THE CARBON ABUNDANCE IN TWO H II

REGIONS OF THE SMALL MAGELLANIC CLOUD

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ABSTRACT

Observations of the ultraviolet spectra of two locations in the H II region NGC 346 and of the entire H II region IC 1644 in the Small Magellanic Cloud (SMC) were made using the International Ultraviolet Explorer (IUE) satellite. From measurements of the C III] λ1909 lines, the abundance of carbon in the nebulae was derived using theoretical model analysis combined with ground-based spectrophotometry of other emission lines. The abundance of C relative to H in the SMC was found to be lower by -0.9 dex compared with the Sun and lower by -0.8 dex compared with the Orion Nebula. This C deficiency is similar to that of O, Ne, S, and Ar in the SMC, but not as great as found for N (≈ - 1.2 dex). Therefore, it is concluded that the sites and history of C nucleosynthesis in galaxies is similar to that of O, Ne, S, and Ar, in contrast to that of N, which appears to be more complex, perhaps because of a mixture of secondary primary sources or a significant contribution from intermediate-mass long-lived stars.

INTRODUCTION

The Large and Small Magellanic Clouds (LMC and SMC) provide a unique opportunity to study in detail the structure and composition of two galaxies representing an earlier epoch in the chemical evolution of galaxies compared with our own. Recent ground-based spectroscopic studies of H II regions in the Clouds by the Peimberts (refs., 1,2), Aller et al. (refs. 3,4), Pagel et al. (ref. 5), and Dufour (refs, 6.7), show that [O/H] is -0.5 in the LMC and -0.9 in the SMC (where the bracketed ratio represents the difference of the logarithm of the abundance ratio between the galaxy and the sun). Nitrogen shows the greatest deficiency of all elements studied (He, N, O, Ne, S, and Ar) with [N/H] ≈ -1.1 in the LMC and [N/H] ≈ -1.4 in the SMC. Also, helium is slightly deficient in H II regions in the Clouds compared with similar nebulae in the Galaxy.

While spectrophotometric studies of H II regions in the Magellanic Clouds with ground-based telescopes have resulted in the accurate determination of the abundances of a number of elements of astrophysical importance, others, such as carbon, can only be readily observed in the ultraviolet. Therefore, we have initiated observations of the ultraviolet spectra in the λλ1135-3255 Å range of several H II regions in the LMC and SMC with the International Ultraviolet Explorer (IUE) satellite. In this note we report the first results of observations of two H II regions in the SMC.

OBSERVATIONS AND RESULTS

The spectra of two H II regions in the SMC, NGC 346 and IC 1644, were obtained in May 1979 with the Short Wavelength Prime (SWP) and Long Wavelength Redundant (LWR) cameras of the IUE at low dispersion. The SWP observations covered the $\lambda\lambda$1135-2085 region with a spectral purity of 30 Å. The 10 x 20 arc second elliptical aperture was used in all of the observations. Emphasis was placed on the SWP observations in order to measure the C III] λ1909 and C IV λ1549 lines necessary for determining the carbon abundance.

The nebula NGC 346 is the most prominent H II region in the SMC located in the northeast area of the main body of stars. It is listed as N66 in Henize's (ref. 8) catalog of LMC and SMC emission nebulae. Since the nebula has a significant apparent size, 490 x 580 arc seconds, two locations were observed: N66A--a bright knot located in the southern part of the nebula, and N66NW--a smooth star-free area located in the northwest lobe of the nebula. These two locations were chosen primarily because there exists published ground-based photoelectric spectrophotometry of them (refs. 2, 7).

The nebula IC 1644 is a small (~ 10 arc second diameter) H II sphere of high surface brightness located southeast of the SMC bar in the Shapley's "wing" feature. It is listed as N81 in Henize's catalog. Dufour et al. (refs. 7, 9) have published photoelectric and photographic spectrophotometry for all significant emission lines in the $\lambda\lambda$3727-7136 spectral region of N81 from ground-based observations.

Generally two or more integrations of each location were obtained with the SWP and LWR cameras. A log of the observations is given in Table I. The observations of NGC 346/N66A and NGC 346/N66NW regions were obtained during the US1 shift and have low particle background. The IC 1644/N81 observations were obtained during the US2 shift and have very high particle noise backgrounds. In addition, the underlying stellar continuum is considerable for NGC 346/N66A and particularly so for IC 1644/N81. Because of the high particle background and stellar continuum encountered in the IC 1644/N81 observations, only two 10-minute SWP integrations were usable for quantitative measurements of the five obtained.

The photometrically and geometrically corrected spectra on the GO tapes prepared by NASA/GSFC were analyzed using interactive picture processing systems at Rice University and at NASA/JSC in Houston. SWP spectra processed with the incorrect Intensity Transfer Function were corrected with the three-agency 4th file method. The resulting 55 line x 602 word spectra background arrays where then analyzed using a FORTH interactive spectral analysis system originally developed by F.H. Schiffer, III at NASA/JSC. This permitted us to use a variety of smoothing, background subtraction, and spectral extraction techniques optimized for each observation. The only prominent lines (other than Ly α predominantly from the geocorona) detected in the nebulae were the C III] λ1909 pair unresolved on our own spectra; as was Mg II $\lambda\lambda$2796,2804, which might have been expected to be detectable on some of the LWR spectra.

Measurements of the C III] λ1909 strengths were made using an interactive Tektronixs cursor routine to set continuum levels and integrate areas. Several measurements of each line were made in an attempt to evaluate the magnitude of possible errors due to the prejudice of the operator in setting the continuum level, estimating the line width, etc. Comparison of the line strengths measured on two different spectra of a given object provided an estimate of the instrumental errors. The areas in instrumental units (FN) were converted to the observed flux in ergs sec^{-1} cm^{-2} using the large aperture SWP calibration for low dispersion derived by Bohlin et al. (ref. 10). These were corrected for interstellar extinction (which is rather small for the SMC) using the UV extinction curve of Savage and Mathis (ref. 11) along with published extinctions for the nebulae from ground-based observations of the $H\alpha/H\beta$ ratios. The 1909 reddening-corrected fluxes were then scaled to the $H\beta$ fluxes observed for each region by previous investigations. For the two regions in NGC 346 we used the ratio of the areas of the IUE and ground-based entrance apertures; while for the smaller nebula IC 1644 we assumed that it was entirely within both the IUE and ground-based apertures.

The line intensities for C III] λ1909 derived from our observations along with those of other important diagnostic lines observed from the ground are presented in Table II. We also present estimated upper limits to the C IV λ1549 and Mg II λ2800 lines derived from the IUE spectra. We give estimated errors for the λ1909 intensities based primarily on the uncertainties in the measurements of the line profiles. The actual errors for λ1909 may be two or three times larger, due to the uncertainties in scaling the IUE λ1909 fluxes to the ground-based $H\beta$ fluxes as well as uncertainties in the absolute calibration of the IUE SWP spectra. The ground-based observations were made with photoelectric scanners and have probable errors of the order of 10 percent. Other relevant data about the nebulae are presented in the tables also.

ANALYSIS AND DISCUSSION

Elemental abundances for H, He, C, N, O, Ne, S, and Ar in the nebulae were derived by Shields using a nebula modeling code similar to that used in previous studies of H II regions in M101 (ref. 12) and M83 (ref. 13). Since all three nebulae have rather similar spectra, we used a single model differential analysis approach. A "standard model" was calculated to match the spectrum of NGC 346/N66A (T^*_{eff} = 45,000°K) and used to derive the temperature fluctuations for various ions compared with $T(O^{++})$ obtained via the [O III] $\lambda\lambda$5007/4363 ratio. The computed fluctuations were used with the observed [O III] temperatures and line strengths to calculate various ionic abundances for those ions with observed lines. Elemental abundances were then inferred from these ionic abundances using ionization corrections for ions without observed lines from the standard model. The final results are presented in Table III.

Using the estimated upper limits to the strengths of the C IV λ1549 lines for NGC 346/N66A in the model, we found that about 92 percent of the carbon in the H^+ zone was in the form of C^{++}. Consequently, the corrections for C^+ and C^{+++} in the SMC nebulae are small, so the fact that we did not observe C IV should not significantly affect the accuracy of the C abundances derived. Based on model and observational uncertainties in $T(O^{++})$ alone, we estimate that the uncertainty in the C abundance for the various nebulae is about 0.1 dex. The good, but possibly fortuitous, agreement of the C abundances between the three nebulae suggests that the accuracy by which the C abundance is now known in the SMC is better than ± 0.2 in the logarithm. Since this model is also the first theoretical model analysis of an H II region in the SMC, it is gratifying to note that the other abundances calculated agree very well with those of previous investigations for which the analyses were based on standard nebular diagnostic formulae.

On the right side of table 3 we give the logarithmic differences between the SMC mean abundances and those determined for the Sun (ref. 14 for C,N, and O; ref. 15 for He, Ne, Mg, S, and Ar) and for the Orion Nebula (ref. 16). It is clear from inspection of the table that the C/O ratio in the SMC is essentially identical to that found for the Sun and the Orion Nebula. The abundance deficiency of C relative to H in the SMC compared with the Sun and Orion is clearly more similar to that of the elements O, Ne, S, and Ar than to that of N, which is substantially more deficient than the others. Therefore, we conclude that the nucleosynthesis of C follows closely that of O, Ne, S, and Ar as predicted by theoretical nucleosynthesis models(refs. 17,18) . The large variation of N/O while C/O remains constant implies that the stellar sources of N do not contribute a large fraction of the C.

It is of interest to compare this result with the recent study of abundances in several high excitation planetary nebulae with the IUE by Aller and Keyes (ref. 19). Several of the nebulae studied were overabundant in N by factors of 5-10 compared to solar and Orion values. None of these N-rich nebulae showed significant enhancements in the C abundance. These results and ours suggest that the site(s) of C nucleosynthesis is the same as that of O, Ne, S, and Ar. The processes, presumably from intermediate mass stars (ref. 20), which subsequently enrich galaxies with N later in their evolution apparently do not significantly affect the relative abundances of C, O, Ne, S, and Ar.

We also note in ending that the Mg abundance found for the two locations in NGC 346 using our estimated upper limit is at least 1.4 dex lower than the solar value. Unless the nucleosynthesis of Mg is similar to that of N in the SMC, which is unlikely, the low abundance of Mg is apparently due to its depletion by dust in the H II regions. The magnitude of this depletion is then rather surprising, when one notes that the dust content of the SMC is very low compared with the LMC and our galaxy.

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TABLE I -- IUE OBSERVATIONS LOG

Nebula	SWP Exposures (min)	LWR Exposures (min)
NGC 346/N66A	30,120	30
NGC 346/N66NW	120,180	30,30
IC 1644/N81	10,10,15*	20,20,20
	20*, 60*	30*

*Not usable due to saturated pixels + high background

TABLE II - LINE INTENSITIES FOR SMC H II REGIONS

λ(Å)	ION	NGC346 / N66A	NGC 346 / N66NW	IC 1644 / N81
1548,1551	C IV	<20	<15	<30
1907,1909	C III]	123.±19.*	120.±10.*	162.±32.*
2796,2804	Mg II	<20:	<20.	-
3726,3729	[O II]	95.5	108.	128.
3869	[Ne III]	44.7	35.0	37.8
4340	Hγ	46.8	46.6	45.5
4363	[O III]	7.08	6.07	6.44
4471	He I	---	3.33	3.50
4861	Hβ	100.	100.	100.
4959	[O III]	---	172.	177.
5007	[O III]	513.	501.	525.
5876	He I	10.2	11.0	11.9
6312	[S III]	2.6:	1.8	---
6563	Hα	282.	286.	286.
6584	[N II]	4.37	6.38	6.30
6678	He I	2.95	3.51	3.08
6716	[S II]	6.76	} 14.4	6.0
6730	[S II]	4.47		5.4
7136	[Ar III]	9.77	--	6.7:
7320,7330	[O II]	2.34	___	
	C(Hβ)	0.17	0.07	0.04
	log I(Hβ)	-11.41	- 11.12	-11.02
	reference (optical)	1	7	7, 9

*Errors quoted for λ1909 are based on comparative statistics between two observations; actual errors due to absolute calibration of IUE and zero point transfers may be two or three times larger.

TABLE III -- MODEL ABUNDANCE RESULTS

	(1) NGC 346 N66A	(2) NGC 346 N66NW	(3) IC 1644 N81	(4) MEAN SMC	(5) SUN (refs. 14, 15)	(6) ORION (ref. 16)	(7) (4) - (5)	(8) (4) - (6)
He	10.91	10.92	10.94	10.92	---	11.00	---	-0.08
C	7.64	7.76	7.85	7.75	8.67	8.52	-0.92	-0.77
N	6.49	6.69	6.68	6.62	7.99	7.76	-1.37	-1.14
O	8.00	8.06	8.06	8.04	8.92	8.75	-0.88	-0.71
Ne	7.23	7.20	7.20	7.21	8.03	7.90	-0.82	-0.69
Mg	<6.1	<6.1	---	<6.1	7.52	---	<1.4	---
S	6.4:	6.6:	6.6:	6.6:	7.20	7.41	-0.6	-0.8
Ar	5.80	---	5.66	5.73	6.57	6.7:	-0.84	-1.0
C/N	1.15	1.07	1.17	1.13	0.68	0.76	0.45	0.37
C/O	-0.36	-0.30	-0.21	-0.29	-0.25	-0.23	-0.04	-0.06