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BRIGHT PLANETARY NEBULAE AS PROBES OF CHEMICAL EVOLUTION

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ABSTRACT

A compilation of observations of planetary nebulae in the Magellanic Clouds has been used to study the utility of bright extragalactic planetary nebulae as distance indicators and as probes of chemical evolution. A planetary nebula's [O III] λ5007 luminosity is shown to be primarily a result of the ultraviolet luminosity of its central star, confirming Jacoby's (1989) original proposal. However, the oxygen abundance is observed to modify the maximum [O III] λ5007 luminosity actually attained. As a result, the planetary nebula luminosity function will overestimate the distances to low-luminosity galaxies. A procedure to correct the distance moduli of low-luminosity galaxies relative to the LMC is outlined. As chemical abundance probes, the brightest planetary nebulae in a galactic population appear to be very promising. A luminosity-limited study will preferentially select the planetary nebulae with the highest oxygen abundances because of the abundance dependence of the [O III] λ5007 luminosity. In the Magellanic Clouds, H II regions and bright planetary nebulae have similar oxygen abundances, so, from a chemical evolution viewpoint, both must represent recent star formation events. Consequently, bright planetary nebulae should be reliable probes of the interstellar medium oxygen abundance during the last episode of star formation, which is especially useful in galaxies that are no longer forming stars. If the width of the SMC's abundance distribution is typical of that in low-luminosity galaxies, only three planetary nebulae are required to determine the oxygen abundance at the last epoch of star formation to within ± 0.1 dex.

Subject headings: H II regions — ISM: abundances — Magellanic Clouds — planetary nebulae: general

1. INTRODUCTION

Extragalactic planetary nebulae have received a great deal of attention lately because of the use of the planetary nebula [O III] λ5007 luminosity function as a distance indicator (e.g., Ciardullo et al. 1989; Jacoby, Ciardullo, & Ford 1990a). These studies have suggested that the shape of the planetary nebula luminosity function and its peak luminosity are independent of the morphological type, metallicity, and environment of the host galaxy. If this is indeed the case, the luminosity function is then an extremely valuable tool for investigating the extragalactic distance scale since planetary nebulae are present in all galaxies. Also, the similarity of the luminosity functions in all galaxies would make them valuable probes of the chemical evolution of galaxies other than the Milky Way.

It is the potential utility of planetary nebulae as probes of galactic chemical evolution that is the main motivation for this study. Planetary nebulae would be valuable abundance probes since they would allow direct measurements of the oxygen abundance in elliptical systems, where no direct method currently exists. To determine accurate chemical abundances, however, the electron temperature must be determined, which necessarily requires observing faint, temperature-sensitive lines (e.g., [O III] λ4363). Consequently, in galaxies at distances beyond the Magellanic Clouds, abundance analyses are only possible for the brightest planetary nebulae. Therefore, it is important to determine the properties of the brightest members of a galaxy's planetary nebula population compared to those of the entire population. As well, it is necessary to relate the abundances in bright planetary nebulae to those in H II regions, the traditional tool of chemical evolution.

The studies that established the planetary nebula luminosity function as a distance indicator have compared the peak luminosities in different galactic environments. Such comparisons, however, only test whether the [O III] λ5007 fluxes from a population of planetary nebulae depend upon global galactic properties. The needs of chemical evolution studies are somewhat more stringent. Because only the brightest planetary nebulae in a galactic population can be observed in enough spectroscopic detail to determine accurate oxygen abundances, the biases inherent in a luminosity-limited selection must be known if the results are to be extended to the whole galactic population. For this reason, the physical properties that have the greatest influence upon the observed [O III] λ5007 fluxes of individual planetary nebulae must be known. To address this issue, observational data for Magellanic Cloud planetary nebulae have been compiled and used to establish which observed properties have the greatest impact upon [O III] λ5007 luminosities. The Magellanic Cloud planetary nebulae are particularly suitable for this purpose since they are near enough that they can be studied in detail individually and, since they are at a known distance, their absolute properties can also be defined.

The data compilation is defined in § 2. This compilation is then used in §§ 3 and 4 to establish the nebular characteristics of bright planetary nebulae by comparing the observed relationships between various physical properties with the predictions of Jacoby's (1989) theory. Many nebular properties were investigated, but only the central star luminosity (§ 3) and the nebular composition (§ 4) were found to have significant effects upon the [O III] λ5007 luminosities. These topics naturally lead to a consideration of the maximum [O III] λ5007 luminosity attained by planetary nebulae in low-luminosity galaxies and its impact upon distance determinations, which is the focus of § 5. In § 6, the original motivation for this study, the suitability of planetary nebulae as chemical evolution probes, is examined. Finally, conclusions are presented in § 7.

2. THE SAMPLE

For this investigation, an attempt was made to compile all the data available in the literature for each planetary nebula in the Magellanic Clouds. Table 1 presents the final compilation for the LMC, while Table 2 lists that for the SMC. In both tables, columns (1)–(8), respectively, list the object name, its electron temperature, its electron density (from [O II] if available; from [S II] otherwise), its oxygen abundance, its nitrogen abundance, its reddening, its apparent [O III] λ5007 flux (not corrected for reddening), and its apparent Hβ flux. Column (9) indicates whether the planetary nebula is of type I (Peimbert & Torres-Peimbert 1983; see below also). Finally, column (10) lists the sources for these data. The planetary nebulae in Tables 1 and 2 are labeled according to their designation in the catalog of Sanduleak, MacConnell, & Phillip (1978) if they are included in that catalog. Otherwise, Tables 1 and 2 use the object's original designation. Cross-reference lists of the various names for each object may be found in Sanduleak et al. (1978), Jacoby (1980), and Meatheringham & Dopita (1991a, b).

With the exception of the Meatheringham & Dopita (1991a, b) spectroscopic data, all the data have been adopted from the literature without modification or reanalysis. Dopita & Meatheringham (1991a, b) computed abundances from the Meatheringham & Dopita (1991a, b) data using a model-fitting procedure. The abundances from most other sources, however, were calculated using ionization correction factor (ICF) schemes such as those described by Torres-Peimbert & Peimbert (1977). For consistency, the author computed ICF oxygen abundances for the Meatheringham & Dopita (1991a, b) data for all objects in which He I λ5876 and [O III] λ4363 were detected. For the remaining objects, the Dopita & Meatheringham (1991a, b) results were adopted. The ICFs were calculated according to the Torres-Peimbert & Peimbert (1977) prescription. For those objects lacking an electron density measurement, the median value for all objects with observed densities in the Meatheringham & Dopita (1991a, b) sample, 4000 cm^{-3}, was adopted. With the exception of the type I planetary nebulae in the sample, the ICF oxygen abundances derived here are in very good agreement with the model results of Dopita & Meatheringham (1991a, b), generally to within 0.15 dex. For the type I planetary nebulae, the ICF oxygen abundances are invariably lower than the model results. However, Dopita & Meatheringham (1991a) point out that their models for these objects do not account for the high [O III] temperatures observed, so the models likely overestimate the oxygen abundances for these objects.

When there were several estimates for a given quantity, the following general guidelines were used to arrive at an adopted value. The data were preferentially selected from large samples in the hope that this would minimize any scatter due to different observing and reduction procedures. For quantities derived from spectroscopic data, preference was given to the highest spectral resolution, but external accuracy was also considered. Other specific procedures are outlined below.

Oxygen abundances derived from the same data as the electron temperature and electron density were preferentially adopted. Usually then, the electron temperatures and electron densities listed in Tables 1 and 2 are those that were used to compute the oxygen abundance. Tables 1 and 2 only list measured electron densities. If an oxygen abundance was calculated using an adopted density, then the electron density listed in Tables 1 and 2 is the highest spectral resolution measurement of this quantity taken from other studies. Note that the oxygen abundances for SMC MG8, LMC N99, and LMC SMP26 (Monk, Barlow, & Clegg 1987) were calculated using an *adopted* electron temperature of 10,500 K. These electron temperatures are noted in Tables 1 and 2.

The nitrogen abundances listed in Tables 1 and 2 are rather inhomogeneous. Except for the nitrogen abundances from Aller et al. (1987) and Dopita & Meatheringham (1991a, b), the nitrogen abundances are calculated using optical data and ICFs based upon $N(\mathrm{O})/N(\mathrm{O}^+)$ (Torres-Peimbert & Peimbert 1977). The $N(\mathrm{O})/N(\mathrm{O})^+$ ratio can often be rather high in planetary nebulae since O^+ is not normally the dominant ionization state of oxygen. Furthermore, this ratio is also often uncertain because an accurate reddening is required to reliably measure the [O II] λ3727 intensity. Thus, model-derived nitrogen abundances are more desirable than those based on ICFs, especially model results constrained by ultraviolet observations (e.g., Aller et al. 1987). For the objects observed by Meatheringham & Dopita (1991a, b), then, Tables 1 and 2 list the nitrogen abundances from the models of Dopita & Meatheringham (1991a, b). Planetary nebulae were designated as type I in Tables 1 and 2 based on the criterion $\log (N/\mathrm{O}) \geq -0.3$ (Peimbert & Torres-Peimbert 1983), but only if their nitrogen abundance was from either Aller et al. (1987) or Dopita & Meatheringham (1991a, b). This is a rather strict type I definition, but the planetary nebulae so designated are likely to be definite type I's.

The [O III] λ5007 fluxes of Jacoby, Walker, & Ciardullo (1990b) were preferentially adopted because of the large size of their sample and the excellent agreement between their photometric fluxes and those of Webster (1969). Likewise, because of the large size of their sample and the photometric precision of their Hβ fluxes, the Meatheringham, Dopita, & Morgan (1988) Hβ fluxes were also preferentially adopted. The remaining fluxes are all from Wood et al. (1987). Only photometric [O III] λ5007 and Hβ fluxes are listed in Tables 1 and 2. As a check, the ratio of the photometric [O III] λ5007 and Hβ fluxes was compared with the spectroscopic ratio, when available, and the two were generally found to be in good agreement.

3. THE EFFECT OF THE CENTRAL STAR'S IONIZING LUMINOSITY

Jacoby (1989) originally hypothesized that the planetary nebula luminosity function stemmed from the luminosity evolution of the central stars. So long as a planetary nebula is optically thick, the Hβ luminosity is a direct measure of its central star's ionizing luminosity (e.g., Osterbrock 1989) or of the total heating in the nebula. Since [O III] λ5007 is the primary nebular coolant, thermal equilibrium dictates that it should also correlate with the central star's ionizing luminosity. In this way, if the planetary nebula luminosity function is due to the central star's luminosity evolution, the [O III] λ5007 and Hβ fluxes should be correlated.

The apparent [O III] λ5007 flux is plotted as a function of the apparent Hβ flux in Figure 1 for all the planetary nebulae in Tables 1 and 2. In this figure, the open symbols identify LMC planetary nebulae, while the filled symbols denote SMC objects. The squares represent type I planetary nebulae. In Figure 1, the [O III] λ5007 and Hβ fluxes for SMC planetary nebulae have been increased by 0.124 dex from the values in Table 2 to account for the 0.31 mag distance modulus differ-

TABLE 1

LMC PLANETARY NEBULA DATA

Name (1)	Te (10^4 K) (2)	log Ne (cm^{-3}) (3)	O/H (4)	N/H (5)	c(Hβ) (6)	log F(5007) ($erg\ s^{-1}\ cm^{-2}$) (7)	log F(Hβ) ($erg\ s^{-1}\ cm^{-2}$) (8)	Type I (9)	sources [a] (10)
J4						-13.51	-14.06		13
J5	1.76	3.04	8.25	7.61	0.76		-13.25		5, 15, 12
J7									
J10	2.01		7.52	7.18	0	-13.69			5, 13
J12						-13.71	-14.15		13
J14									
J15	1.14		8.61	7.61	0.21				5
J16									
J17	3.50		6.69	6.36	0.18				5
J18						-13.37	-14.07		13
J20	1.55	2.48	8.18	8.07	0	-13.0	-13.97		5, 13
J21	1.85		7.96		0.09				5
J22	2.41		7.69	8.34	0.45				5
J23						-13.53			13
J24	1.80	3.28	7.75	8.23	0.17				5
J26						-13.21			13
J31	1.27		8.51	7.99	0.94				5
J32									
J33	1.30		8.17		0				5
J38	1.60	2.00	8.49	8.33	0				5
J41	1.59		7.87		0				5
N16									
N99	1.05[b]		8.76	7.41					6
SMC1									
SMP1	1.15	3.54	8.29	7.48	0.17	-11.548	-12.46		2, 11, 12
SMP2	1.05		8.17	7.15	0.10	-12.744	-13.18		1, 11, 12
SMP3	1.38	3.86	7.75	7.00	0.29	-11.858	-12.48 [c]		1, 11, 12
SMP4						-12.391	-13.52		11, 13
SMP5	1.17	3.27	7.98	6.68	0.83	-12.384	-12.85		2, 11, 12
SMP6	1.33	4.14	8.43	7.40	0.56	-11.580	-12.67		2, 11, 12
SMP7	1.98	3.01	8.20	8.11	0.37	-12.052	-13.12	yes	1, 11, 12
SMP8	1.07	3.74	8.19	7.43	0.23	-11.938	-12.74 [c]		2, 11, 12
SMP9						-12.424	-13.38		11, 12
SMP10						-12.033	-13.15		11, 12
SMP11						-12.917	-13.15		11, 12
SMP12						-12.797			11
SMP13	1.48	3.83	8.27	6.98	0.51	-11.806	-12.82		1, 11, 12
SMP14	2.12	2.48	8.05	8.15	0.44	-12.802	-13.69	yes	1, 11, 12
SMP15	1.29	3.71	8.33	7.20	0.51	-11.513	-12.66		2, 11, 12
SMP16	2.31	2.96	7.85	8.18	0.47	-12.312	-13.30	yes	1, 11, 12
SMP17						-13.016			11
SMP18						-12.467	-13.36		11, 12
SMP19	1.38	3.31	8.45	7.54	0.35	-11.692	-12.73		1, 11, 12
SMP20	1.94	3.16	7.88	8.08	0.32	-12.542	-13.37	yes	2, 11, 12
SMP21	2.03	3.38	7.91	8.30		-11.728	-12.76	yes	7, 8, 11, 12
SMP22						-12.676			11
SMP23	1.12	3.73	8.31	7.20	0.06	-11.769	-12.68		2, 11, 12
SMP24	1.28	2.94	8.38	7.34	0.36	-12.751	-13.77		1, 11, 13
SMP25						-11.433			11
SMP26	1.05[b]	3.88	7.54	7.20					6
SMP27						-12.497	-13.40		11, 12
SMP28						-12.390	-13.35		11, 13
SMP29	2.00	3.74	7.91	8.17	0.08	-11.714	-12.71	yes	1, 11, 12
SMP30						-12.639	-13.45		11, 12
SMP31	1.22	3.90	7.36				-12.91		2, 12
SMP32	1.59	3.47	8.27	7.11	0.16	-11.750	-12.80		1, 11, 12
SMP33	1.34	3.67	8.48	7.64	0.36	-11.748	-12.81		1, 11, 12
SMP34						-12.181			11
SMP35	1.33	3.20	8.37	7.32	0.04	-11.713	-12.81		1, 11, 12
SMP36	1.45		8.41	8.08		-11.965	-12.72		6, 11, 12

TABLE 1—*Continued*

Name (1)	Te (10^4 K) (2)	log Ne (cm^{-3}) (3)	O/H (4)	N/H (5)	c(Hβ) (6)	log F(5007) ($erg\ s^{-1}\ cm^{-2}$) (7)	log F(Hβ) ($erg\ s^{-1}\ cm^{-2}$) (8)	Type I (9)	sources [a] (10)
SMP37	1.36	3.90	8.46	7.95	0.33	-11.806	-12.85		2, 11, 12
SMP38	1.29	4.11	8.28	7.63	0.21	-11.492	-12.62		1, 11, 12
SMP39						-12.152			11
SMP40	1.46	3.08	8.37	7.59	0.20	-12.297	-13.25		1, 11, 12
SMP41	1.55	3.06	8.32	7.53	0.03	-12.123	-13.33		1, 11, 13
SMP42	1.49		8.05	7.90	0.22	-12.146	-13.11	yes	1, 11, 12
SMP43						-12.016			11
SMP44	2.07	3.15	8.26	8.11	0.01	-12.449	-13.59	yes	1, 11, 13
SMP45	1.59	3.16	8.03	7.43	0.44	-12.022	-13.17		1, 11, 13
SMP46	1.50	3.60	8.20	7.78	0.12	-12.419	-13.60		1, 11, 13
SMP47	1.44	3.70	8.23	8.18	0.08	-11.472	-12.53	yes	2, 11, 13
SMP48	1.32		8.01	7.34	0.10	-11.594	-12.43		1, 11, 12
SMP49						-12.142			11
SMP50	1.33	3.68	8.24	6.70	0.19	-11.655	-12.71		2, 11, 12
SMP51	1.20		8.34	7.40		-12.000			6, 11
SMP52	1.23	3.43	8.31	6.81	0.28	-11.421	-12.52		2, 11, 12
SMP53	1.58		8.11	7.60		-11.523	-12.62		6, 11, 12
SMP54	2.11	2.79	8.00	8.26	0.23	-12.469	-13.51	yes	1, 11, 13
SMP55	1.24	4.58	7.90	7.38	0.26	-12.475	-12.66		2, 11, 12
SMP56	1.29		7.90	6.78	0.11	-12.611	-13.13		2, 11, 12
SMP57						-12.533	-13.41		11, 12
SMP58	1.12	4.82	8.32	7.08	0.29	-11.645	-12.48		2, 11, 12
SMP59						-12.622			11
SMP60	1.63		8.34	7.23	0.24	-12.412	-13.50		2, 11, 12
SMP61	1.10	4.60	8.44	7.52	0.19	-11.538	-12.48		2, 11, 12
SMP62	1.57	3.80	8.14	7.36	0.21	-11.261	-12.31		1, 11, 12
SMP63	1.12	3.95	8.41	7.20	0.23	-11.451	-12.48		2, 11, 12
SMP64					0.31		-12.70		2, 12
SMP65	1.05		8.37		0.08	-12.565	-13.31		2, 11, 12
SMP66	1.18		8.56	6.91		-11.809	-12.95		6, 11, 12
SMP67	1.24	3.54	7.83	8.04	0.15	-12.267	-12.81	yes	2, 11, 12
SMP68						-12.318			11
SMP69						-12.419	-13.17		11, 12
SMP70						-12.619	-13.55		11, 13
SMP71	1.25		8.62	8.28		-11.778	-12.86		6, 11, 12
SMP72	1.94		8.15	7.28	0.03	-12.665	-13.64		1, 11, 13
SMP73	1.31	3.60	8.43	7.51	0.38	-11.359	-12.54		1, 11, 12
SMP74	1.25	3.67	8.41	6.90	0.55	-11.570	-12.66		1, 11, 12
SMP75	1.15		8.38	7.54		-11.522			6, 11
SMP76	1.20	4.14	8.10	7.08	0.33	-11.712	-12.54		1, 11, 12
SMP77	1.10	3.57	8.04	7.00	0.26	-12.122	-12.78		2, 11, 12
SMP78	1.41	3.64	8.36	7.45	0.37	-11.398	-12.58		1, 11, 12
SMP79						-11.526	-12.63		11, 12
SMP80						-12.392			11
SMP81	1.40		8.28	7.28		-11.460	-12.61		6, 11, 12
SMP82						-12.510			11
SMP83	1.74	3.39	8.09	7.65	0.15	-11.747	-12.65		2, 11, 12
SMP84	1.33		8.15	6.88		-11.814	-12.63		6, 11, 12
SMP85	1.00		8.17	7.49	0.26	-11.899	-12.42		2, 11, 12
SMP86						-12.879	-13.68		11, 12
SMP87	2.68	3.24	7.80	8.49	0.50	-11.943	-12.91	yes	1, 11, 12
SMP88	2.55		7.36	7.52	0.77	-12.616	-13.26	yes	2, 11, 12
SMP89	1.23	3.67	8.46	7.20	0.67	-11.460	-12.61		2, 11, 12
SMP90						-12.685			11
SMP91						-12.619	-13.55		11, 12
SMP92	1.34	3.97	8.49	7.54	0.47	-11.414	-12.54		1, 11, 12
SMP93	1.35		8.61	8.80		-12.669	-13.36	yes	6, 11, 12
SMP94							-12.99		12
SMP95						-12.421	-13.47		11, 12
SMP96	2.28	3.50	7.71	8.20	0.12	-12.385		yes	2, 11
SMP97	1.39	3.30	8.52	7.15	0.42	-11.874	-12.85		2, 11, 12

TABLE 1—*Continued*

Name (1)	Te (10^4 K) (2)	log Ne (cm^{-3}) (3)	O/H (4)	N/H (5)	c(Hβ) (6)	log F(5007) ($erg\ s^{-1}\ cm^{-2}$) (7)	log F(Hβ) ($erg\ s^{-1}\ cm^{-2}$) (8)	Type I (9)	sources [a] (10)
SMP98	1.28		8.49	8.04		-11.303			6, 11
SMP99	1.27	3.36	8.42	7.81	0.35	-11.377	-12.54		1, 11, 13
SMP100						-11.778	-12.86		11, 12
SMP101	1.52	3.68	8.40	7.23	0.19	-11.839	-12.89		1, 11, 12
SMP102						-12.326	-13.22		11, 12
SMP103							-13.53		12

[a] SOURCES.—(1) Meatheringham & Dopita 1991b; (2) Meatheringham & Dopita 1991a; (3) Dopita & Meatheringham 1991a; (4) Meatheringham et al. 1990; (5) Henry, Liebert, & Boroson 1989; (6) Monk, Barlow, & Clegg 1988; (7) Aller et al. 1987; (8) Barlow 1987; (11) Jacoby et al. 1990b; (12) Meatheringham et al. 1988; (13) Wood et al. 1987; (15) Dopita et al. 1988.

[b] Adopted electron temperature.

[c] The Hβ fluxes for SMP 3 and SMP 8 from Meatheringham et al. 1988 have been corrected according to Jacoby et al. 1990.

ence between the SMC and the LMC (Feast 1988). None of the [O III] λ5007 or Hβ fluxes have been corrected for reddening since the wavelength baseline is so short that only a huge reddening could produce a significant differential effect [e.g., for $E(B-V) = 1.0$, the differential reddening between [O III] λ5007 and Hβ is less than 0.06 dex based upon the Schild 1977 reddening law].

Figure 1 demonstrates that the apparent [O III] λ5007 and Hβ fluxes for Magellanic Cloud planetary nebulae are correlated over a range of approximately 2 dex in both quantities. Much of the scatter can be attributed to the effects of the central star's temperature and luminosity evolution, which will have a significant effect on the [O III] λ5007/Hβ ratio. The existence of a correlation between the [O III] λ5007 and Hβ fluxes, in spite of these evolutionary effects, demonstrates a fundamental property of planetary nebulae and of their evolution. Indeed, the relation provides observational confirmation of the central star's dominant role in generating the planetary nebula luminosity function, as originally postulated by Jacoby (1989).

4. THE EFFECT OF THE NEBULAR OXYGEN ABUNDANCE

When considering nebular parameters that could have a significant effect upon a planetary nebula's [O III] λ5007 luminosity, the oxygen abundance is probably the most obvious one to consider. In Figure 2, the [O III] λ5007 fluxes are plotted versus oxygen abundance for all the planetary nebulae with known oxygen abundances. The symbols have the same meaning as in Figure 1. Also as in Figure 1, all fluxes for SMC planetary nebulae have been increased by 0.124 dex from their values in Table 2. The solid line in Figure 2 is a theoretical relation derived by Dopita, Jacoby, & Vassiliadis (1992) for optically thick nebular models (their equation [4.1]) expressing the peak efficiency for converting stellar photons to [O III] λ5007 photons as a function of the nebular oxygen abundance. In Figure 2, this relation has been shifted to fit the upper envelope of the observations. Its equation is given by

$$\log F(5007) = -36.02 + 5.47x - 0.30x^2 , \quad (1)$$

where $x = 12 + \log(\text{O/H})$.

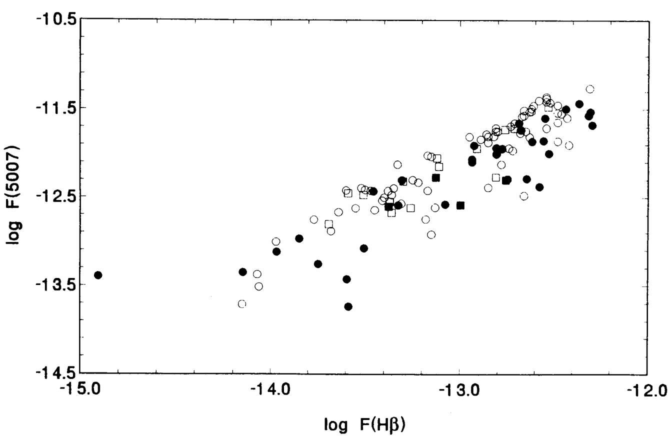

FIG. 1.—The [O III] λ5007 flux for Magellanic Cloud planetary nebulae plotted as a function of the Hβ flux. The open symbols denote LMC points, while the closed symbols denote SMC points. The squares denote type I planetary nebulae. All the fluxes for SMC planetary nebulae have been increased by 0.124 dex from those listed in Table 2 to account for the SMC's greater distance (see text).

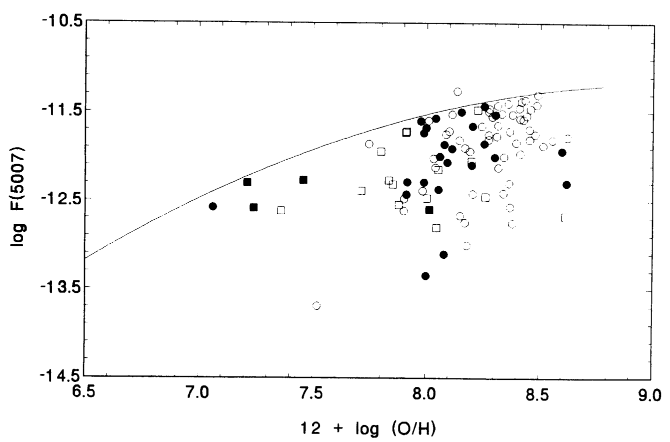

FIG. 2.—The observed [O III] λ5007 luminosity plotted as a function of the oxygen abundance for Magellanic Cloud planetary nebulae. The symbols have the same meaning as in Fig. 1. The solid curve that has been fitted to the upper envelope of the points is based upon a relation derived by Dopita et al. (1992) expressing the efficiency of converting stellar ionizing photons to [O III] λ5007 photons as a function of the nebular oxygen abundance.

TABLE 2

SMC PLANETARY NEBULA DATA

Name (1)	Te (10^4 K) (2)	log Ne (cm^{-3}) (3)	O/H (4)	N/H (5)	c(Hβ) (6)	log F(5007) ($erg\ s^{-1}\ cm^{-2}$) (7)	log F(Hβ) ($erg\ s^{-1}\ cm^{-2}$) (8)	Type I (9)	sources [a] (10)
J2		1.70				-13.52	-15.03		8, 13
J4	2.59		7.63	7.94	0.21				5
J6						-14.55			13
J9									
J17									
J18									
J21									
J23	7.92		6.08	5.45	1.65				5
J24									
J25	2.54		6.49		0.0				5
J27									
MG 1			8.00		0.29	-13.47	-14.27		3, 13
MG 2						-13.09	-13.97		13
MG 3						-13.20	-13.63		13
MG 4						-12.345	-14.15		13
MG 5							-13.8		13
MG 6						-13.38	-13.87		13
MG 7	1.23					-13.86	-13.71		13
MG 8	1.05[b]	2.97	8.08	7.32		-13.227			6, 11
MG 9									
MG 10						-13.55	-13.72		13
MG 11						-13.24	-14.09		13
MG 12									
MG 13							-13.51		13
N8									
SMP1	1.07	3.98	7.92	6.75	0.24	-12.412	-12.77		2, 11, 12
SMP2	1.62	3.48	7.98	7.5	0.26	-11.728	-12.67		1, 7, 11, 12
SMP3	1.35	3.29	8.09	7.28	0.04	-12.192	-13.06		2, 11, 12
SMP4						-12.070	-12.90		11, 12
SMP5	1.45	3.57	8.20	7.17	0.10	-11.783	-12.81		1, 7, 11, 12
SMP6	1.51	4.41	7.99	7.57	0.55	-11.861	-12.80		1, 11, 12
SMP7	1.79	3.29	7.91	6.90	0.07	-12.554	-13.58		2, 11, 13
SMP8	1.25		8.08			-11.990	-12.74		6, 11, 12
SMP9	1.30	2.43	8.62	7.36	0.0	-12.426	-13.43		5, 8, 11, 13
SMP10	1.10	3.33	8.30			-12.134	-12.93		6, 11, 12
SMP11	1.26		7.99	6.52	0.3	-12.416	-12.87		5, 11, 12
SMP12						-12.711	-13.45		11, 13
SMP13	1.28	3.25	8.15	6.46	0.43	-11.620	-12.56		2, 11, 12
SMP14	1.50	3.54	8.11	6.74	0.25	-12.035	-13.05		1, 7, 11, 12
SMP15	1.09	4.88	8.30	7.62	0.17	-11.655	-12.43		2, 11, 12
SMP16	1.07	4.12	8.05	6.54	0.72	-12.499	-12.70		2, 11, 12
SMP17	1.23	3.66	8.26	7.50		-11.557	-12.49		6, 7, 11, 12
SMP18	1.06	3.86	8.06	7.35	0	-12.124	-12.65		5, 15, 11, 13
SMP19	1.15	3.59	8.60	7.58	0	-12.062	-12.93		5, 11, 12
SMP20	1.20	4.54	8.00	7.10		-11.802	-12.42		7, 15, 11, 12
SMP21	2.44	4.60	7.46	7.76	0.00	-12.395	-13.25	yes	2, 11, 12
SMP22	2.66	3.74	7.21	7.47	0.16	-12.426	-12.88	yes	2, 7, 11, 12
SMP23	1.20		8.20		0.0	-12.222	-13.06		5, 11, 12
SMP24	1.09	4.00	8.26	6.92		-11.980	-12.68		6, 11, 12
SMP25	3.39		7.06		0.44	-12.701	-13.20		2, 11, 12
SMP26	1.50	3.12	8.01	7.86	0.55	-12.726	-13.5	yes	2, 11, 13
SMP27	1.30	3.81	8.04	7.04		-11.694	-12.44		6, 11, 12
SMP28	2.52	3.33	7.24	7.81	0.21	-12.708	-13.12	yes	4, 11, 12
SP32						-12.902			11
SP34						-12.909			11

[a] SOURCES.—(1) Meatheringham & Dopita 1991b; (2) Meatheringham & Dopita 1991a; (3) Dopita & Meatheringham 1991a; (4) Meatheringham et al. 1990; (5) Henry, Liebert, & Boroson 1989; (6) Monk, Barlow, & Clegg 1988; (7) Aller et al. 1987; (8) Barlow 1987; (11) Jacoby et al. 1990b; (12) Meatheringham et al. 1988; (13) Wood et al. 1987; (15) Dopita et al. 1988.

[b] Adopted electron temperature.

It is clear from Figure 2 that the maximum [O III] λ5007 fluxes observed in planetary nebulae are a function of the oxygen abundance. This upper limit, however, would be much more convincing if there were more objects below log (O/H) $= -4$. To verify the reality of the trend in Figure 2, the data were first divided into three sets: log (O/H) ≤ -4.1, $-4.1 <$ log (O/H) ≤ -3.8, and log (O/H) > -3.8. Using the binned data, two statistical tests were applied. First, the differences between the mean [O III] λ5007 fluxes in adjacent bins were compared using Student's *t*-test to determine whether the means were significantly different. In all cases, the means were found to be significantly different at a confidence limit exceeding 98%. Second, the analysis of variance technique, which compares the dispersion within the above bins to that between them, was used to determine whether the data in all the bins came from the same parent population. The results of this test were even more convincing, with the probability that the data in all the bins came from the same parent population being less than 0.01%. Thus, except for one point, SMP62 in the LMC, the observations indicate that the maximum attainable [O III] λ5007 flux is a function of the nebular oxygen abundance. The cause of LMC-SMP62's discrepant position is unknown, independent measurements that confirm the adopted oxygen abundance and [O III] λ5007 flux exist.

The theoretical relation derived by Dopita et al. (1992) fits the upper envelope of the observations very well. Dopita et al. (1992) derived this relation to describe the efficiency of converting of stellar photons to [O III] λ5007 photons in their models as a function of the model oxygen abundance. In their derivation (their eq. [4.1]), the stellar luminosity was left as a scale factor. To achieve the fit in Figure 2, only a zero-point shift was applied to their relation. It is rather remarkable that a single shift is able to fit observations covering a 1.5 dex range in oxygen abundances since this implies a constant maximum luminosity (and mass) for central stars over this metallicity range.

5. [O III] λ5007 LUMINOSITIES IN LOW-LUMINOSITY GALAXIES

The abundance dependence of the maximum [O III] λ5007 luminosities attained in low abundance planetary nebulae has severe repercussions for the use of the luminosity function as a distance indicator in low luminosity galaxies. It is well known that both spheroidal (e.g., NGC 205) and irregular galaxies follow metallicity-luminosity relations (e.g., Skillman, Kennicutt, & Hodge 1989), with lower luminosity galaxies having lower oxygen abundances. Thus, the brightest planetary nebulae in low metallicity galaxies will be fainter than those in more metal-rich galaxies. Consequently, adopting the absolute magnitude of the planetary nebula luminosity function peak in M31 or the LMC in distance modulus studies of low-luminosity galaxies will systematically overestimate the true distance moduli for low-luminosity galaxies. Furthermore, because the oxygen abundance decreases with decreasing luminosity in dwarf galaxies, the error in the distance modulus will be a function of the galaxy's luminosity.

More reliable distance moduli for low luminosity galaxies can be obtained if the [O III] λ5007 luminosities of their planetary nebulae are corrected for their oxygen abundance. If one assumes that equation (1) gives the maximum attainable [O III] λ5007 luminosity, at least in the abundance range defined by the observations, then it can be used to correct the [O III] λ5007 luminosities of low-abundance planetary nebulae relative to those in the LMC. Ideally, one should know the oxygen abundance of the planetary nebula in question when using equation (1), but, unfortunately, this is not the usual case in distance modulus studies. An initial estimate of the oxygen abundance can be made by estimating the distance from the raw luminosity function of the planetary nebulae and then applying the metallicity-luminosity relation for galaxies (e.g., Skillman et al. 1989). Equation (1) can then be evaluated at this initial oxygen abundance and at log (O/H) $= -3.67$ (the mean abundance for LMC planetary nebulae within 1 mag of the brightest object), the difference between the two values being used to adjust the luminosity function's peak luminosity. A few iterations of these steps are required to converge on a consistent abundance and distance. Implicit in this correction scheme is the assumption that the brightest planetary nebulae have a metallicity that is typical of the entire population (see § 6).

To demonstrate this abundance correction procedure, it is applied here to the planetary nebula luminosity function distances for NGC 3109 and the SMC. Richer & McCall (1992) used the brightest planetary nebula in NGC 3109 to determine an upper limit of 26.17 ± 0.36 mag for its distance modulus. Based upon this distance modulus, a total *B* magnitude of 10.39 mag (de Vaucouleurs et al. 1991), and a galactic foreground extinction of 0.16 mag in *B* [$E(B-V) = 0.038$; Burstein & Heiles 1984], NGC 3109's absolute *B* magnitude is -15.94 mag. Thus, log (O/H) $= -4.06$ (Skillman et al. 1989), for which equation (1) yields an [O III] λ5007 flux that is 0.22 dex lower than at log (O/H) $= -3.67$. Consequently, the distance modulus limit for NGC 3109 should be decreased by 0.55 mag to 25.62 ± 0.36 mag. Iterating to obtain a consistent abundance and absolute magnitude yields a distance modulus of 25.39 ± 0.36 mag. For comparison, Capaccioli, Piotto, & Bressolin (1992) recently determined Cepheid distance moduli of $\Delta(m - M)_B = 6.81 \pm 0.11$ mag and $\Delta(m - M)_V = 6.90 \pm 0.08$ mag relative to the LMC. The precise value of the galactic foreground reddening to the LMC is somewhat uncertain, but it is within the range $E(B-V) = 0.04$–0.08 mag (McNamara & Feltz 1980; Schwering & Israel 1991). Given the previous galactic extinction toward NGC 3109, allowing for the range of galactic extinctions toward the LMC, and adopting a true distance modulus of 18.52 ± 0.13 mag for the LMC (McCall 1993, based upon the SN 1987A distance modulus from Panagia et al. 1991), yields a Cepheid distance modulus to NGC 3109 between 25.39 ± 0.20 mag and 25.54 ± 0.20 mag, which is in good agreement with the planetary nebula result.

A similar procedure can be applied to the SMC's planetary nebula distance modulus. Jacoby et al. (1990b) found that the SMC's distance modulus was 0.65 mag greater than the LMC's. If this distance modulus difference is corrected for the SMC's mean oxygen abundance, log (O/H) $= -3.88$ (for planetary nebulae within 1 mag of the brightest one, see Table 3), it decreases to 0.37 mag, which is much closer to the value of 0.31 mag recommended by Feast (1988).

6. PLANETARY NEBULAE AS CHEMICAL ABUNDANCE PROBES

Both observation and theory indicate that planetary nebulae should be good probes of the oxygen abundances in galaxies. Although type I planetary nebulae may modify their initial oxygen abundances, observations indicate that normal planetary nebulae do not (Henry 1989; Perinotto 1991). As a result,

TABLE 3

MAGELLANIC CLOUD ABUNDANCE DISTRIBUTION

Cloud (1)	Cutoff (mag) (2)	12 + log (O/H) (dex) (3)	σ (dex) (4)	Number (5)
LMC.........	0.5	8.38	0.11	10
	1.0	8.33	0.13	22
	1.5	8.30	0.19	38
	2.0	8.28	0.20	46
	All	8.20	0.26	70
SMC.........	0.5	8.15	0.14	5
	1.0	8.12	0.13	8
	1.5	8.17	0.17	14
	2.0	8.16	0.16	16
	All	8.01	0.36	48

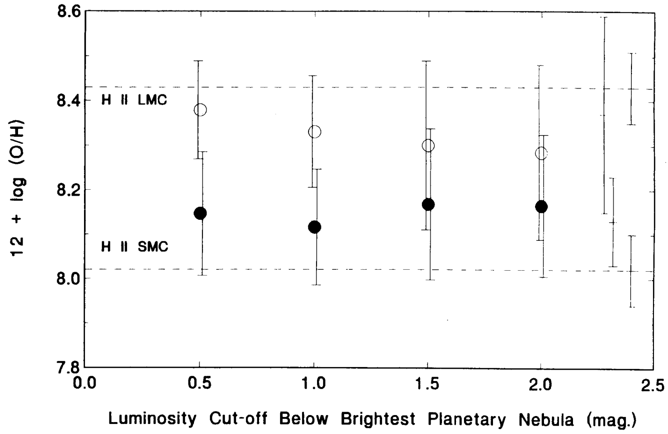

FIG. 3.—The mean oxygen abundance for Magellanic Cloud planetary nebulae whose [O III] λ5007 luminosities exceed various cutoff luminosities plotted as a function of the cutoff luminosity. The open symbols denote the LMC points, while the filled symbols denote the SMC points. The error bars show the standard deviations of the abundance distributions. For clarity, the error bars for the LMC points have been shifted to the left, and those for the SMC points have been shifted to the right. The horizontal lines denote the Magellanic Cloud H II region abundances from Dufour (1984; *dashed*) and Russell & Dopita (1990; *dotted*). The error bars on the lines indicate the standard deviations of the H II region oxygen abundance distributions.

the oxygen abundances observed in planetary nebulae should reflect those which persisted in the interstellar medium when their progenitors formed and should also indicate the extent to which chemical evolution had progressed up to that time. Three questions must be answered regarding bright planetary nebulae. First, how do the oxygen abundances of bright planetary nebulae compare with those for the rest of the population? Second, how do any biases associated with luminosity-limited samples affect the utility of bright planetary nebulae as chemical abundance probes? Third, how to the oxygen abundances in bright planetary nebulae compare with those in H II regions? Establishing a relationship between the oxygen abundances in bright planetary nebulae and those in H II regions extends the usefulness of planetary nebula abundances by simplifying their interpretation in galaxies lacking H II regions.

As Figure 2 shows, the [O III] λ5007 luminosity attainable in planetary nebulae depends upon oxygen abundance. Since low-abundance objects do not reach the highest luminosities, it is not surprising that, on average, the mean oxygen abundance decreases as the luminosity decreases. One could question, then, if the mean oxygen abundance derived for a planetary nebula sample might depend upon the luminosity range spanned by the sample. This can be tested by computing the mean oxygen abundance for planetary nebulae whose [O III] λ5007 luminosities exceed some threshold. By lowering the threshold, any dependence of the mean oxygen abundance upon the luminosity range should become evident.

The results of this test are given in Table 3 and are displayed graphically in Figure 3. For each threshold (defined as a cutoff magnitude fainter than the brightest planetary nebula), Table 3 lists the mean abundance for all objects whose [O III] λ5007 luminosities exceed the threshold, the standard deviation of the abundance distribution, and the number of objects. In Figure 3, the mean oxygen abundances for Magellanic Cloud planetary nebulae are plotted as a function of the [O III] λ5007 cutoff luminosity. In Figure 3, LMC points are plotted with open symbols and SMC points are plotted with filled symbols. The standard deviations of the abundance distributions are shown by the error bars attached to the mean abundance points. (For clarity, LMC error bars are shifted slightly to the left and SMC error bars are shifted slightly to the right.) In Figure 3, a minimum cutoff luminosity of 2 mag below the brightest object was chosen because the planetary nebula populations in the Magellanic Clouds are believed to be complete to this limit (Jacoby et al. 1990b). The horizontal lines in Figure 3 denote the mean oxygen abundances for H II regions in the LMC and the SMC from Dufour (1984, *dashed*) and Russell & Dopita (1990, *dotted*), with the error bars again indicating the standard deviations in these abundance distributions.

Figure 3 shows that any dependence of the mean oxygen abundance upon cutoff luminosity is, at most, very slight for bright planetary nebulae (within 2 mag of the brightest object). In the SMC, the mean oxygen abundance shows no dependance upon the cutoff luminosity for bright objects. In the LMC, as the cutoff luminosity decreases, the mean oxygen abundance for bright planetary nebulae decreases slightly and the abundance dispersion increases slightly. Even if one compares the mean abundance for all objects with that for objects within 0.5 mag of the brightest, ignoring incompleteness considerations at low luminosities, one finds that the mean abundance for all objects is lower by only 0.17 dex in the LMC and 0.15 dex in the SMC. The important point is that, if only bright objects are considered, the mean metallicity is not sensitive to the cutoff luminosity.

Another feature of Figure 3 is that, within errors, the brightest planetary nebulae have abundances that are identical to those of the H II regions in the same galaxy. Since Type II supernovae are the dominant source of oxygen enrichment in galaxies, this abundance similarity suggests that there has been little star formation between the star formation episode that is currently underway and that during which the planetary nebula progenitors formed. Since the H II region abundances define the current state of chemical evolution, bright planetary nebulae must also represent a recent star formation episode, at least from a chemical evolution viewpoint. Although some star formation has occurred between these two episodes (the brightest planetary nebulae in the Magellanic Clouds do not contain the most massive central stars; Dopita & Meatheringham 1991a, b), bright planetary nebulae and H II regions are equally good probes of the current oxygen abundance in the Magellanic Clouds. Indeed, no serious error would be committed by adopting the oxygen abundance in bright planetary nebulae, within 1 mag of the brightest object for example, as the current interstellar medium oxygen abundance in the Magellanic Clouds. Even in star-forming galaxies, then, it is clear that bright planetary nebulae probe the interstellar oxygen abundance very near the last epoch of star formation.

It is not too surprising that there is no trend between the mean oxygen abundance and the cutoff luminosity for bright planetary nebulae in the SMC, but that a slight trend might exist in the LMC. Because the slope of the upper envelope in Figure 2 becomes steeper as the abundance decreases, the abundance range that bright planetary nebulae may occupy becomes increasingly restricted with decreasing abundance. Substituting high and low abundances, x_2 and x_1, respectively, into equation (1) and taking the difference yields

$$\Delta F(5007) = \Delta x(5.47 - 0.60\bar{x}) , \qquad (2)$$

where $\Delta F(5007)$ is the change in the maximum [O III] λ5007 flux across the abundance range $\Delta x = x_2 - x_1$, centered on mean abundance $\bar{x}$. Given a fixed luminosity interval about the brightest object, therefore, the allowable abundance range will decrease as the mean abundance decreases. Consequently, bright planetary nebulae in the LMC may occupy a larger abundance range than is allowable in the SMC because the LMC's mean oxygen abundance is higher. This is a particularly useful result for low-luminosity galaxies since the mean abundance at the last epoch of star formation can then be determined from the abundances of only a few objects. In fact, if the abundance dispersion among planetary nebulae in low-luminosity galaxies is similar to that observed in the SMC, $\sigma \sim 0.15$ dex, only three planetary nebulae within 1 mag of the brightest object are required to determine the mean oxygen abundance to ± 0.1 dex.

There is no obvious reason that the chemical characteristics of the brightest planetary nebulae in other galaxies should be different from those in the Magellanic Clouds. Therefore, bright planetary nebulae should be good oxygen abundance probes in all galaxies, regardless of whether they are currently forming stars. In a galaxy where star formation has long since ceased, the brightest planetary nebulae would be those with the largest oxygen abundances, whose progenitors would have formed during the last star formation episode. As a result, bright planetary nebulae in galaxies without star formation should be exact analogs of H II regions in star-forming galaxies; both should provide an accurate measure of the oxygen abundance during the last episode of star formation. Bright planetary nebulae should, therefore, be useful probes of the final state of chemical evolution in galaxies where star formation has now ceased.

7. CONCLUSIONS

Based upon a compilation of Magellanic Cloud planetary nebula data, both the central star's ionizing luminosity and the nebular oxygen abundance have significant influences upon the nebular [O III] λ5007 luminosity. Of the two, the central star luminosity is the most important. The [O III] λ5007 and Hβ fluxes from Magellanic Cloud planetary nebulae are correlated over a range of 2 dex in both quantities. Since the Hβ luminosity is directly related to the ionizing luminosity absorbed by the nebula, this correlation clearly demonstrates that the observed [O III] λ5007 luminosity is a direct result of the luminosity evolution of the planetary nebula central stars and observationally confirms the central hypothesis of Jacoby's (1989) theory. The nebular oxygen abundance modifies the maximum [O III] λ5007 luminosity attained by Magellanic Cloud planetary nebulae, with higher luminosities being attained at higher abundances. The upper envelope of the [O III] λ5007 luminosity-oxygen abundance distribution was found to be in good agreement with a relation derived by Dopita et al. (1992) expressing the efficiency of converting ionizing photons to [O III] λ5007 photons as a function of oxygen abundance. Notably, the fit of this relation to the data implies that, over a 1.5 dex oxygen abundance range, central stars attain similar maximum luminosities.

The observed dependence of the [O III] λ5007 luminosity upon oxygen abundance indicates that, in low-luminosity galaxies, planetary nebulae will not reach the [O III] λ5007 luminosities attained in higher metallicity systems. Thus, planetary nebulae will systematically overestimate the true distance moduli for low-luminosity galaxies. Fortunately, corrections based upon the upper envelope of the abundance–[O III] λ5007 luminosity distribution (Dopita et al. 1992 relation) can be made in a straightforward manner. This procedure has been demonstrated using the luminosity function distance modulus estimates for NGC 3109 and the SMC as examples.

Bright planetary nebulae appear to be good probes of chemical evolution. Through the abundance dependence of the [O III] λ5007 luminosity, a luminosity-limited sample will preferentially select planetary nebulae from the most oxygen-enriched stellar population that is old enough to produce bright planetary nebulae. In the Magellanic Clouds, bright planetary nebulae and H II regions have identical abundances. In a chemical evolutionary sense, therefore, bright planetary nebulae also represent a relatively recent star formation episode. Consequently, from a chemical evolution viewpoint, the bright planetary nebulae in a galaxy devoid of star formation should be analogs of the H II regions in star-forming galaxies. As such, bright planetary nebulae should be useful for probing the final chemical evolution state attained in elliptical and spheroidal galaxies. The slope of the upper envelope of the [O III] λ5007 luminosity-oxygen abundance distribution is steeper at lower abundances, so planetary nebulae within 1 mag of the brightest object in low-metallicity environments will be constrained to narrower abundance ranges. If the SMC's abundance distribution is typical of that in low luminosity galaxies, three planetary nebulae within 1 mag of the brightest should suffice to determine the mean oxygen abundance at the last star formation epoch to within ± 0.1 dex.

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