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THE ENRICHMENT OF NITROGEN AND HELIUM IN PLANETARY NEBULAE

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ABSTRACT

The ratios of the abundances of the singly ionized states of nitrogen and oxygen are derived from published data for 93 planetary nebulae, including 10 in the Magellanic Clouds. The question of whether we can set N/O identical to N^+/O^+ is largely resolved. For medium excitation planetaries N/O = N^+/O^+ is correlated with He/H, which implies the validity of the identity and also shows that enrichment of nitrogen in planetary shells is closely tied to that of helium. The N^+/O^+ ratios of low-excitation planetaries are inversely correlated with the temperature of the central star T_*. For log $T_* \leq 4.65$, N^+/O^+ does not reflect N/O, implying an ionization imbalance between N and O. High-excitation nebulae with $He^{2+}/He \geq 0.5$ show little correlation between N^+/O^+ and He/H, which may also indicate an ionization imbalance.

The N^+/O^+ = N/O identity is tested by plotting N^+/O^+ against O/O^+. A weak negative correlation is found, but it is due to a primary weak negative correlation between O/O^+ and He/H being reflected through the (N/O, He/H)-relation. An increased amount of helium in the nebula probably modifies the radiation field of the star such that fewer highly ionized oxygen species and more O^+ are produced.

The He/H ratio is correlated with distance from the galactic plane, and there is good evidence that N/O is also. Disk nebulae appear to have both higher minimum N/O (between 25% and 50%) and He/H (about 20%) than do halo nebulae, indicating a general enrichment of the Galaxy in N and He with time. However, no radial gradient in N/O can be seen, possibly because of too few nebulae with low nitrogen enrichment.

The correlation between N/O and He/H improves if we consider only disk objects, since within the disk the initial abundances for different objects are similar. For halo nebulae the correlation is not as evident, probably because it is smeared by a larger variation of initial conditions, and possibly because of a smaller range of initial stellar masses. The helium and nitrogen enrichments generally seem to be produced by convective dredging of fusion products before ejection of the planetary. Except for a few nebulae with very high He/H, the correlation agrees with Iben's, and Becker and Iben's, predictions for the surface abundances of asymptotic branch stars, which thus provides a successful test of the theory of the late stages of stellar evolution.

Subject headings: nebulae: abundances — nebulae: planetary

I. INTRODUCTION

Nitrogen to oxygen (N/O) ratios in gaseous nebulae have been studied in some detail for the past decade. Ionic oxygen abundances are measurable both for O^+ and O^{2+}, and for higher-excitation planetaries the O^{3+} abundances can be estimated from He^{2+}/He^+ (Seaton 1968). But for nitrogen, only the N^+ abundance is derivable, and at least for the majority of planetary nebulae, only a small fraction of the N is in the form N^+. It is usually assumed that N/O is identical to N^+/O^+ (Peimbert 1968).

Using this identity, Peimbert and Torres-Peimbert (1971*a*) found that nitrogen was generally enhanced by a factor of from 3 to 5 in planetary nebulae, which was ascribed to nuclear burning processes in the parent star. Torres-Peimbert and Peimbert (1977) find much the same thing in their study of galactic gradients. Boeshaar (1975) also found that N/O was dependent on population type, in that Population II nebulae tend to have lower N/O. Both Torres-Peimbert and Peimbert (1977) and Barker (1978*a*) find a rough positive correlation between He/H and N/H, which implies the mixing of processed matter from the central star. Peimbert (1978) also recognizes a set of nebulae which exhibit both high N/O and high He/H, which includes such objects as NGC 2440 and Pb 6.

The general and quantitative validity of the identity N/O = N^+/O^+ is still open to question, however. The O/O^+ ratio, and consequent correction from N^+/H to N/H, is often very large, sometimes exceeding a factor of 100. A number of studies have been made which support the relation. Peimbert and Costero (1969) found that N^+/O^+ stayed fairly constant among four regions in the Orion Nebula, even though O/O^+ varied considerably. Torres-Peimbert and Peimbert (1977) could find no correlation between N/O and O/O^+ among the planetaries they observed. Hawley and Miller (1977) found that N^+/O^+ was fairly constant over six regions of the Ring Nebula, NGC 6720, even though O/O^+ varied by a factor of 30. Grandi and Hawley (1978) found that N^+/O^+

represented N/O quite well from a theoretical model of diffuse nebulae. But discordances are found. Aller and Epps (1975) found that N^+/O^+ in the low-excitation ansae of NGC 7009 is 6 times higher than it is in the bright ring. Torres-Peimbert and Peimbert (1977) also point out that the identity may not be valid for all conditions, particularly for low-excitation planetaries.

The purpose of this paper is to make use of all available data to determine: (1) the validity of the $N/O = N^+/O^+$ relation; (2) the degree of the enrichment of nitrogen, and the correlation between N/O and He/H; and (3) the general variation of N/O with position in the galaxy. The essential results for point (2) have already been published by Kaler, Iben, and Becker (1978, hereafter KIB). They showed that the observed correlation developed in the present paper between N/O and He/H was in agreement with the predictions by Iben (1972) and Becker and Iben (1979) of N and He surface enhancements caused by convective dredge-up in evolving giant stars. This work also indicated that stars with masses of up to about 6 $M_\odot$ could produce planetaries.

In this paper the observations and calculations of N^+/O^+ are discussed in § II. The $N/O = N^+/O^+$ relation is examined in § III, and the correlation between N/O and He/H is discussed in § IV. A problem of oxygen ionization which also relates to tests of $N/O = N^+/O^+$ is considered in § V, and the radial galactic N/O gradient is examined in § VI. Finally, a summary and discussion are presented in § VII.

II. CALCULATION OF N^+/O^+

a) The Data

The N/O ratio is chosen for examination rather than the N/H ratio because of the known wide variation of N/H and O/H among planetaries (see the references in the preceding section) and because the calculation of N^+/O^+ is less subject to error due to temperature fluctuation than is N^+/H^+. However, N^+/H^+ and O^+/H^+ are calculated first and then combined to produce N^+/O^+. The O^+/H^+ ratio is found from the λ3727 [O II]/Hβ ratio by using Saraph and Seaton's (1970) solution of the balance equations, and Brocklehurst's (1971) effective recombination coefficients. The N^+/H^+ and O^{2+}/H^+ ratios were derived from λ6584 [N II]/Hα and (λ5007 + λ4959) [O III]/Hβ, and from solutions of Aller's (1956) presentation of the balance equations for p^2 ions. In the case of NGC 6302, the λ5754/Hβ ratio was also used. Collision cross sections and transition probabilities for N^+ and O^{2+} were taken from Seaton (1975) and Nussbaumer (1971).

The line intensities are taken from Kaler's (1976*a*) catalog, from Torres-Peimbert and Peimbert (1977), Barker (1978*b*), Hawley and Miller (1977, 1978), Hawley (1978*a*), Sabbadin (1976, 1977), and Webster (1976). Both Hα and Hβ were corrected for blends with the He II Pickering lines.

The data were taken from the most accurate source or sources rather than from averages. It is preferable to use one observer's work in which λ3727 and λ6584 are observed at the same time, so that stratification can be avoided. Interstellar extinction coefficients *c* are taken from the catalog or derived from the above references. Most are given by Kaler (1978*c*), but those nebulae not discussed therein are referenced in Table 2. Whitford's (1958) extinction curve was used. The nebulae, the results of the calculations, and related data are presented in Table 1. Column (1) gives the name of the nebula, and columns (2) and (3) the electron temperature times $10^{-4}(t)$ and the electron density $N_e \times 10^{-3}$, respectively, which enter into the calculations of N^+/O^+. If possible, the electron temperatures used are derived from the [N II] lines. If λ5754 of [N II] is not observed, or if it is too weak to give reliable results, T_e is derived from [O III] according to the following scheme: if He II λ4686 < 60, on the scale $I(H\beta) = 100$, then T_e[N II] = T_e[O III], but if He II λ4686 ≥ 60, then T_e[N II] = T_e[O III]/1.4 (see Kaler 1978*b*; Torres-Peimbert and Peimbert 1977). If no temperature is measured, *t* is adopted on the basis of I(λ4686) (see Kaler 1978*b*). The electron densities are derived preferably from the [O II] λ3726, λ3729 intensity ratio. If this ratio is not available, densities are derived instead from [Cl III] λλ5537, 5517, or from [S II] λλ6731, 6717. If forbidden-line ratios are not observed, rms densities are calculated from the distance and flux, or they are adopted from the reference from which the line intensities were taken. Densities from forbidden lines were calculated from the solutions of Saraph and Seaton (1970), without their recommended correction. The source of the density from which N^+/O^+ was calculated is indicated by a symbol in column (3) (see notes to Table 1).

The results of the calculations, log N^+/O^+, are presented in column (4) of Table 1. In the cases of NGC 1535 and NGC 2022, only an upper limit is known. Columns (5)–(8) contain information to be used in the analysis of the N^+/O^+ data. Column (5) gives log O/O^+, where the O^{2+} abundance was calculated on the basis of the [O III] electron temperature and [Cl III] density, where available, and the O^{3+} and higher states were estimated from the He^{2+}/He^+ ratio. Column (6) gives values of He/H from Kaler (1978*c*) for nebulae with no neutral helium (log central star temperature $T_* \geq 4.65$), or computed from data referenced in column (8).

Column (7) contains either log T_* for low-excitation nebulae, for which I(λ4686) ≤ 5, or Ex = He^{2+}/He for high-excitation nebulae. Values of log T_* are taken from Kaler (1976*a*, 1978*c*) or calculated from the I(λ5007)/I(Hβ) ratio (Kaler 1978*a*), and values of Ex are from Kaler (1978*c*), or the references cited.

Next, columns (8) and (9) present reference codes and remarks which refer to explanations at the end of the table. References are indicated in two cases: (1) when the data were taken from accurate single sources—that is, when λ3727 and λ6584 were observed at the same time; and (2) when the data are not included in the Kaler (1976*a*) catalog. Otherwise, averages are used, and the references can be found in the catalog.

TABLE 1
N/O RATIOS

Nebula	t	10^{-3} Ne	log N^+/O^+	log O/O^+	He/H	log T_* / Ex	Ref	Rmks	wts.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
				Galactic Planetaries					
NGC 40	1.17*	1.5x	- .309	0.04	---	4.50			2,
650	1.18*	5.6c	- .326	0.76	.131	0.41		1	1,3
1535	1.15*	3.2x	<- .88	1.89	.097	0.11	P		3,4
2022	1.10†	1.6x	<- .012	2.45	.121	0.87	T		3,2
2346	1.29	0.39c	- .244	0.58	.124	0.16			2,3
2371	1.06	5.1s	+ .005	1.52	.126	0.78	T		4,4
2392	1.24	2.6x	- .215	1.29	.092	0.53			3,4
2438	1.04*	2.1s	- .553	0.75	.103	0.35	T		3,3
2440	0.97	1.9x	+ .397	0.79	.146	0.39	T		4,4
2452	0.93†	1.2s	- .303	1.28	.112	0.63	T		3,3
2610	1.20	0.30r	----	2.17	.110	0.74	T		4,4
2792	0.99†	1.1r	- .907	2.00	.116	0.72	T		3,3
2818	1.24	0.34r	+ .062	0.92	---	0.67‡	T		4,
2867	1.04*	2.3r	- .522	1.13	---	0.30‡			2,
3132	0.89	0.55x	- .352	0.21	.126	0.03	T		4,4
3211	0.93†	0.87r	- .779	0.50	.152	0.50	T		3,3
3242	1.25	3.4x	- .764	2.27	.107	0.27	T,B		3,4
3587	1.04	0.17r	- .514	0.51	.097	0.17	T		3,3
3918	0.84	8.7r	- .612	0.95	.108	0.35	T	2	2,4
4361	1.41†	0.30r	- .685	2.34	.135	0.82	T,B	3	3,3
5307	1.30*	2.2r	- .634	2.00	.097	0.26	T		3,4
5315	0.88	30s	- .292	0.66	.127	4.75	T	4	2,4
5882	0.89	3.8c	- .618	1.49	.116	4.79	T		4,4
6210	0.96*	6.0x	- .851	1.10	.099	4.76	B		4,4
6302	1.33†	3.2x	- .154	0.57	.225	0.28		5	1,2
6309	0.96†	3.5x	+ .26	1.58	---	0.58‡	Pr		2,
6445	0.93†	0.70x	- .02	0.52	.23	0.27	A	6	2,1
6543	0.81*	7.5x	- 1.14	1.04	.121	4.65	O		3,4
6567	1.06*	3.2x	- .522	1.55	.122	4.75	B		3,4
6572	1.05*	8.4x	- .378	1.04	.110	4.78	P		3,4
6644	1.32	7.3x	- .609	1.33	.117	0.13	B		4,4
6720	0.96	0.9s	- .56	0.39	.114	0.28	H	7	4,3
6741	1.11*	3.0x	- .133	1.15	.136	0.30			2,3
6803	0.96	5.6x	- .222	1.07	.127	4.79	P		4,4
6818	1.01†	3.3x	- .460	1.27	---	0.62‡			2,
6826	0.84	1.6x	- .885	1.11	.104	4.67			2,4
6833	1.27*	9.0x	- .277	1.34	.097	4.69	B		3,4
6853	1.22	2.5x	- .250	0.81	.133	0.26			2,3
6857	1.10*	1.1r	- .993	0.71	---	4.59			2,
6884	1.14	8.5x	- .434	1.32	.108	0.12	P,Pr		4,3
6886	1.29*	6.8x	- .533	0.74	.125	0.30	Pr		3,1
6891	1.01*	2.5x	- .846	1.37	---	4.69			2,
7009	1.10	3.5x	- .414	1.75	.112	0.10	P		4,4
7026	1.04*	7.3c	- .717	0.90	.101	0.09			2,3
NGC 7027	1.17*	15.8x	- .269	1.44	.111	0.38			3,4
NGC 7293	1.61	0.59s	- .02	0.26	.19	----	HA	8	4,2
7354	0.96§	5.8r	---	0.79	.132	0.43			1,1
NGC 7662	1.29*	3.1x	- .733	2.10	.094	0.42	P		3,3
IC 351	1.15*	5.3x	- .460	2.00	.095	0.33	B		3,4
418	0.80	30x	- 1.026	0.03	---	4.50	P,T,O		4,
1747	1.18*	3.5x	- .299	1.71	.086	0.22			2,3
2003	1.19*	3.8c	- .569	1.63	.109	0.44	B,T		3,3
2149	0.85	2.3x	- .771	0.39	---	4.56	B,T		4,
2165	0.83	2.6x	- .634	0.71	.115	0.31	T		4,2
2448	1.24*	1.8r	- .593	2.35	.095	0.23	T	9	3,3
2501	0.98	10r	- .604	0.77:	.108	4.71	T	10	2,4
3568	1.08*	5.5x	- 1.135	1.74	.092	4.79	B		3,4
4406	0.93	1.5r	- .462	0.34	.141	0.05			4,4

TABLE 1—*Continued*

Nebula	t	10^{-3} Ne	log N^+/O^+	log O/O^+	He/H	log T_* / Ex	Ref	Rmks	wts.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
4593	0.88*	2.0x	- 1.156	0.79	---	4.64	B,Pr		3,
4732	1.58*	2.7r	---	1.68	0.117	4.81			2,1
4776	1.10*	4.9x	- .03	---	---	4.68:		11	1,
4846	1.09*	10.0x	- .769	1.14	.087	4.79	B		3,3
5117	1.12*	9.5x	- .613	0.82	.119	0.10	Pr		3,3
IC 5217	1.13	9.6x	- .464	1.45	.094	0.05	P,Pr		3,3
BB 1	1.07	1.9x	+ .38	1.54	.099	0.20	H	12	4,3
BD+30°3639	0.82	7.2x	- .240	0.01	---	4.43	O,P		4,
Cn 2-1	1.03	4.0r	- .230	1.57	.137	0.03	W		3,1
Cn 3-1	0.67	3.2x	- .542	0.00	---	4.40	B		4,
Ha 1-35	0.99*	7.0r	- .66	0.77	---	4.63	W		3,2
Ha 1-54	1.08	7.0r	- .67	0.44	---	4.56	W		3,2
Ha 4-1	1.02	0.5s	- .551	0.54	.115	0.08	H		4,4
He 2 - 108	1.05*	1.2r	- .503	0.31	---	4.47	T		3,
He 2 - 131	0.72	14r	- .38	0.01	---	4.42	T	13	3,
He 2 - 138	0.70*	3.9r	- .051	0.02	---	4.34	T	14	3,
Hu 1-1	0.96	6.1s	- .699	0.37	.090	0.13	B		4,3
Hu 1-2	1.38†	6.6c	+ .168	1.07	.170	0.57			2,2
Hu 2-1	1.11	10.0x	- .720	0.53	---	4.56	B		4,4
J 320	1.49	4.2s	- .416	1.69	.106	4.76	B		4,4
J 900	1.20*	4.6c	---	1.33	.096	0.43			3,
M 1-1	1.07†	2.3x	- .571	1.64	.112	0.82	B		3,3
5	1.08	8.9s	- .608	0.51	---	4.58	B		4,
14	0.96	5.0r	- .865	0.21	---	4.55	T		4,
64	1.10*	0.33r	- .35	0.42	---	4.68:		15	1,
67	0.70	4.7s	- .111	0.00	---	<4.40	B		4,
74	1.12	6.8x	- .427	1.39	.110	4.79	B		4,4
M 1-80	1.71*	5.9s	+ .25	1.24	---	0.47			2,
M 2-9	0.84	10.0s	- .845	0.06	---	4.47	B		4,
M 2-23	1.29*	20r	- .480	1.41	.079	4.74	W		3,2
M 2-27	0.89*	5r	+ .12	1.19	.144	4.73	W		3,2
M 2-50	1.16*	17r	- .674	1.29	.079	4.79	B		3,3
Me 2-2	1.27	8.4x	+ .301	1.25	.162	4.66	B,Pr		4,4
Pb - 4	1.05*	1.1r	- .590	1.63	.139	0.13	T		3,2
Pb - 6	1.21	1.0r	+ .237	1.32	.187	0.57	T		4,2
Ps - 1	1.24*	2.0x	- .553	1.04	---	>4.43	H		3,
Sn - 1	0.98*	3.1s	- .876	1.53	.084	4.77	B		3,4
Vy 1-1	1.12*	1.0r	---	1.06	.139	4.72			2,1
Vy 1-2	0.93	5.0r	- .661	1.32	---	0.17	B		3,
Ym 29	0.96†	0.57s	- .427	0.83	---	0.66	L		2,
			Small Magellanic Cloud						
N 2	1.36*	3.0x	- .783	1.52	0.159	0.21	W,Os	16	2,2
N 5	1.31*	5.0x	- .25	1.57	0.11	0.37	W		1,2
N 67	1.24	8.4s	- .206	0.42	0.161	0.36	D,Os		4,2
N 87	1.22*	4.0r	- .48	1.00	---	4.64	W		1,
			Large Magellanic Cloud						
P 7	0.98	3.7s	- .090	0.51	0.149	0.44	D,Os		4,1
P 8	0.93*	1.0r	- .576	1.51	0.127	0.07	Os		3,2
P 24	1.12*	4.0r	- .503	0.77	---	4.65	W		1,1
P 33	1.20*	0.40s	- .806	1.00	0.078	0.27	D		3,2
P 38	1.41*	4.0r	- .70	1.12	0.20:	0.08	W		2,1
P 40	1.17†	1.0r	- .893	1.93	0.077	0.89	Os		3,2

* t from [OIII]

† t from T_e[OIII]/1.4

‡ Assume He/H = 0.11

§ t adopted

REMARKS TO TABLE 1

1. NGC 650: t is from [O III]; $t/1.4$ yields too high an O/H. Chopinet (1963) also shows t[N II] > t[O III].
2. NGC 3918: High density ($\sim 10^4$); uncertain results.
3. NGC 4361: rms density used. [O II] density is $> 10^4$, in which case N/O would be lower.
4. NGC 5315: High density, uncertain results; [Cl III] gives $N_e = 6 \times 10^4$.
5. NGC 6302: N/O from eye estimate of [N II]/Hα ratio, and uncertain λ5754/Hβ ratio.
6. NGC 6445: [N II] blended with Hα, mostly [N II].
7. NGC 6720: entries are an average of Hawley and Miller's (1977) six regions.
8. NGC 7293: Log T_*/Ex unknown, but log $T_* > 4.65$ from [O III] observations of Warner and Rubin (1975); λ4686 not observed, so Ex probably low. Nebula falls in mid-range where N/O = N^+/O^+.
9. IC 2448: Ne uncertain. T use a value 10 times higher, in which case log N/O ≈ -1.1.
10. IC 2501: High density ($\sim 10^4$), uncertain results.
11. IC 4776: t is an estimate. [N II]/Hα ratio eye estimate. High N/O is indicated, but very approximate
12. BB 1: Object discovered by Boeshaar and Bond (1976) = 108−76°1.
13. He 2–131: N_e may be high, so N/O is a lower limit.
14. He 2–138: Measured $t = 0.6$ gives too high an O/H; $t = 0.7$ is adopted. If $t = 0.6$, log N/O = −0.23; N/O clearly high.
15. M1–64: t adopted; N/O very approximate.
16. W observed λ3727, Os λ6584.

REFERENCE KEY.—B, Barker 1978*b*. D, Dufour and Killen 1977. H, Hawley and Miller 1977, 1978. HA, Hawley 1978*a*. L, Liebowitz 1975. O, O'Dell 1963. Os, Osmer 1976. P, Peimbert and Torres-Peimbert 1971*b*. Pr, Perinotto 1974. T, Torres-Peimbert and Peimbert 1977. W, Webster 1976.

Column (3) symbols indicate spectrum from which N_e was derived: *x*, [O II]; *c*, [Cl III]; *s*, [S II]; *r*, rms, assumed, or adopted from chief reference.

b) The Errors

Column (10) of Table 1 presents relative weights for some of the preceding data. The first number gives a subjective estimate of the weight for the value of log N^+/O^+ on a scale from 1 to 4 (the higher the number, the lower the error). It is not possible to place a real error on the N^+/O^+ ratios, as there is usually only one good observation. In the best cases, Torres-Peimbert and Peimbert (1977) estimate line-intensity errors of $\pm 10\%$ which, including the resultant error in T_e and c, translates to an error in log N^+/O^+ of about ± 0.08. For weight 1, an error of ± 0.3 might be realistic. General assignment of weight was made according to the following scheme: (1) weight 4, both λ6548 and λ3727 observed by the same observer and the electron temperature is derived from [N II]; (2) weight 3, same as (1) above, but T_e taken from [O III]; (3) weight 2, λ6548 and λ3727 data taken from two sources; (4) weight 1, λ6548 an eye estimate, or data are anomalous. There are exceptions to the above system; for example, if N_e is high and unreliable (see below), the weight is downgraded. These weights generally apply to the O/O^+ ratio of column (5) as well. The second number in column (10) is a weight inversely proportional to the He/H mean error e as follows: 4, $0 < e \leq \pm 0.006$; 3, $\pm 0.006 < e \leq \pm 0.012$; 2, $\pm 0.012 < e \leq \pm 0.018$; 1, $e > \pm 0.018$.

Given the wide range in log N^+/O^+ (from −1.2 to +0.4), errors in electron temperature are not serious. For the most part, T_e is accurately known from [O III] or [N II], with the largest error introduced in trying to relate T_e[N II] to T_e[O III] when the former is not measured. The error in the estimated T_e[N II] is probably of the order of $\pm 20\%$. A 40% variation in T_e results in a 60% change in N^+/O^+ or 0.21 in the log, and it is unlikely that the error in T_e would be this high. Specific cases of uncertainty are indicated in the notes to Table 1. The electron densities are generally known with less certainty than are the temperatures. However, at least at low densities, N^+/O^+ is rather insensitive to errors in density. At $N_e = 10^3$ cm^{-3} an increase of N_e by a factor of 2 produces a 12% decrease in N^+/O^+. The effect increases with N_e. At $N_e = 10^4$ cm^{-3}, an increase of a factor of 2 produces a change in N^+/O^+ of 40%. Values of N^+/O^+ in nebulae for which N_e is much above 10^4 are suspect, and are indicated in the notes. An erroneously high value of N_e also produces an anomalously high O/H. In some cases, N_e and T_e were adjusted so as to give reasonable O/H (see the notes). Probably the biggest source of error is stratification within nebulae which were observed in the red and blue by different observers. Where there was sufficient information given by the reference, similar positions within the nebula were chosen for the red and blue observations.

The N^+/O^+ ratios were checked against the results given by Torres-Peimbert and Peimbert (1977) and Barker (1978*a*). The values in Table 1 are systematically somewhat higher than those found in either of

TABLE 2

DATA FOR NEBULAE NOT FOUND IN KALER (1978*c*)

Nebula (1)	c (2)	R kpc (3)	$\|Z\|$ kpc (4)	$\|v_r\|$ km s^{-1} (5)	Population (6)
NGC 2346......	0.87	11.1	0.09	42	I
NGC 2867......	0.44	9.4	0.22	15	I
NGC 6853......	0.02	9.9	0.02	54	I
NGC 7293......	0.09	9.9	0.12	15	I
Cn 2–1.........	0.54	5.9	0.32	271	II
Ha 1–35........	1.04	...	...	...	...
Ha 1–54........	0.69	...	...	...	...
M1–80..........	0.44	13.4	0.26	56	II
M2–23..........	1.12	8.0	0.10	216	II
M2–27..........	1.15	6.1	0.26	181	II
Vy 1–2..........	0.06	8.3	3.67	98	II

these papers. The differences are due to higher temperatures and lower densities used in the present work, both of which act to increase N^+/O^+. Both of the above references make use of nebular-to-auroral ratios to determine N_e, which yields higher densities than do the nebular ratios used in this paper. The higher densities also depress the electron temperature. Torres-Peimbert and Peimbert (1977) also set T_e[N II] = T_e[O III]/1.25, if $I(\lambda 4686) \geq 25$ (when the former is not measured), whereas in the present work, T_e[N II] is not dropped below T_e[O III] until $I(\lambda 4686) > 60$. In addition, the cross sections for N^+ used here are lower than those used by Barker (1978*a*).

III. IONIZATION EFFECTS AND THE $N/O = N^+/O^+$ RELATION

In § I a number of studies were described which tested whether or not we can set $N/O = N^+/O^+$. The results are mixed, but the evidence seems to suggest that the relation is generally correct. A good test, one used by Torres-Peimbert and Peimbert (1977), is to see whether or not N^+/O^+ correlates with O/O^+. Figure 1 presents a plot of $\log N^+/O^+$ against $\log O/O^+$, coded for three different stellar temperature, or nebular excitation, regimes ($\log T_* \leq 4.65$; $\log T_* > 4.65$, Ex < 0.5; and Ex ≥ 0.5). There appears to be a very weak negative correlation. The nebulae with $\log O/O^+ > 1.6$ have $\log N^+/O^+$ noticeably less than those with $\log O/O^+ < 1$. especially if the lowest excitation group is ignored. Ordinarily, a correlation of this sort might not be viewed as significant, but since we are trying to test the relation by a lack of correlation, any suggestion of one becomes important. We will see later in the analysis that Figure 1 shows a secondary correlation which does not bear upon the validity of $N/O = N^+/O^+$. Figure 1 also appears to exhibit a correlation with regard to excitation. The low-excitation objects collect toward the lower left, and there seems to be a high preponderance of high-excitation nebulae toward the upper right. This feature will be commented on later.

Another test is to see whether N^+/O^+ shows any relation to the temperature of the central star. Figure 2 shows $\log N^+/O^+$ plotted against a combination of $\log T_*$ and Ex = He^{2+}/He. The Ex parameter is used because of the lack of central-star temperatures for nebulae with significant He^{2+}, and because Ex gives a good measure of nebular excitation conditions (see Kaler 1978*b*). The two scales are joined such that Ex = 0 at $\log T_* = 4.75$, at the point where λ4686 becomes visible. In Figure 2, the low-excitation nebulae ($\log T_* \leq 4.65$) show a clear correlation between $\log N^+/O^+$ and $\log T_*$. As $\log T_*$ increases from 4.3 to 4.65, N^+/O^+ drops by an order of magnitude. This correlation strongly suggests that for low-excitation planetaries $N/O \neq N^+/O^+$, a point also suggested on other grounds by Torres-Peimbert and Peimbert (1977). Note also that at $\log T_* = 4.65$, helium begins to go neutral (see Kaler 1978*c*). For low-temperature stars, N^+ is overabundant with respect to O^+. It is known (see Dalgarno 1978) that $O^+ \rightarrow O^0$ (neutral) has a large cross section for charge exchange. Possibly the O^+ goes to the neutral state for low-excitation nebulae faster than does the N^+.

Also noticeable in Figure 2 is the rather sudden jump in minimum N^+/O^+ at $\log T_* \approx 4.8$. Below 4.8, many objects have N^+/O^+, which would indicate subsolar N/O, solar being between 0.16 (Withbroe 1976) and 0.125 (Ross and Aller 1976). However, the minimum $\log N^+/O^+$ is very nearly solar for nebulae

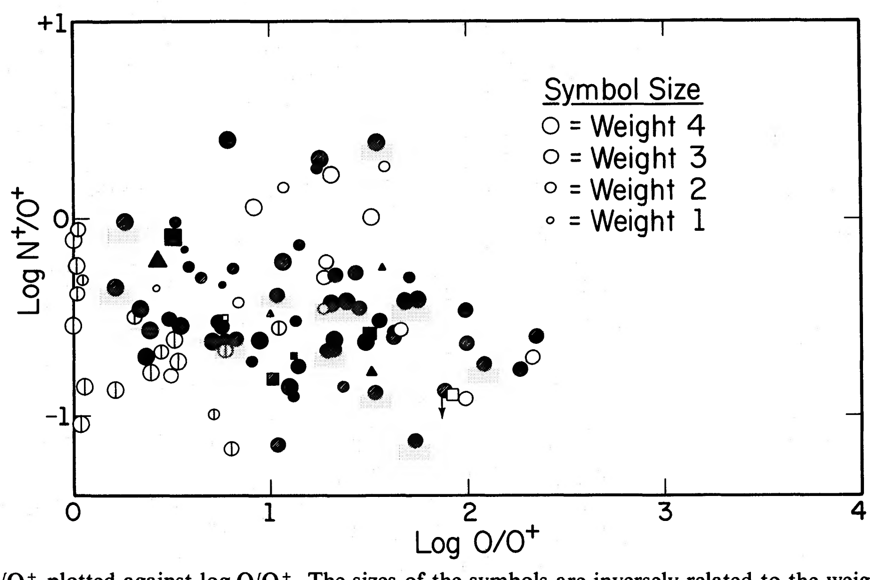

FIG. 1.—Log N^+/O^+ plotted against log O/O^+. The sizes of the symbols are inversely related to the weights of the points; see the legend in the figure. The weights are the first numbers in column (10) of Table 1. *Filled symbols*, $\log T_* > 4.65$, Ex < 0.5; *open symbols*, Ex ≥ 0.5; *crossed circles*, $\log T_* \leq 4.65$; *circles*, galactic planetaries; *boxes*, LMC planetaries; *triangles*, SMC planetaries.

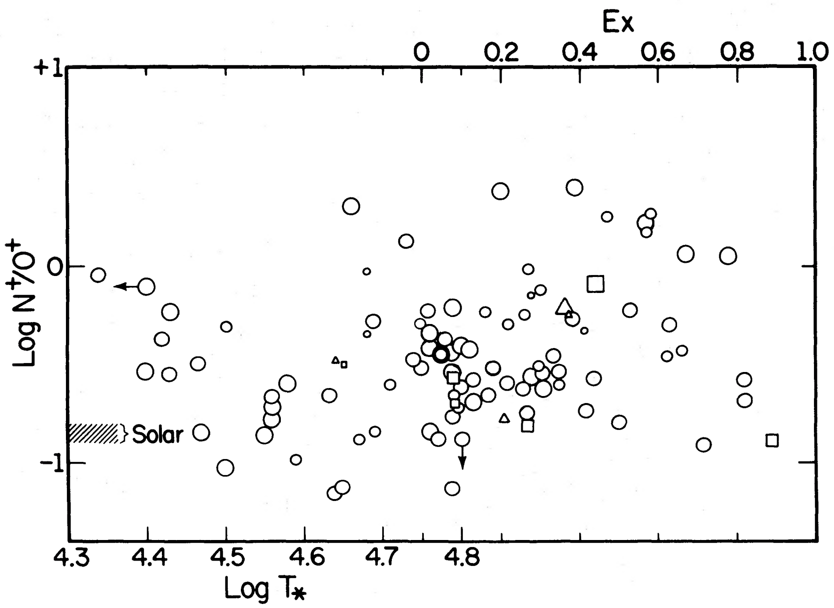

FIG. 2.—Log N^+/O^+ plotted against log T_* or Ex = He^{2+}/He. Solar N/O is indicated. See the legend to Fig. 1 for the explanation of symbol sizes.

above log $T_* = 4.8$, or Ex = 0. This feature of Figure 2 is also seen in Figure 1 in the congregation of low-excitation points mentioned above.

If we examine only those nebulae with Ex > 0, no significant correlation is evident. Kaler (1978*d*) indicated that N^+/O^+ generally increased with Ex, but additional data (notably from Barker 1978*b*) did not support it. Kaler (1978*d*) did show the correlation below log $T_* = 4.65$. In at least one excitation regime now (log $T_* \leq 4.65$), the $N^+/O^+ = N/O$ relation is definitely not valid, at least for planetaries.

This correlation has a disturbing implication regarding studies of galactic nitrogen gradients, since these studies are conducted by using diffuse nebulae for which log T_* is generally less than 4.65. Smith (1975), for example, shows that N^+/O^+ varies by about a factor of 4 from the center to the edge of spiral galaxies. Shields (1974) shows a similar variation. Shields and Tinsley (1976) suggest that the temperature of the exciting stars of diffuse nebulae increases radially outward. These two quantities then correlate in the same sense as the low-excitation planetaries of Figure 2. It is not known whether or not the correlation of N^+/O^+ with T_* would also be valid for the much more massive diffuse nebulae. N/O was plotted against log T_* for the diffuse nebulae recently observed by Hawley (1978*b*), Peimbert, Torres-Peimbert, and Rayo (1978), and Shields and Searle (1978), and no clear relation between the two is found. Nevertheless, this is a problem which should be considered in galactic nitrogen studies.

In the next section, the remaining nebulae will be tested for abundance correlations, and other regimes for the validity—or lack of it—of $N^+/O^+ = N/O$ will be defined.

IV. THE RELATION BETWEEN NITROGEN AND HELIUM

a) Validity of $N/O = N^+/O^+$

Both Torres-Peimbert and Peimbert (1977) and Barker (1978*a*) indicate a rough correlation between N/H and He/H. Such a correlation is to be expected on the basis of stellar evolution theory. However, N/O should correlate better with He/H than does N/H because of the wide galactic O/H and N/H variation. Iben (1964) pointed out that in climbing the giant branch, a star will convectively dredge up newly made nitrogen and so enrich the surface abundance of this element. Iben (1972) also showed that on the star's second ascent of the giant branch, helium and additional nitrogen will be dredged up and brought to the surface. Figure 2 was examined to see whether an excitation regime could be found in which N/O would correlate with He/H. Presumably, such a correlation would validate the assumption that $N/O = N^+/O^+$. The nebulae of Figure 2 are broken into four excitation groups: (1) log $T_* \leq 4.65$; (2) log $T_* > 4.65$, Ex < 0.20; (3) $0.20 \leq$ Ex < 0.50; and (4) Ex $\geq$ 0.50. The first group can be rejected immediately because of the argument presented in the last section. The other three groups are all shown in Figure 3, where log N^+/O^+ is plotted against He/H. The three groups are coded according to the legend of the figure. The Magellanic Cloud planetaries are denoted by boxes and triangles as indicated in the legend. We see from Figure 3 that the highest-excitation group (Ex $\geq$ 0.5) shows large scatter and no clear correlation, but that the lower two groups show a good correlation between N^+/O^+ and He/H. Group (3) above ($0.20 \leq$ Ex < 0.50) is shifted somewhat to the right of group (2), but these two groups

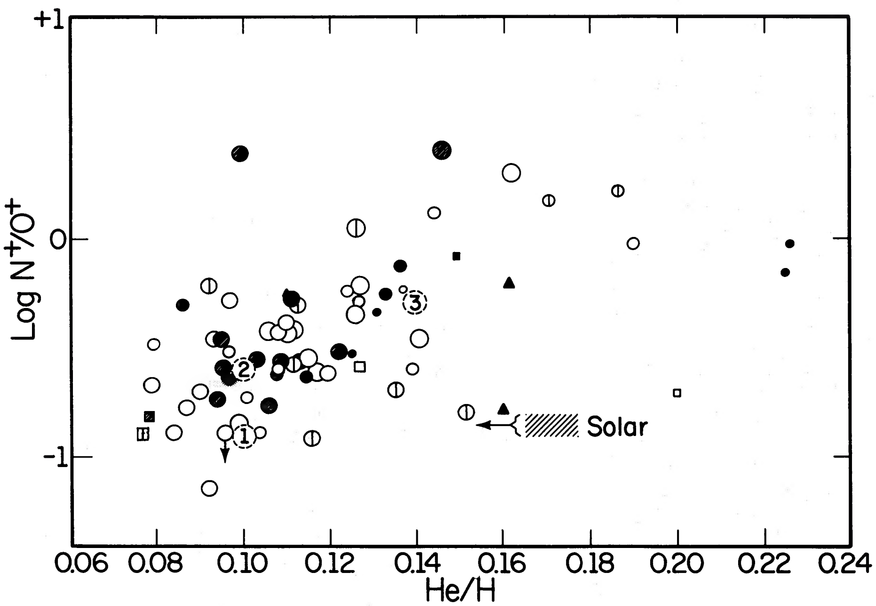

FIG. 3.—Log N^+/O^+ plotted against He/H for all planetaries with log $T_* > 4.65$. *Open symbols*, log $T_* > 4.65$, Ex < 0.2; *filled symbols*, $0.2 \leq$ Ex < 0.5; *symbols with vertical slash*, Ex ≥ 0.5; *circles*, *boxes*, and *triangles*, galactic, LMC, and SMC planetaries, respectively; *numbered dotted circles*, theoretical points given by Iben (1972) for a 7 $M_\odot$ star. See the legend to Fig. 1 for symbol-size explanation. The weight is the smaller value of the numbers in column 10 of Table 1.

blend into one another with the same slope. Note also that group (4) seems to scatter even farther to the right. This effect is similar to the one seen in Figure 1, where the high-excitation nebulae are shifted to the upper right. These correlations with excitation (for log $T_* > 4.65$) probably reflect the upward trend of He/H with Ex seen in Kaler's (1978*c*) Figure 9 and may in part be due to observational selection.

Note that the lower left end of the correlation fits, to a first approximation, with the solar or local galactic abundances, assuming He/H (solar) ≈ 0.1. Included in Figure 3 are calculations of surface abundances made by Iben (1972) for a 7 $M_\odot$ star, denoted by dotted circles. Circle (1) denotes the starting point, He/H = 0.1, N/O = 0.125. Point (2) shows the enhanced nitrogen abundance which occurs on the giant branch before helium ignition. Point (3) shows the final abundances for the star the second time up the giant branch with a helium-burning shell before hydrogen reignition. The theoretical points fit very well with the general run of observed points for excitation groups (2) and (3).

It is highly unlikely that such a correlation could exist, especially one which fits the theory so well, unless the $N/O = N^+/O^+$ relation were valid. We can therefore conclude that, in general, $N/O \approx N^+/O^+$ for planetaries of medium excitation, that is, nebulae for which log $T_* > 4.65$ and Ex < 0.5. The error that remains in this relation is not known, but it is probably less than the mean error in the observations, which from § II*b* might be of the order of $\pm 30\%$. For low-excitation nebulae (log $T_* \leq 4.65$) there are as yet unexplained ionization imbalances that render $N/O \neq N^+/O^+$. For high-excitation objects (Ex ≥ 0.5), little can be said. Either there is an ionization imbalance or there really is little correlation between He/H and N/O. These objects must be examined more carefully.

b) *The Enrichment of Nitrogen and Helium*

The current helium and nitrogen contents of planetaries depend upon (1) the initial composition of the parent star, and consequently the composition of the interstellar medium originally local to the star, and (2) fusion and dredging processes within the star which enrich the part of the star that is ejected as a planetary. The relation between He/H and N/O will then depend upon the details of the fusion process and gradients which exist within the galaxy. These two effects are both present in Figure 3, and must be separated from one another.

In order to perform this separation, the planetaries are divided into various groups which depend upon the kinematics and galactic positions of the nebulae. Kaler (1978*c*) separated the nebulae into sets of population groupings. Population I consisted of nebulae with radial velocity $|v_r| < 70$ km s^{-1}, distance from the galactic center projected onto the plane $R < 12$ kpc (on the Cahn-Kaler [1971] scale, with the Sun at 10 kpc), and distance from the galactic plane $|Z| < 1$ kpc. Any nebula exceeding any of these limits is considered to be Population II. A more restricted definition, called Population I′, required that $|Z|$ be less than 400 pc. KIB separated the nebulae on the basis of $|Z|$ alone, at $|Z| = 400$ pc.

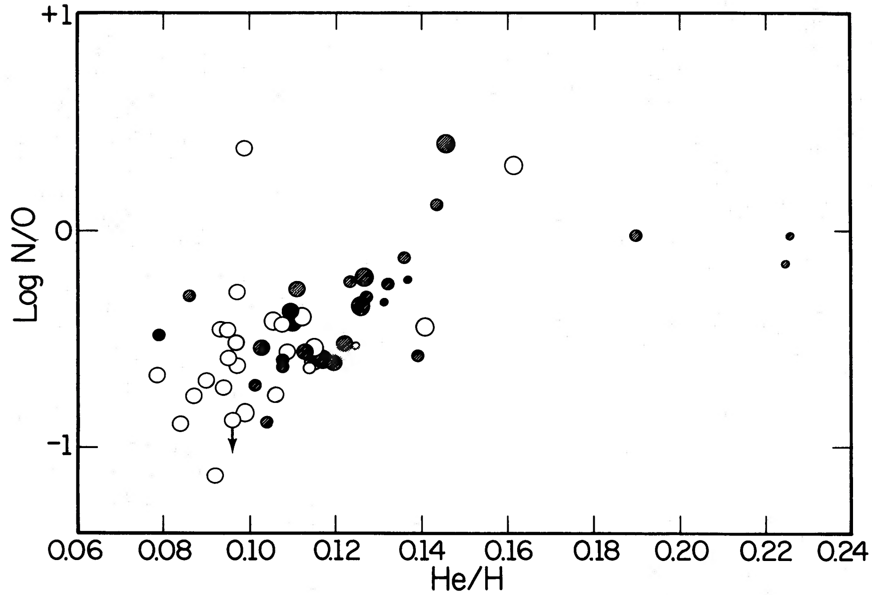

FIG. 4.—Log N/O plotted against He/H for galactic planetaries. *Open and filled circles*, nebulae with $|Z|$ less than and greater than 400 pc, respectively. For symbol sizes, see the caption to Fig. 1.

R, $|Z|$, and $|v_r|$ are given for most of the nebulae by Kaler (1978*c*). Data for nebulae not in that list are given in Table 2.

The relations among N/O, He/H, and galactic parameters are examined in Figures 4–8. Figure 4 is taken from KIB and shows log N/O versus He/H, where the filled circles are disk nebulae with $|Z| <$ 400 pc. As pointed out by KIB, the disk planetaries are shifted to higher He/H and higher N/O in comparison with the halo objects, implying that the interstellar matter in the disk has been enriched over the initial matter in the halo. KIB and Kaler (1978*c*) both suggest a disk helium enrichment of about 20%, from 0.08–0.085 in the halo to 0.10–0.105 in the disk. It is evident from Figure 4 that interstellar N/O is also enriched in the disk, as was earlier suggested by Boeshaar (1975).

These enhancements can also be seen in Figure 5, where log N/O is plotted against $|Z|$. In this figure, the filled circles show nebulae with He/H > 0.12, the open circles show He/H < 0.10, and the crossed circles show $0.10 \leq$ He/H ≤ 0.12. Here, we see again that nebulae with high He/H are concentrated to the disk. There is also a general downward trend of N/O with increasing $|Z|$, which is reflected in the difference between the two groups of nebulae in Figure 4. For $|Z|$ less than or greater than 400 pc, the general minimum log N/O ≈ -0.7 and -0.9, respectively, so that the disk shows roughly a 50% enhancement. The downward trend of the minimum with increasing $|Z|$ seems secure. On the basis of the distribution of nebulae with $|Z| > 400$ we would expect 12 nebulae with $|Z| < 400$ pc, log N/O < -0.65; there are only two.

From Figure 5 it appears that the minimum N/O for the halo nebulae is roughly solar, and that for the disk objects is greater than solar. Becker and Iben (1979; see also KIB) show that all the nebulae should show N/O enhancements. The enrichment of surface layers in low-mass stars will occur on the first ascent of the giant branch. The minimum enrichment is about 50%, so that the original N/O for the disk stars that produced the planetaries is 50% lower, and roughly solar. The original N/O for halo planetaries then becomes subsolar, as would be expected.

The different correlation characteristics for the two groups is somewhat difficult to see in Figure 4, so log N/O versus He/H is replotted for each group separately in Figure 6. The lines drawn in the figure are theoretical curves, and are discussed later. The halo nebulae ($|Z| > 400$ pc) are shown in Figure 6*a* (*upper*) and the disk nebulae in Figure 6*b* (*lower*). We see that the correlation is clearly better for the disk nebulae than it is for the halo nebulae, especially if the two left-hand points in the plot for the disk are ignored. These are both high-velocity nebulae which may simply be passing through the disk. The halo nebulae alone do not show a very clear correlation, probably because they display a range of initial He/H and N/O ratios which smears the correlation. The correlation for disk objects is clearer because their parent stars had more similar compositions. The range in N/O and He/H for disk nebulae is due more to individual enhancement, although part of the scatter, especially for N/O, may still be due to galactic effects. The N/O ratio is also still certainly affected by ionization effects to some degree, and some scatter is introduced by the approximations to T_e[N II] when a measurement is not available.

The nebulae are replotted (log N/O versus He/H) in Figure 7, and are now coded according to population type. The filled circles are Population I, as

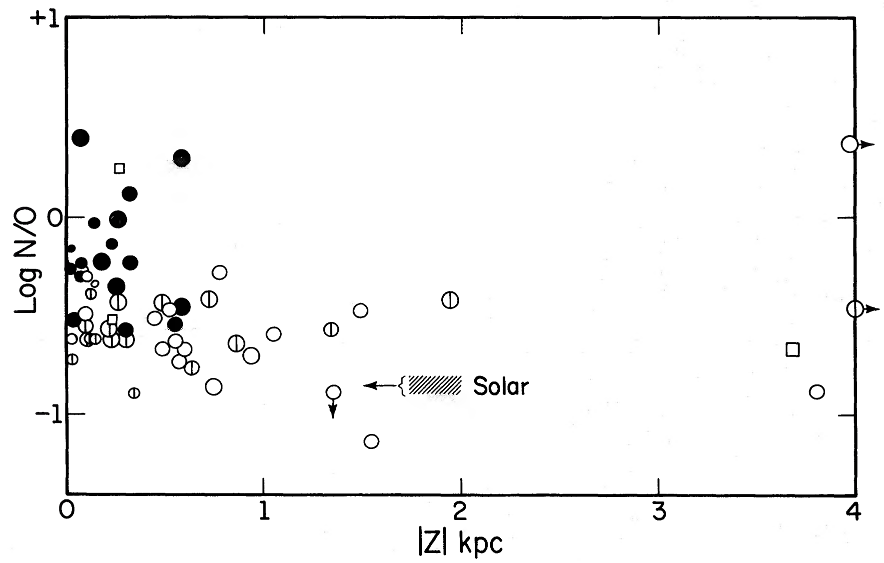

FIG. 5.—Log N/O plotted against $|Z|$ in kpc. *Filled and open circles*, nebulae with He/H > 0.12 and less than 0.10, respectively; *symbols with vertical line*, nebulae with 0.10 ≤ He/H ≤ 0.12. For symbol sizes, see legend to Fig. 1.

described above ($R < 12$ kpc, $|Z| < 1$ kpc, $|v_r| < 70$ km s^{-1}). The open circles are Population II. The half-filled circle is Pb 4, whose population is unknown, since v_r has not been measured. The Magellanic Cloud planetaries are again plotted in this figure; the Large Cloud planetaries as boxes, the Small Cloud objects as triangles. The Magellanic Cloud nebulae show little correlation by themselves, probably because of high observational error. If Webster's (1976) points, which probably have the lowest accuracy, are removed, the remaining four points do fit the correlation. In Figure 7, we again see that the disk Population

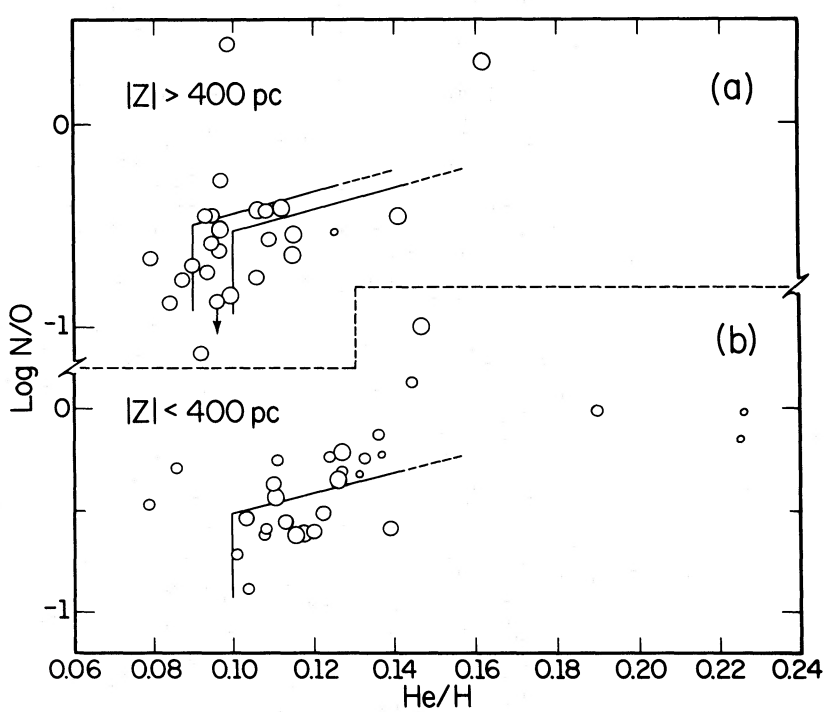

FIG. 6.—Log N/O plotted against He/H separately for nebulae with $|Z| > 400$ pc (Fig. 6*a*, *upper*) and $|Z| < 400$ pc (Fig. 6*b*, *lower*). *Lines*, theoretical curves. The end of the solid line on the right indicates abundances for a star of 7 $M_\odot$, $Z = 0.02$. The end of the dotted line indicates 7 $M_\odot$, $Z = 0.01$. The break in the curve occurs at about 3 $M_\odot$. Symbol sizes are explained in Fig. 1.

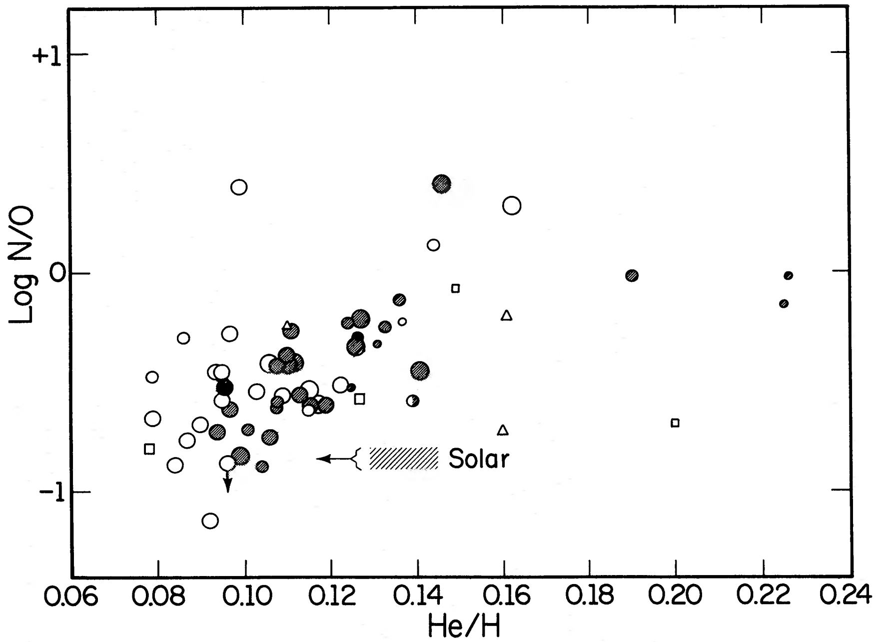

FIG. 7.—Log N/O plotted against He/H, with population type indicated. *Circles*, *boxes*, and *triangles*, galactic, LMC, and SMC planetaries, respectively; *filled and open circles*, Population I ($R < 12$ kpc, $|Z| < 1$ kpc, $|v_r| < 70$ km s^{-1}) and Population II, respectively; *half-filled circles*, unknown population. See Fig. 1 for an explanation of symbol sizes.

I nebulae are shifted to higher He/H. The shift to higher N/O is not apparent here because the definition of the disk is extended to 1000 pc.

The nebulae, now grouped according to population, are plotted separately in Figure 8. The top (Fig. 8*a*) and middle (Fig. 8*b*) plots are for Population II and Population I, respectively. Again, the disk Population I nebulae define a clearer correlation than do the halo objects, for the same reasons as given above for the difference between high and low $|Z|$ nebulae.

The lowest plot, Figure 8*c*, exhibits the restricted disk, Population I′ ($|Z| < 400$ pc) nebulae. This plot should be compared to Figure 6*b*, where *all* nebulae with $|Z| < 400$ pc are plotted. We see now that the correlation is even tighter. The scatter present in Figure 6*b* is reduced in Figure 8*c* because the high-velocity planetaries (and those with unknown velocity) have been removed. We also see that the lower limits to He/H are increased as we proceed from Figure 8*a* to Figure 8*c*, showing that the original He/H increases rather continuously as we approach the disk from the halo (see Kaler 1978*c*). The increase in minimum N/O as we go to Population I′ is not as clear as it was when we discriminated on the basis of $|Z|$ alone, as was done in Figures 5 and 6, but it is present. On the basis of the Population II′ distribution (where Population II′ is the counterpart of Population I′; the figure is not shown) we would expect over five Population I′ nebulae with $\log \mathrm{N/O} < -0.7$, and there are two. The reason for this difference in minimum N/O as found from Figures 5 or 6 and from Figure 8 is not clear. It may simply be due to the small number of nebulae which are Population I′.

In Figures 4 through 8 we are looking at evidence for two different correlations. The first involves the changes in composition of the interstellar gas out of which the stars are formed; as we approach the disk from the halo, interstellar N/O and He/H both increase. Second, we see a correlation between He/H and N/O which is caused by fusion processes within the parent stars, and which should reflect the initial masses of the stars. This correlation is evident primarily for Population I objects. The correlation is characterized by a strong concentration toward the theoretical curves with a few outlying nebulae (which are discussed in the next section). If we drop the nebulae with $\mathrm{N/O} > 1$ and $\mathrm{He/H} \geq 0.19$, a least-squares fit through the Population I points gives a highly significant correlation coefficient r of 0.73. It is about the same for the nebulae with $|Z| < 400$ pc, Figure 6*b*, if the two nebulae with the lowest He/H are dropped (these have high velocity, characteristic of halo objects). For the Population I′ points (again excluding the four outlying objects), r increases to 0.80. And if these four points are included in the Population I analysis, r is still 0.67. Although a least-squares fit is not really applicable (see the theoretical curves discussed in the next section), the high values of r show the reality of the correlation. Is this second correlation intrinsic or does it reflect only the interstellar correlation? The evidence is that it is intrinsic, since the correlation improves as we restrict ourselves to the disk. It should also not reflect radial galactic gradients in N/O and He/H. Although a radial N/O gradient may exist (Smith 1975; Hawley 1978*b*), Kaler (1978*c*) and Hawley (1978*b*) find no radial

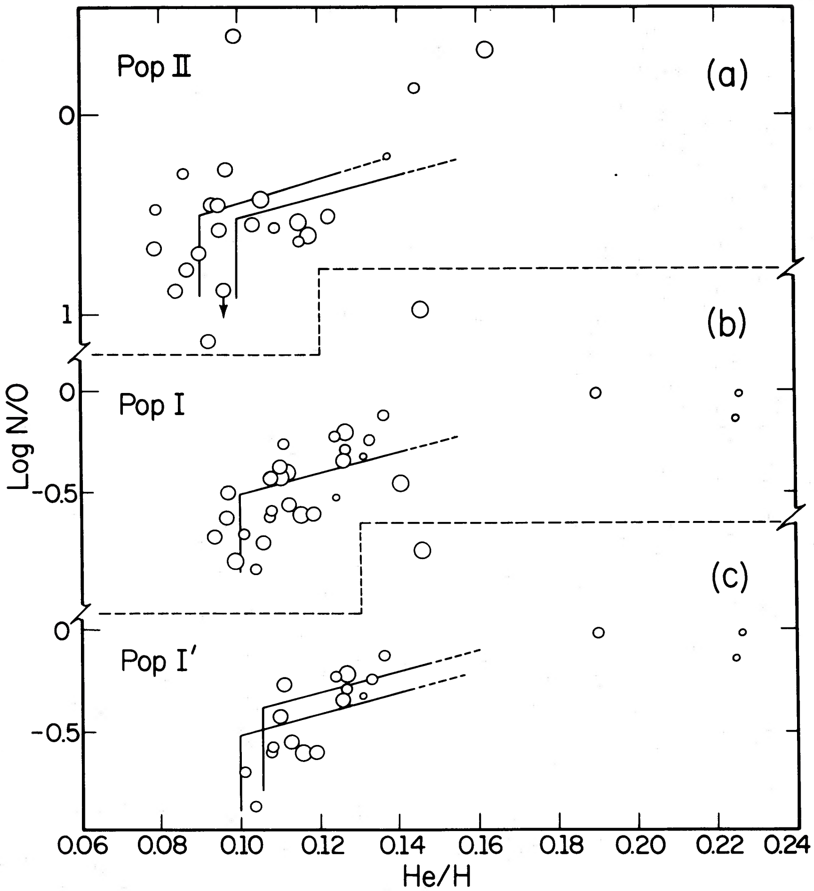

FIG. 8.—Log N/O plotted against He/H separately for nebulae of different population type. *Top* (Fig. 8*a*), Population II, based on $|Z| > 1000$ pc. *Middle* (Fig. 8*b*), Population I ($R < 12$ kpc, $|Z| < 1000$ pc, $|v_r| < 70$ km s^{-1}); *bottom* (Fig. 8*c*), Population I′ (same as above, except $|Z| < 400$ pc). Theoretical curves are indicated for different initial conditions (see Fig. 6). For an explanation of symbol sizes, see the caption to Fig. 1.

He/H gradient. In addition, KIB show that the correlation agrees with theoretical predictions for stellar surface enhancements of N and He.

c) *Theoretical Implications*

KIB and Becker and Iben (1979) discuss the theoretical implications of the correlations presented in the last section, and the reader is referred to those papers for details. Theoretical curves adapted from KIB and Becker and Iben (1979) are placed in Figures 6 and 8 for a variety of initial conditions. The mass of the star increases upward and then to the right. The break in the curves occurs at about 3 $M_\odot$, the exact value depending upon the fractional mass Z of heavy elements. The end of the solid line on the right indicates a star of 7 $M_\odot$ at $Z = 0.02$, and the end of the dotted line shows one of 7 $M_\odot$ at $Z = 0.01$. We see that for the disk planetaries, Figures 6*b* and 8*b*, the fit is good. The observed slope seems to be somewhat steeper than the theoretical. This feature is especially noticeable for the restricted Population I′ in Figure 8*c*; it is not known whether it is real, or whether it is due to an insufficient number of observations. In Figure 8*c* the planetaries for which He/H > 0.12 are fitted well with initial conditions He/H = 0.105, log N/O = −0.8. If we use initial log N/O = −0.7, indicated by Figure 5, the theoretical curve is too high for the nebulae with He/H > 0.12. A halo-disk increase in N/O of ~25% rather than the 50% estimated from Figure 5 may be more reasonable. Clearly, we must be careful here about trying to draw conclusions that are too fine. There are too few Population I′ points and it is likely that ionization effects still enter into the $N/O = N^+/O^+$ relation. More observational work should be done on disk nebulae.

KIB suggest that stars must have masses greater than 3 $M_\odot$ before helium is enriched, which happens the second time up the giant branch. The mass of the star increases rightward along the nonvertical portion of the curve. The maximum mass which can produce a planetary is indicated by the right-hand edge of the point distribution, which seems to be in the neighborhood of 6 $M_\odot$, or He/H ≈ 0.14. There are two problems to be considered, both of which involve the distribution of points as He/H increases. The first pertains to the distribution up to the above limit of He/H ≈ 0.14. If the correlations in Figures 6*b* and 8*b* represent a stellar mass sequence increasing to the right, we should expect the number of observed points to fall off in accord with the Salpeter (1955) mass function, or $N(M) \sim M^{-2.35}$, where M is the initial stellar mass and $N(M)$ is the number of nebulae per unit stellar mass interval. First the distribution of Population I points is converted to a distribution in initial stellar mass through the theoretical curves in Figures 6*b* and 8*b*. Then in order to increase the numbers, the nebulae in Table 1 with measured He/H, but for which N/O could not be determined, can be added in. The distribution in He/H (which excluded the three high error points, and to which NGC 2346 and NGC 6853 should be added) can be seen in Kaler (1978*c*). If we normalize the observed and theoretical distributions at 4 $M_\odot$, the two match reasonably well between 4 and 7 $M_\odot$; however, there is a serious deficiency of observed points at 3 $M_\odot$ (below which limit no fresh helium is brought to the surface). A probable reason is that for Population I nebulae there is still a mixture of nebulae with varying initial He/H ratios, i.e., a mixture of halo and disk objects. A better check on the distribution is obtained if we further restrict ourselves to the disk and to a more uniform set of initial conditions, that is, to Population I′. For the (He/H–mass) conversion we should use the upper curve in Figure 8*c* which begins at He/H = 0.105 (and which indicates a lower maximum stellar mass limit than the curve in Fig. 8*b*). Kaler (1978*c*) shows the distribution, again without the nebulae mentioned above. The fit, normalized to an average of 3 and 4 $M_\odot$, is qualitatively reasonable, but we are now hampered by a paucity of points. The distribution of nebulae in He/H will provide a good test of the theory for enrichment of He and N, and the number of Population I′, or extreme-disk nebulae observed should be substantially increased.

The second problem involves the points that fall off the main stream of the correlation. In Figures 4 and 7 we see that three high-weight points fall above log N/O > 0.2; from the left they are BB 1, NGC 2440, and Me 2–2. The latter two fit the correlation in the sense that they both have high He/H and N/O, but they have much higher N/O than expected from the general run of nebulae and from the theoretical prediction. Quite possibly an ionization effect is involved such that $N^+/O^+ > N/O$. Or there may be unusual stellar processes at work. Note that BB 1, which shows the highest anomaly in N/O, is also the only object to show an anomalously high Ne/O ratio (see Kaler 1978*b*), a fact which, of course, may be entirely accidental. Note also that IC 3568 at He/H = 0.092 may also exhibit an ionization effect. It is seen in Figure 2 as the low point at $\log T_* = 4.79$, and may be the extreme point in the N^+/O^+ versus $\log T_*$ correlation discussed in § III.

Finally, there are six nebulae which fall significantly above the He/H limit for a 7 $M_\odot$ star. Four of these are shown in the figures: Me 2-2 at He/H = 0.162; Population II; NGC 7293 at He/H = 0.19; and NGC 6445 and NGC 6302, which have He/H > 0.2. The last three are Population I. The observations all seem reliable. Me 2-2 was observed to have high He/H by both Barker (1978*a*) and Kaler (1976*a*). Hawley's (1978*a*) observations of NGC 7293 give consistently high values from several helium lines at several positions within the nebula. NGC 6445 and NGC 6302 are given low weight because their N/O ratios are not well determined, but the high He/H ratio seems secure. Aller, Czyzak, Craine, and Kaler (1973) observed several He I lines in NGC 6445 which give consistent results, and NGC 6302 has been observed by both Oliver and Aller (1969) and Danziger, Frogel, and Persson (1973) to have high helium. Two more high points can be added from Table 1: Hu 1–2 at He/H = 0.170, and Pb 6 at He/H = 0.187. Pb 6 has been observed only once, but a high He/H for Hu 1–2 is confirmed by observations made by D'Odorico, Rubin, and Ford (1973) and Aller (private communication).

The three nebulae with He/H ≥ 0.19 fall roughly on the extended line determined from the correlation in Figure 8*b*. We cannot, however, fit these points by increasing the stellar mass. Theoretically, a star of higher mass for which $Z \leq 0.02$ (see Figs. 7 and 8, and Becker and Iben 1978) evolves too rapidly to dredge up a large amount of helium. These points could be fitted only if the initial He/H were very high ($Y \approx 0.36$, He/H ≈ 0.145; see KIB), but there is no evidence for initial helium this high. The explanation of convective dredging offered by KIB to explain the enhancements may have to be supplemented by second-order processes.

The question here is whether there is a sharp curtailment of points at He/H ≈ 0.14 with a few objects tailing out to higher He/H, or whether there is a continuous distribution. The distributions shown in Figures 4 and 7 indicate a well-defined cutoff at He/H ≈ 0.14, 6 $M_\odot$; the more complete data presented by Kaler (1978*c*) show a somewhat similar, though less clear, effect. The question can be resolved only through further observation.

V. OXYGEN IONIZATION

Figure 1 showed the possibility of a relation between N^+/O^+ and O/O^+, which might imply that $N/O \neq N^+/O^+$. Values of O/O^+ are plotted against He/H in Figure 9. The shaded circles are nebulae for which $\log T_* > 4.65$, Ex < 0.5, and the open circles are the higher excitation objects with Ex ≥ 0.5. There is a great deal of scatter, but a negative correlation is present for each of the groups. Note that the higher excitation group lies at higher O/O^+, as might be expected.

For each group, as He/H increases, we find more oxygen in the O^+ state. The origin of the correlation is not known, but we might speculate that an increase in helium will modify the star's radiation field by absorbing more high-energy photons, resulting in a lowering of the ionization level of oxygen, and of other heavy elements. The weak correlation between

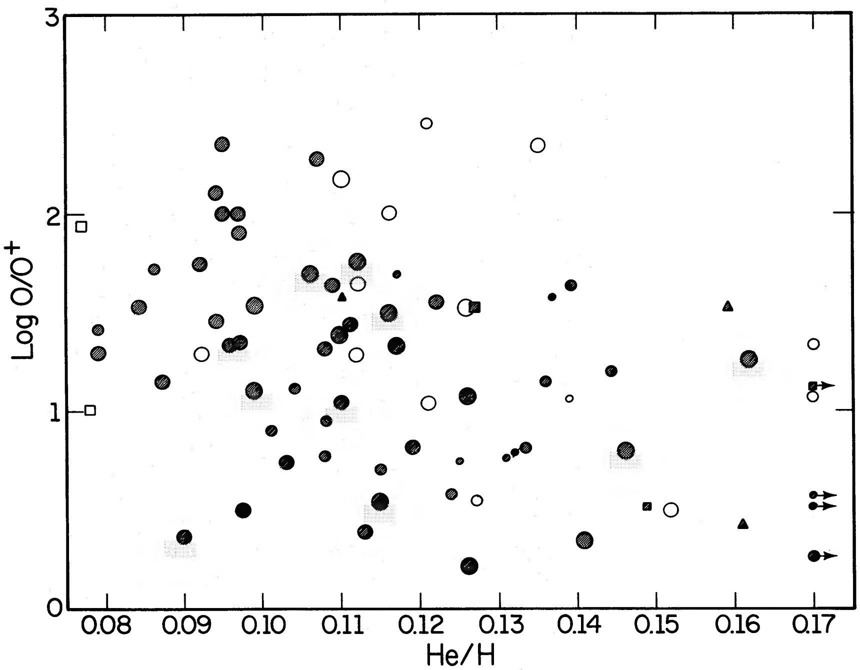

FIG. 9.—Log O/O^+ plotted against He/H. *Circles*, *boxes*, and *triangles*, galactic, LMC, and SMC planetaries, respectively; *filled circles*, log $T_* > 4.65$, Ex < 0.5; *open circles*, Ex ≥ 0.5. For an explanation of symbol sizes, see the caption to Fig. 1.

N^+/O^+ and O/O^+ seen in Figure 1 can now be understood. The primary correlation is between O/O^+ and He/H, seen in Figure 9, which is then reflected through the (N/O, He/H)-correlation of Figure 4 to yield the secondary correlation of Figure 1. Thus, there is apparently no physical relation between N^+/O^+ and O/O^+.

The following question must now be considered. If the correlations of Figures 1 and 9 are in fact both primary and due to ionization effects, might they not combine to give a false correlation between N^+/O^+ and He/H? The answer is that is seems extremely unlikely. First, the correlations in Figures 1 and 9 are weak, with much scatter, whereas those in Figures 4, 6, 7, and 8 are quite clear. Second, if the (N/O, He/H)-relation were due to an ionization effect involving a modification of the radiation field by increased He, we would expect it to be the same for each population type, that is, independent of whether we choose nebulae in the disk or in the halo. The fact that the correlation improves as we confine ourselves to the disk indicates that it is not an ionization effect.

VI. THE RADIAL N/O GRADIENT

A number of investigations have shown that radial abundance gradients exist within the planes of spiral galaxies. For example, Searle (1971), Shields (1974), Smith (1975), and Shields and Searle (1978) all show that O/H and N/H decrease outward from galactic centers. Smith (1975) shows that N/O drops by a factor of about 4 from the center to the edge in M101 and M33. Peimbert, Torres-Peimbert, and Rayo (1977) and Hawley (1978*b*) find qualitatively similar gradients in our galaxy from studies of diffuse nebulae, as do Peimbert and Torres-Peimbert (1977) from a study of planetaries.

Figure 10 shows log N/O plotted against the distance from the galactic center, projected onto the plane, the latter taken from Kaler (1978*c*) and Table 2. According to Becker and Iben (1979; see also KIB), all planetaries should show some nitrogen enrichment. In order to choose the least enriched, nebulae with low He/H were chosen. Population II nebulae with He/H < 0.10 are shown in Figure 10 as half-filled circles; Population I with He/H < 0.11, as filled circles.

For the total set of low He/H objects, no significant correlation is found between N/O and *R*. Of the 22 low-helium nebulae, half are halo objects. If we wish to examine the gradient in the disk, we should choose true disk, or population I, nebulae. For this figure, nebulae with $R > 12$ kpc are considered to be Population I if they have $|Z| < 1000$ pc, and $|v_r| < 70$ km s^{-1}. These 11 nebulae show no trend, but the number is too small for a significant study. With one exception, they are all bunched between 8 and 11 kpc. Considering that the enrichment process may make planetaries generally unsuitable for this kind of study, and that estimates of N/O ratios from diffuse nebulae may be open to question because of low central-star temperatures (see § III), the radial galactic N/O gradient, or at least the numerical value of the gradient, seems somewhat insecure.

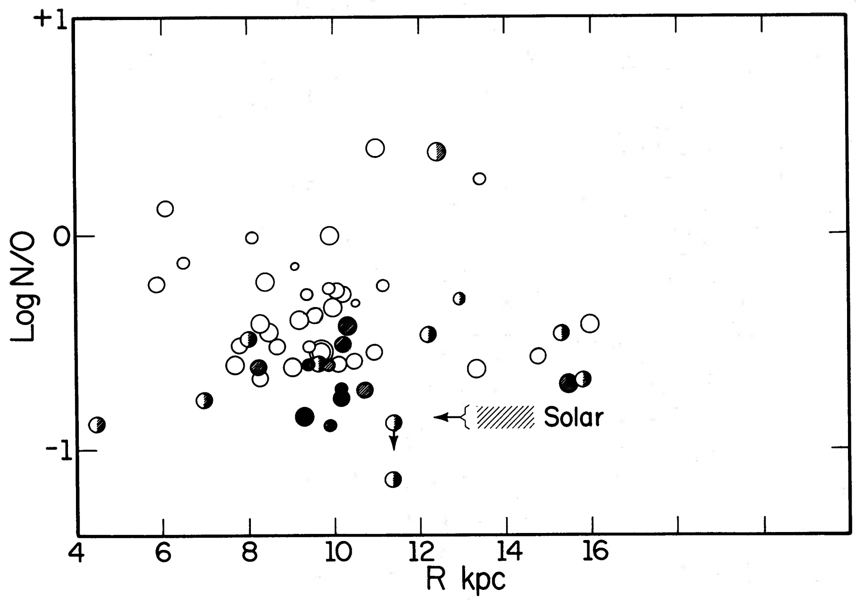

FIG. 10.—Log N/O plotted against distance from the galactic center projected onto the plane *R*. *Half-filled circles*, Population II nebulae for which He/H < 0.1; *completely filled circles*, Population I nebulae for which He/H < 0.11, for which N/O enrichment should be minimal. For an explanation of symbol sizes, see Fig. 1.

VII. SUMMARY AND DISCUSSION

The principal observational conclusions of this paper are as follows: (1) For medium excitation planetaries ($\log T_* > 4.65$, $He^{2+}/He < 0.5$), it is generally true that $N^+/O^+ = N/O$, at least roughly to within the accuracy of the observations. (2) For nebulae with $\log T_* < 4.65$, the N^+/O^+ ratio is negatively correlated with T_*, implying that $N/O \neq N^+/O^+$. For Ex ≥ 0.5, N/O may also not equal N^+/O^+. (3) Based on the medium-excitation planetaries, N/O is clearly correlated with He/H. The correlation becomes stronger when the sample of nebulae is restricted to the disk. (4) Initial N/O and He/H ratios increase by ~25–50% and ~20%, respectively, as we approach the disk from the halo. (5) O/O^+ is negatively correlated with He/H. (6) There is no evidence from planetaries of a radial N/O gradient, possibly because the sample is too small.

What is presented here is a consistency argument. We say that $N/O = N^+/O^+$ for medium-excitation nebulae because for these objects there exists a strong correlation between He/H and N/O which is also expected on theoretical grounds. If $N^+/O^+ \neq N/O$, we would not expect a correlation unless it were due to some ionization effect. This latter might be a possibility, since O/O^+ does correlate with He/H. But the (N/O, He/H)-relation improves as we restrict ourselves to disk planetaries. If the correlation were an ionization effect, it should be equally present among halo objects.

The data are consistent with galactic variation in N/O and He/H in the sense that the interstellar matter of the disk has become enriched in N and He as compared with the initial matter of the halo. They are also consistent with helium and nitrogen enhancements in the surface layers of individual stars before planetary ejection, where the degree of enhancement is related to the initial stellar mass. The existence of the (N/O, He/H)-correlation strengthens Kaler's (1978*c*) contention that He/H ratios of planetaries above the minimum for a given distance from the galactic center are due to helium enrichments.

The data indicate that stars initially as massive as $\sim 6\, M_\odot$ can produce a planetary. However, the existence of some nebulae with very high He/H means that some process in addition to simple convective dredging might be at work, so that the limiting mass may not be this high. Finally, even though the limiting initial masses of planetary central stars may be open to some question, the good fit between the observations and Becker and Iben's (1979) surface abundances provides a good, apparently successful, test for the theory of the late stages of stellar evolution.

Directions for further work are suggested. The data which enter into the (N/O, He/H)-correlation for medium-excitation nebulae need to be improved, so that they can be compared better with the theoretical predictions. In particular, our knowledge of T_e[N II] needs improving. The correlation between N^+/O^+ and $\log T_*$ for $\log T_* < 4.65$ is not understood; nor do we yet know why the correlation between He/H and N^+/O^+ for high excitation nebulae is poor. The relation between O/O^+ and He/H should be examined in more depth. The origin of He/H ratios in the neighborhood of 0.2 must also be investigated. Finally, we need to improve our knowledge of the numerical distribution of nebulae as functions of He/H and N/O, and to determine better the limits on the values.

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