ and T* $\sim 1\times10^5$ °K for the central stars of P40 in the LMC and N2 and N5 in the SMC. The central star masses are higher than those of average PN in the Galaxy (Schoenberner and Weidemann 1983) which might be due to: a) errors in the distance determinations of galactic PN, b) severe selection effects towards brighter objects with more massive progenitors, and c) stellar evolution differences between MC and galactic PN. The masses of the progenitor stars in the main sequence are expected to be around 4 $M_\odot$ and would correspond to He-N rich objects, which they are not.

VI. CHEMICAL ENRICHMENT AND STELLAR EVOLUTION MODELS

Renzini and Voli (1981) (see also: Iben and Truran 1978; Becker and Iben 1979, 1980; Iben and Renzini 1982*a*,1982*b*,1983) have reviewed the evolution of the surface abundances of He, C, N and O for IMS, from the main sequence until the ejection of the PN envelope, or until C ignition in the core. Torres-Peimbert (1984) has compared these predictions with observations of galactic PN, the agreement in general is good but she notices two important differences: a) Type I PN show an anticorrelation between O and N probably indicating that some O has been converted into N,and b) C enrichment is more efficient than predicted and extends to masses as low as 0.8 $M_\odot$.

Since the initial abundances of He, C, N and O relative to H are considerably smaller for the progenitors of MC PN than for those of galactic PN (see Table 1), the expected relative enrichments for MC objects are higher, therefore the observations provide stronger constraints to the stellar evolution models.

In Figure 1 we show the relative enrichment of N and He for MC PN (Table 1 and references therein) compared with galactic PN (Torres-Peimbert 1984 and references therein). The MC values are higher than those of galactic PN for several reasons: a) their original He/H values are smaller, and higher relative enrichments are expected for a given mass (Renzini and Voli 1981), b) some Type II galactic PN in the anticenter direction started with smaller N/O and He/H values than those of the Orion Nebula, which invalidates the region with $[N/O] \lesssim 0.3$ and $[He/H] \lesssim 0.4$. The N enrichment for He-N rich PN is higher than expected under the assumption of secondary production of N from C (see also Table 1), indicating that most of the N in these objects is of primary

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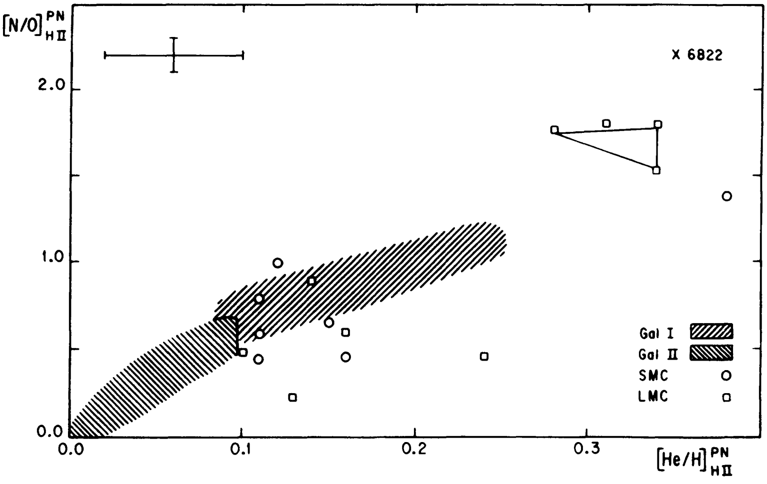

Fig. 1. Relative enrichment of N and He in PN where $[A/B]^{PN}_{HII}$ = log $(A/B)_{PN}$ - $\log(A/B)_{HII}$. The shaded areas correspond to Type I and Type II galactic PN normalized to the Orion Nebula values. The PN in the local group galaxy NGC 6822 is included. The error bars in the upper left hand corner are typical of extragalactic determinations at the one sigma level. The three squares joined with straight lines correspond to N97 observed by Osmer (1976), Barlow *et al.* (1983), and Aller (1983).

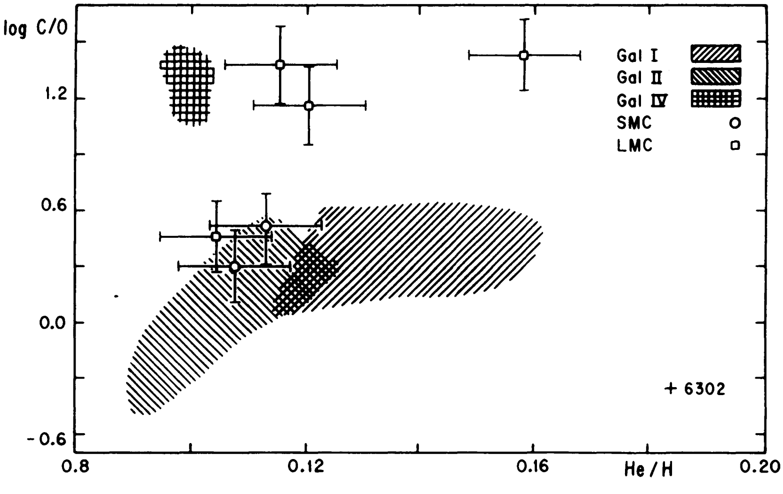

Fig. 2. log N(C)/N(O) versus N(He)/N(H) values for MC and galactic PN.

origin, unless N is produced by secondary mechanisms from O instead of C, see below.

In Figure 2 the C/O versus He/H diagram is presented where the MC PN (Table 1 and references therein) are compared with galactic PN (Torres-Peimbert 1984 and references therein). Again the relative enrichment of C is considerably higher in the MC PN than in the galaxy, considering the underabundance of C present in the Clouds (see Table 1); this result indicates that indeed PN are producing C and again is in agreement with the predictions by Renzini and Voli (1981). The three values with C/O$\sim$ 1.0 were obtained from the λ4267 C II recombination line and may correspond to upper limits due to probable overestimates of this very weak line, on the other hand the three values with log C/O $\sim$ 0.4 were derived from IUE data and may correspond to lower limits due to probable overestimates of T_e and to the possible effect of dust absorption on the λ1550 C IV lines that was not considered. Under the assumption that C/O = C^{++}/O^{++} and from the 1909/1663 intensity ratios for NGC 6302 by Aller *et al.* (1981*b*) and Barral *et al.* (1982), it is obtained that log C/O = -0.35. These results are in agreement with models by Renzini and Voli (1981) with α $\sim$ 2 and M_i $\sim$ 8 $M_\odot$; Barlow *et al.* (1983) obtain for N97 similar abundances to those of NGC 6302 (see Table 1). These values support the results of Koester and Reimers (1981) and Reimers and Koester (1982) who found that white dwarfs do occur up to progenitor masses of $\sim$7 $M_\odot$.

In Figure 3 the relative enrichment of O versus N/O is presented for PN of Type I (Table 1 and references therein; Peimbert and Torres-Peimbert 1983). As it was noticed before (Aller 1983; Ford 1983; Peimbert and Torres-Peimbert 1983) there is a strong anticorrelation between [O/H] and N/O which implies that: a) there is a systematic effect in the abundance determinations, or b) the effect is real and there has been a substantial conversion of O into N. With the exception of the values by Barlow *et al.* (1983) for N97, all the other values have been obtained from optical data and the following equations:

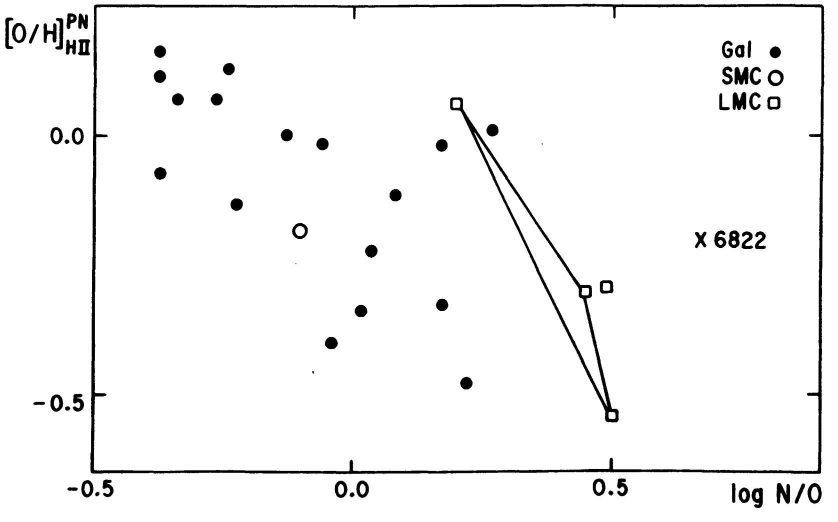

Fig. 3. Relative enrichment of O versus log N(N)/N(O), symbols as in Figure 1.

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$$\frac{N(N)}{N(O)} = \frac{N(N^+)}{N(O^+)} , \qquad (2)$$

and

$$\frac{N(O)}{N(H)} = \frac{N(O^+) + N(O^{++})}{N(H^+)} \; \frac{N(He^+) + N(He^{++})}{N(He^+)} \; . \qquad (3)$$

Equation (2) is a valid approximation even for objects where $N(N^+)/N(N) \sim 0.01$, like NGC 7662 for which Harrington *et al.* (1982) find that equation (2) is accurate within 10%. Equation (3), which is the crucial one, is in very good agreement with models for NGC 3918 by Torres-Peimbert *et al.* (1980) and models for NGC 7662 by Harrington *et al.* (1982). Alternatively Aller *et al.* (1981*b*) partially based on the O IV]1402 line derives for NGC 6302 an O/H value a factor of two higher than that given by equation (3). The O/H value by Barlow *et al.* (1983) for N97 is also partially based on the O IV]1402 line, but from the published results it is not possible to say if it is in disagreement with equation (3). Another possible source of systematic error is due to the $N(O^{++})/N(H^+)$ ratio which might be underestimated if there are regions of very high density contributing to λ4363 and not to λ5007 producing a spuriously high electron temperature.

If the O abundance determinations in Figure 3 are correct, the O depletion reaches factors of two to three in some objects which is not explained by present stellar evolution models where the O depletion is of at most a few percent (Renzini and Voli 1981). If there is no O depletion the excess N is mostly primary; alternatively if there is O depletion then the excess N is mostly secondary.

VII. GALACTIC CHEMICAL EVOLUTION

Tinsley (1978) on quite general grounds has shown that an overabundance X(PN)/X(H II) larger than a factor of seven would indicate that PN precursors are the main source of enrichment of the element considered. This estimate was made under the assumption of a shell mass of 0.3 $M_\odot$ for PN. Since the average mass of the progenitors in the main sequence is $\sim$1.5 $M_\odot$ (Alloin *et al.* 1976) and the average mass of the PN central stars is $\sim$ 0.6 $M_\odot$ (Shoenberner and Weidemann 1983) about 0.6 $M_\odot$ have been ejected prior to the PN formation, this material could already show some C and N overabundances thus lowering the estimate by Tinsley. From Figures 1 and 2 and Table 1 it follows that PN might be the main responsibles for C and N enrichment in the MC.

Based on earlier results Osmer (1976) reached the conclusion that PN are an inadequate source of N by a factor of ten; Dufour and Killen (1977) reached the conclusion that N enrichment of the Clouds interstellar medium is provided by sources other than PN; and Williams (1982) concluded that novae were the main contributors to the N enrichment in

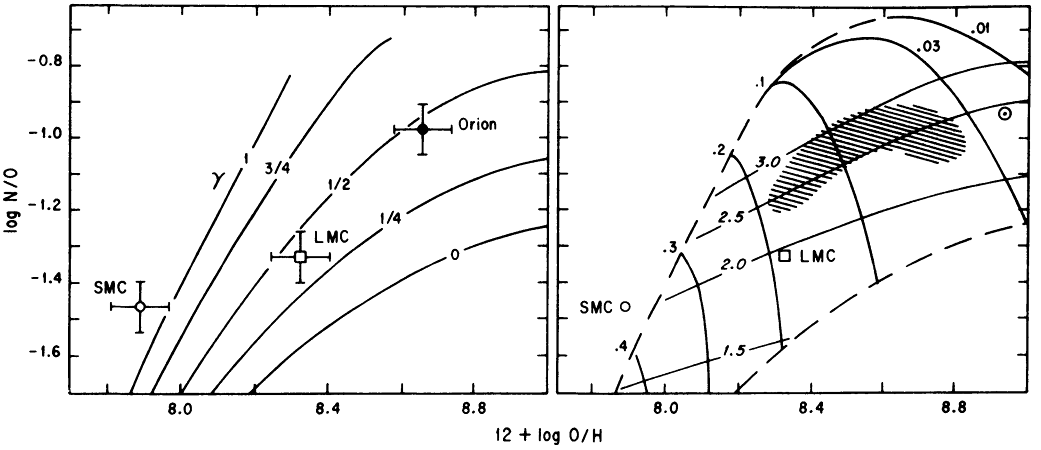

Fig. 4a. Galactic evolution models by Serrano and Peimbert (1983) where the following assumptions were made: a) secondary production of N, b) η = 1.75 a parameter proportional to the star formation rate, c) constant star formation rate, d) variable yield with $p_Z = 0.002+0.6Z$. γ denotes the ratio of accretion to star formation rates.

Fig. 4b. Isochrones and lines of constant Mg/M_{tot} for the models in Figure 4a, the nearby horizontal lines are isochrones and are labelled by the value t/τ_N, where $\tau_N \sim 3\times10^9$ years. The nearby vertical lines are labelled by the value Mg/M_{tot}, which is constant along each time. The shaded area denotes galactic H II regions and the position of the sun is also reproduced in this diagram.

the Clouds, in this case most of the N would be of primary origin. Alternatively Aller *et al.* (1981*a*) concluded that the SMC PN contribute nearly enough N to enrich the ISM, but that massive stars may also be involved; moreover Serrano and Peimbert (1983) made models in which most of the N is of secondary origin and has been produced by IMS.

In Figure 4 models by Serrano and Peimbert (1983) are shown, these models are in agreement with the observed N/O versus O/H diagram of galactic and extragalactic H II regions. From this figure, it follows that in the SMC the star formation rate is almost equal to the accretion rate ($\gamma \sim 1$) and that in the LMC, γ, the ratio of star formation to accretion rates is about 1/2. The predicted M_{gas}/M_{tot} ratios are 0.17 and 0.38 for the LMC and the SMC respectively in good agreement with the observed values of 0.12 and 0.42 (Lequeux *et al.* 1979). From a $\tau_N \sim$ 3 Gyr it is obtained that the MC have an age of 5-6 Gyr in good agreement with the results of Cohen (1982) and Mould and Aaronson (1982).

Maran *et al.* (1982) by comparing the C abundances in PN to those of HII regions (Table 1) concluded that most of the C enrichment in the MC is due to PN. Serrano and Peimbert (1981) from chemical evolution models of the solar neighborhood concluded that stars of $M \geq 10\ M_{\odot}$ contributed with 0.25 and stars of $1 \leq M/M_{\odot} \leq 8$ (IMS) contributed with 0.28 to the C/O ratio. The value of C/O = 0.13 for the SMC determined by Dufour *et al.* (1982) implies that if the initial mass function is the same in the SMC and the Galaxy, then stars with $M \geq 10\ M_{\odot}$ contribute at most with 0.13 to the C/O ratio in the solar neighborhood; consequently α, the ratio of the convective mixing length to the pressure scale height, for IMS has to be larger than 2. The C/O value in the solar neighborhood, the C/O values in N97 and NGC 6302 and the very low C/O values in the MC all indicate that α for the IMS has to be > 2.

Dufour and Shields (1982) have discussed several possible explanations for the very low C/O values in the MC. Support in favor of the low C/O values comes from the shape of the interstellar extinction curve where the 2200 A feature attributed to C also becomes fainter when going from the Galaxy to the LMC and to the SMC (e.g., Seaton 1979; Roca-Volmerange *et al.* 1981; Koornneef and Code 1981; Nandy *et al.* 1982). It seems to me that a reasonable explanation for the low C/O values in the MC is a delay in the C production, considering that the MC are somewhat younger than the solar vicinity, which again indicates that most of the C production is due to PN. The N/O behaviour indicates that most of the C production takes place later than most of the N production, which apparently is in contradiction with the idea that most of the N is of secondary origin, this contradiction is not very strong due to three reasons: a) at least part of the C comes from massive stars (Arnett 1978), b) N/C is smaller than 1 even in the SMC, and c) part of the N might be of secondary origin but produced by O instead of C.

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DISCUSSION

Graham: Just a remark. The distribution of the planetaries as shown in Sanduleak's survey looks roughly similar to that of the novae. Jacoby's survey for faint planetary nebulae was made only in the Bar region of the LMC. His results do not necessarily imply that they concentrate towards the Bar.

Feast: A. Walker (S.A.A.O.) has doubled the number of planetaries with measured radial velocities in each cloud. A preliminary result of his is that the expanded sample in the SMC now shows no division into two velocity groups such as appeared in the earlier work (although the values of previous individual velocities are confirmed).

Peimbert: From the near encounter between the SMC and the LMC about 200 million years ago (see both Fujimoto and Mathewson in these proceedings) this result might indicate that the large majority (if not all) of the progenitors of the observed PN have masses smaller than 4 $M_{\odot}$.

Bessel: N abundances derived for a good sample of galactic G-K dwarfs by three groups (Mt Stromlo, Yale and Texas) show no variation of N/C with Fe/H or O/H. This indicates that N is mostly of primary origin at least over two decades in [Fe/H].

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