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ULTRAVIOLET SPECTROSCOPY OF PLANETARY NEBULAE IN THE MAGELLANIC CLOUDS

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ABSTRACT

Ultraviolet spectra of three high excitation planetary nebulae in the Magellanic Clouds (LMC P40, SMC N2, SMC N5) were obtained with the *International Ultraviolet Explorer*. The results are analyzed together with new visual wavelength spectrophotometry of LMC P40 and published data on SMC N2 and SMC N5 to investigate chemical composition and, in particular, to make the first reliable estimates of the carbon abundance in extragalactic planetary nebulae. Although carbon is at most only slightly less abundant in the LMC and SMC planetary nebulae than in galactic planetaries, it is almost 40 times more abundant in the SMC planetaries than in the SMC interstellar medium, and is about 6 times more abundant in the LMC planetary than in the LMC interstellar medium. According to our limited sample, the net result of carbon synthesis and convective dredgeup in the progenitors of planetary nebulae, as reflected in the nebular carbon abundance, is roughly the same in the Galaxy, the LMC, and the SMC.

Subject headings: abundances — nebulae: planetary — stars: carbon — ultraviolet: spectra

I. INTRODUCTION

Planetary nebulae (PN) are ejecta of intermediate mass stars, apparently enriched by nucleosynthesis within their progenitors. Comparison of chemical abundances in PN with abundances in the interstellar medium is thus of interest in studies both of galactic chemical evolution and of stellar interiors and evolution.

Ultraviolet spectroscopy enables one to measure the strong emissions of C III] and C IV, which are significant PN coolants. The measurements can be used to improve the PN models from which many chemical abundances are obtained, in addition to making it possible to determine the C abundance.

Various lines of evidence indicate that star formation and chemical evolution proceed differently in various galaxies. Thus, it is of interest to determine how processes in the PN progenitors may vary among galaxies. As a first step toward detailed ultraviolet spectroscopy of extragalactic PN, we have begun observing nebulae in the Magellanic Clouds with the *International Ultraviolet Explorer* (*IUE*). Visible wavelength work on the Magellanic PN is discussed in Aller *et al.* (1981) and references therein. Several investigators, including Peimbert and Torres-Peimbert (1974), Dufour (1975), Aller, Czyzak, and Keyes (1977), Pagel *et al.* (1978), and, most recently, Dufour, Shields, and Talbot (1982, hereafter DST), have determined chemical abundances in Magellanic Cloud H II regions. DST used *IUE* to establish the C abundances.

The targets were selected from known PN in the Clouds on the basis of high excitation and low interstellar reddening. (Reddening may vary significantly from object to object due to differences in absorption along the lines of sight within the Clouds.) Excitation is judged from the strength of [Ne V] $\lambda 3426$ or, when observations of that line are unavailable, from the ratio of He II $\lambda 4686$ to Hβ.

Positions (Table 1) were measured with a PDS microdensitometer on IIIa-J "quick survey" plates of the ESO-SRC Southern Sky Atlas. Reference stars were taken from the Yale Zone Catalogue for Declinations $-70°$ to $-90°$ and from unpublished work of F. W. Fallon. The nebulae are too faint to be seen with the *IUE* white-light slit jaw camera, the Fine Error Sensor.

II. OBSERVATIONS

The *IUE* observations were made on 1980 May 23 and 26. We used the *IUE* low dispersion cameras and the large entrance apertures (each about $10'' \times 20''$). The high excitation Magellanic PN appear stellar under ground-based telescopic examination. Thus, in each case, the entire PN was sampled, as it was in the ground-based spectrophotometry with which we have interpreted the results. A monochromatic nebular image would fall on a

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TABLE 1

NEBULAR PARAMETERS

Parameter	LMC P40	SMC N2	SMC N5
Right ascension (1950.0) ...	$06^h10^m36^s.56$	$00^h30^m33^s.13$	$00^h39^m26^s.02$
Declination (1950.0)	$-67°55'33''.7$	$-71°58'32''.1$	$-73°01'43''.2$
N_H(cm^{-3})	3000	10,400	3600
Outer radius (pc)	0.049	0.025	0.051
Strömgren radius (pc)	0.068	0.029	0.059
T_e(K) (observed)...........	15,000	12,800	13,000
T_e(K) (model)	14,000	13,300	13,200

TABLE 2

IUE LINE INTENSITY MEASUREMENTS

Wavelength (Å)	Ion	LMC P40 (ergs cm^{-2} s^{-1})	SMC N2 (ergs cm^{-2} s^{-1})	SMC N5 (ergs cm^{-2} s^{-1})
1239...........	N V	$\lesssim$ 2.7 (−14)	...	$\lesssim$ 2.7 (−14)
1403...........	O IV]	$\lesssim$ 7.7 (−14)	...	$\lesssim$ 5.2 (−14)
1488...........	N IV]	$\lesssim$ 7.1 (−14)	...	$\lesssim$ 9.4 (−14)
1550...........	C IV	1.59(−12)	1.47(−12)	8.8 (−13)
1640...........	He II	4.1 (−13)	2.87(−13)	1.65(−13)
1663...........	O III]	6.8 (−14)	7.0 (−14)	6.1 (−14)
1909...........	C III]	9.1 (−13)	3.1 (−13)	1.08(−12)
2422...........	[Ne IV]	1.06(−13)	...	...

NOTE.—Data are corrected for instrumental sensitivity but not for interstellar reddening.

single 3″ *IUE* detector pixel. The spectral resolution was 6 Å. Good spectra of each target were obtained with the short wavelength spectrograph, and a useful spectrum of LMC P40 was obtained with the long wavelength spectrograph.

The standard *IUE* flux calibration was applied to the data; results are summarized in Table 2. The estimated uncertainty in the line intensities ranges from about 10% for the strongest lines to about 50% for the weakest lines. The uncertainty is dominated by measurement error (statistics) for the weak lines and by systematic error (calibration) for the strong lines.

Visual wavelength spectrophotometry analyzed together with the *IUE* observations was derived from two sources. For SMC N2 and SMC N5, the data are those of Aller *et al.* (1981). For LMC P40, the visual fluxes are taken from vidicon spectrophotometry done at the Cassegrain focus of the Cerro Tololo Inter-American Observatory (CTIO) 4 m telescope by Aller during 1979 December 26–28. Due to instrumental limitations, the CTIO spectra did not extend far enough to the blue to include the [Ne V] λ3426 line. Full details will be published later.

The interstellar extinction for each PN was determined from the ratio of the λλ1640, 4686 He II lines, its intrinsic value taken as calculated according to Seaton (1978), and from the observed Balmer decrement, compared with theoretical decrements (Clarke 1965; Brocklehurst 1971). The form of the mean interstellar extinction law was taken from Seaton (1978). Table 3 lists the extinction-corrected intensities of the observed ultraviolet lines (normalized to Hβ), together with the corrected intensities of visual lines used in the model fitting. The values $C = 0.23, 0.14$, and 0.33, where C is the log of the extinction at Hβ, were used to correct the *IUE* data and are our best estimates of the extinction to LMC P40, SMC N2, and SMC N5, respectively. Values of $C = 0.0, 0.12$, and 0.0, estimated from ground-based observations of the same respective PN, were obtained by fitting Balmer decrements. These coefficients differ from the *IUE* determinations due to cumulative effects of errors in assumed energy distributions of standard stars, atmospheric dispersion, and the assumption that the atmospheric extinction equaled the standard value for the observing site.

III. ANALYSIS OF THE NEBULAR SPECTRA

The analysis is based on the techniques described by Shields *et al.* (1981), Aller, Keyes, and Czyzak (1981), and Aller *et al.* (1981). We assess the appropriate levels of ionization and excitation from the measured intensity ratios of He II λ4686/He I λ5876; [O III] λλ(4959 + 5007)/[O II] λ3727; and (if available) [Ne III] λ3868/[Ne V] λ3426. Then we calculate a nebular model to match these ratios and all observed line intensities as closely as possible. The observed T_e (Table 1) obtained from the [O III] lines is used in an iterative process to derive a model T_e that best fits the other ratios mentioned above. The model provides ionization correction

TABLE 3

OBSERVED AND COMPUTED LINE INTENSITIES (Units: $I(H\beta) = 100$)

WAVELENGTH (Å)	ION	LMC P40 Obs.	LMC P40 Comp.	SMC N2 Obs.	SMC N2 Comp.	SMC N5 Obs.	SMC N5 Comp.
1239	N V	$\lesssim 41$	41.5	...	...	$\lesssim 52$	23
1403	O IV]	$\lesssim 95$	16	...	...	$\lesssim 91$	8.5
1488	N IV]	$\lesssim 84$	16.5	...	...	$\lesssim 155$	9.3
1550	C IV	1850	1730	1007	920	1400	1585
1663	O III]	67	37	82	28	93	43
1909	C III]	1083	1230	905	1020	1770	1819
2422	[Ne IV]	119	50	...	...	...	...
3426	[Ne V]	...	...	8.2	7.7	32	32
3727	[O II]	22:	24.8	24.5	25.5	80	82.3
3868	[Ne III]	47.9	51.0	49.8	51.7	87	88.7
4068	[S II]	2.3	0.17	2.3	0.2	5.0	1.2
4267	C II	0.35	0.22	0.79	0.25	...	...
4363	[O III]	18.5	16.1	13.2	14.5	15	16.7
4471	He I	1.9	1.9	3.8	3.4	3.6	3.3
4686	He II	64.4	69.6	29	39	41	47
4725	[Ne IV]	1.31	0.46	0.25	0.25	0.43	0.26
4740	[Ar IV]	5.9	4.2	3.2	1.6	2.6	1.9
4959	[O III]	291	305	295	304	334	362
5007	[O III]	889	893	...	...	...	...
5876	He I	5.1	5.0	10.9	9.2	11.5	8.8
6312	[S III]	1.5	1.7	0.78	1.0	...	...
6584	[N II]	4.1	5.2	8.1	8.2	25	28
6717	[S II]	1.0	0.40	1.7	0.2	...	2.8
6731	[S II]	1.45	0.62	1.9	0.5	8.6[a]	4.5
7005	[Ar V]	1.9	1.1	...	...	...	...
7135	[Ar III]	6.1	9.0	4.9	5.5	7.1	9.7

NOTE.—The observed line intensities have been corrected for interstellar extinction.
[a]Sum of λλ6717, 6731.

factors (ICFs), with which we obtain elemental abundances from ionic concentrations. The results reflect some simplifying assumptions. Homogeneity is assumed, so it is reasonable that [S II] and [S III] intensities often are not reproduced simultaneously. [S II] emission usually appears in clumps. Also, Ar lines present difficulties; some discordances may arise from inadequacies in cross sections and transition probabilities, as suggested by Czyzak *et al.* (1980) for Ar IV. $F(\lambda 1488)$ of N IV always exceeds that predicted by a model fitted to measured [N II] and N V intensities. The features found at λλ1239, 1403, and 1488 (Table 2) are barely above the noise. If real, they may arise in the PN nuclei, in which case λ1403 probably is due to Si IV (see Willis [1980] on such features in WR stars). C IV λ1550 is usually weaker than predicted, probably due to absorption by nebular grains (Harrington, Lutz, and Seaton 1981).

IV. CHEMICAL COMPOSITION

The preliminary models (gross parameters in Table 1) are intended to represent observed ionization and excitation levels well enough to estimate ICFs adequate to derive abundances from ionic concentrations. The abundances so found are summarized in columns (2), (3), and (4) of Table 4, along with data on galactic PN and on the interstellar medium in the Magellanic Clouds; the solar composition is listed in column (9) as a familiar standard. The tabulated quantity is equal to $12 + \log N(X)/N(\mathrm{H})$. This information appears in Table 4 as follows: in column (5), the mean abundances in 27 high excitation galactic PN (Aller and Czyzak 1981); in column (6), the mean abundances of a sample of low, moderate, and high excitation galactic PN (Aller 1978); in columns (7) and (8), the mean composition of H II regions in the LMC and SMC, respectively, according to DST; and in column (9), the solar composition (Ross and Aller 1976; Lambert 1978; Aller 1980). Note that the data listed in columns (5) and (6) are taken from investigations that used theoretical procedures similar to those adopted here so that the abundance differences discussed below will be more meaningful.

Inspection of Table 4 reveals several interesting circumstances. However, each of the following remarks must be taken with the provisos that (a) our nebular models are preliminary; (b) the results are based on a *very* small sample of PN in each Cloud; (c) the results are probably affected by unresolved emission components from the central stars; (d) our N abundances are considered uncertain; (e) the abundances adopted for

TABLE 4

CHEMICAL COMPOSITION OF THE MAGELLANIC PLANETARIES

Element (1)	P40 (2)	N2 (3)	N5 (4)	Galactic Planetaries (5)	(6)	H II Regions LMC (7)	SMC (8)	Sun (9)
He	11.02	11.03	11.05	11.04	11.02	10.92	10.92	11.03
C	8.70	8.60	8.87	8.89	8.8:	7.90	7.16	8.65
N	7.5:	7.42	7.60	8.39	7.97	6.94	6.60	7.96
O	8.33	8.30	8.36	8.66	8.66	8.38	8.05	8.87
Ne	7.62	7.53	7.79	8.02	8.02	7.68	7.34	8.05
S............	6.42	6.26	...	7.03	6.98	7.01	6.61	7.23
Ar	6.19	6.04	6.02	6.48	6.38	6.10	5.77	6.57

SOURCES OF DATA.—Cols. (2), (3), (4): present work; Col. (5): Aller and Czyzak 1981; Col. (6): Aller 1978; Cols. (7), (8): Dufour, Shields, and Talbot 1982; Col. (9): Ross and Aller 1976, Lambert 1978, Aller 1980.

galactic PN are average values of samples that show some significant variations from nebula to nebula. With these caveats in mind, we conclude that: (1) The relative abundances found in LMC P40 are about the same as the mean relative abundances of the two SMC PN. (2) Helium is equally abundant in the Magellanic and galactic PN, although more abundant in the Magellanic PN than in the H II regions of the Clouds. (3) N, O, Ne, S, and Ar are all less abundant in the Magellanic PN than in the galactic PN. Various observers (Peimbert and Torres-Peimbert 1974; Dufour 1975; Aller, Czyzak, and Keyes 1977; Pagel *et al.* 1978; DST) find that these same elements are less abundant in Magellanic H II regions than in galactic H II regions. (4) Although there are no large differences among the C abundances of the Magellanic and galactic PN, C is almost 40 times more abundant in the SMC PN than in the SMC interstellar medium (ISM) and is ~ 6 times more abundant in P40 than in the LMC ISM. This reflects DST's finding that C is much less abundant in the SMC ISM than in the LMC ISM, and much less abundant in the latter than in Orion. Thus, the C abundance in PN is unrelated to the gas-phase ISM C abundance and must reflect the efficiency with which C is synthesized and transported to the envelope in the progenitors. (Presumably the ISM in which the PN progenitors formed in each galaxy was even less C-rich than the present ISM.) Note that our estimated Magellanic PN C abundances are more likely to be low than high, since, if dust exists in the nebula, $N(C^{3+})$ determined from C IV $\lambda1550$ is too low and thus the C abundance of a high excitation PN will be underestimated (Harrington, Lutz, and Seaton 1981). Given the problems with the preliminary models, the referee has noted that the C^{+2} ionic concentrations alone, based on C III] $\lambda1909$ and evaluated with the observed T_e([O III]) for each object, give lower limits to C/H ($> 1.9 \times 10^{-4}$, $> 4.0 \times 10^{-4}$, and $> 5.7 \times 10^{-4}$ for P40, N2, and N5, respectively) that are already well above the C/H ratios for the Magellanic ISM. We conclude that the net result of C synthesis and convective dredgeup (Becker and Iben 1980) is roughly the same in the stars that produced the observed PN in the Galaxy, the LMC, and the SMC, and that this process is effective. (5) Assuming the UV ionic N lines (if real) arise from the PN nuclei, the N abundance derived from [N II] is enhanced in Magellanic PN compared to the corresponding ISM, but is smaller than in galactic PN of similar excitation. Red giant envelope N abundance strongly depends on mass and dredgeup phase (Becker and Iben 1980). (6) $N(X)_{\rm PN}/N(X)_{\rm ISM}$ is larger in the SMC than in the LMC for C, N, O, Ne, S, and Ar; this mostly reflects Cloud ISM differences noted by DST and others.

V. CONCLUSIONS

The present work yields the first reliable C abundances for extragalactic PN. The results are consistent with the general picture of nucleosynthetic C production and its transport to the stellar envelope via episodes of convective dredgeup in the progenitors of PN, as outlined by Becker and Iben (1980), but do not test the details of the theory.

The photometric and spectroscopic properties of carbon stars provide additional means for investigating the validity of dredgeup models (Renzini 1981). So do their relative frequencies. Relative to the late M giants, carbon stars are about 170 times as common in the LMC and 2500 times as common in the SMC as in the solar neighborhood (Blanco and McCarthy 1981). Perhaps this condition arises from the relative deficiencies in O in the ISM of the Clouds, compared to galactic H II regions: less O is available in the stellar atmospheres to form CO and, hence, the atomic C abundances are increased. (O synthesized within the progenitor presumably does not reach the envelope, since dredging just reaches C in the Becker and Iben models.) Further, additional processes for bringing C out of the core, as proposed by Iben (1981), may be at work, or certain reaction rates and neutrino loss rates adopted in the models may be in error, as also noted by

Iben. It is interesting that despite substantial differences in the current populations of the putative progenitor stars, PN chemical compositions are rather similar in the Galaxy, the LMC, and the SMC.

What is the primary source of C in the ISM? Supernovae are unlikely to account for the C in the present ISM of both the Galaxy and the LMC, since the latter appears to have a significantly higher supernova rate (cf. Felten 1981) yet has a much lower ISM C abundance (DST, see also their discussion). The time scale for supernovae, even the intermediate mass C deflagration supernovae, is much shorter than the time scale for evolution through the PN state by the progenitors of currently observed PN, since the latter have masses of only 0.8–5 $M_{\odot}$ (Peimbert 1981). It appears from our small sample that PN and the stellar winds of their progenitors are major suppliers of C to the ISM of the Magellanic Clouds.

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