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THE OXYGEN ENRICHMENT OF THE GALAXY

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ABSTRACT

Oxygen-to-hydrogen ratios are calculated for the 97 planetary nebulae for which there are sufficient data and for which the correction for unobserved ionization states is not too large. As a part of this study, emission-line fluxes are presented for 19 planetaries. The ratios are strongly correlated with population type. Almost all planetaries with absolute LSR radial velocity greater than about 85 km s^{-1} and distance from the galactic plane greater than 1 kpc have low O/H; high values of O/H are confined to the galactic disk. The radial gradient within the disk is not easily discerned from the planetaries. An apparent gradient is seen because the planetaries with distances from the galactic center greater than about 11 kpc are dominantly halo objects with high velocity or large distance from the plane. The planetaries are divided into relative age groups which depend upon the nebular velocities, distances from the galactic plane, excitation levels, and He/H ratios. The mean O/H for each group increases with decreasing age. The available evidence shows that this effect is not due to nuclear processing in individual stars and is consequently an effect of galactic evolution. Galactic O/H has increased by a factor of between 5 and 10 from the time of the formation of the early halo to the present, consistent with earlier studies. The relative oxygen enrichment rate of the Galaxy is characterized by a large early increase from the old to the intermediate halo, followed by a smaller but steady relative enrichment rate among the identified age groups.

Subject headings: galaxies: Milky Way — galaxies: structure — nebulae: planetary

I. INTRODUCTION

The variation of the oxygen-to-hydrogen ratio in the Galaxy has been closely examined in a number of papers over the past several years by the analysis of the spectra of gaseous nebulae. From a study of planetary nebulae, Kaler (1970) found that O/H tended to decrease with increasing velocity and distance from the galactic plane. From a new examination of 37 planetary nebulae, Barker (1978*a*) negated the above conclusion and suggested that planetaries all tended toward the same O/H no matter what their kinematical properties. However, Peimbert (1973), Hawley and Miller (1978), and Torres-Peimbert and Peimbert (1979) have each examined one or more of the three extreme halo planetaries and found that their oxygen abundances are up to a factor of 10 deficient as compared with those of disk planetaries or the Sun.

Torres-Peimbert and Peimbert (1977, hereafter TPP) found what appeared to be a radial O/H gradient in the galactic disk, also from a study of planetaries, which was consistent with such gradients found in other galaxies by, for example, Searle (1971), Smith (1975), and Shields and Searle (1978). The concept of a negative radial gradient is in fact supported by studies of diffuse nebulae by Peimbert, Torres-Peimbert, and Rayo (1978, hereafter PTPR), Hawley (1978*b*), and Talent and Dufour (1979).

An increase in the Galaxy's oxygen abundance with time is expected theoretically, as oxygen is steadily produced by supernovae; see, for example, Tinsley (1979). Thus we might expect a continuously changing O/H ratio as we proceed from the oldest members of the Galaxy to the youngest. Various papers, such as those by Conti *et al.* (1967), Peimbert (1973), and Sneden, Lambert, and Whitaker (1980) indicate that old populations are relatively poorer in metals than they are in oxygen, implying a more rapid initial buildup of the latter. Thus it is of considerable importance to try to establish the details of the enrichment of galactic oxygen. The planetary nebulae are ideal objects for the examination of O/H variations. First, the O/H ratio found in a planetary should, except in extreme cases, be nearly the same as the original ratio with which the star was born. Second, planetary nebulae can be seen for great distances, they are found in both the halo and the disk, and they are produced by stars which have a very wide spread in ages. For example, a very old star must have produced the planetary in the globular cluster M15. But planetary nebulae can also be produced by quite young stars, as many of them are highly enriched in helium (Kaler 1978*a*). Becker and Iben (1980, hereafter BI) show that this enrichment can be produced only by relatively massive stars ($M > 3\ M_{\odot}$) which are certainly less than 10^9 years old. Diffuse nebulae, on the other hand, represent only the youngest component of the Galaxy. Finally, O/H can be found easily and accurately from planetaries, whereas its determination from stellar spectra is still difficult.

The purpose of this paper is to make as complete an assessment of O/H in planetaries as is possible, by making use of all the available reliable data. Section II treats the calculation of the abundances and observational data, and § III considers correlations with regard to various galactic parameters. The influence of the progenitor star on the nebular O/H and the variation of O/H in the Galaxy with time are discussed in § IV. Finally, a summary is presented in § V.

II. DATA AND ABUNDANCES

The values of O^+/H^+ and O^{2+}/H^+ are calculated in a straightforward manner from the ratios of the intensities of λ3727 [O II] and λ4959 + λ5007 [O III] to that of Hβ. The method of calculation is given in detail by Kaler (1978*b*), § II*b*. References to the atomic data can be found there as well. The abundance of the unobserved higher ionization states is estimated from Seaton's (1968) suggestion that

$$\frac{O^{3+} + O^{4+} + \cdots}{O^+ + O^{2+}} = \frac{He^{2+}}{He^+} \qquad (1)$$

as a result of the close coincidence of ionization potentials. The total O/H ratio is then the sum of the ionic ratios.

Criteria for selection of nebulae were (1) either accurate He/H ratios must be known, or it must be certain that He II λ4686 is weak or absent; (2) the correction in equation (1) must not be large in order to avoid errors in the estimation of the abundances of higher ionization states. Harrington's (1969) model shows that the relation is very good at $He^{2+}/He^+ = 0.86$. Nebulae were chosen only if $He^{2+}/He^+ \leq 1$, which is probably conservative. There are currently sufficient data so that these criteria are met for 97 planetary nebulae.

The data were taken from Kaler's (1976*a*) catalog, from Kondratyeva (1978, 1979), Sabbadin (1977), Hawley (1978*b*), Hawley and Miller (1978), Torres-Peimbert and Peimbert (1979), Kaler (1976*b*, 1978*a*), TPP, Barker (1978*b*), and Aller and Czyzak (1979, hereafter AC). Where possible, the data were taken all from one source, and the last three references above were given precedence. Where one object was observed by more than one of these three references, the individual O/H values were averaged. See the above references also for information on interstellar extinction. Helium abundance ratios were taken from Kaler (1978*a*, 1979), this paper (see below), and AC.

Additional new data are derived from recent observations at the University of Illinois Prairie Observatory by means of interference filter photometry (Kaler 1976) and are presented in Table 1. The first three

TABLE 1

OBSERVED FLUXES

Nebula	PK	-log F(Hβ) ergs cm^{-2} sec^{-1}	I(λ), I(Hβ) = 100 λ6584 [NII]	λ6563 Hα	λ4959 [OIII]	λ4686 He II	λ4471 He I	λ3727 [OII]	Notes
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	
NGC 6309	9+14°1	11.17±.01					2.1±1.7		
6629	9- 5°1	10.81±.02			247± 8		5.9±1.2		
6644	8- 7°2	11.00±.01					4.2± .4		
6751	29- 5°1	11.57±.02					5.5± .8		1
6778	34- 6°1	11.12±.01	313±41	646± 50	207±10		6.7± .4		
6804	45- 4°1					85 ± 4	<1.9		
6807	42- 6°1	11.48±.01[a]					4.8± .7		
6818	25-17°1	10.47±.01			622±30	47 ± 9	2.7± .3	46± 3	2
6886	60- 7°2	11.31±.01[b]					4.3± .4		
6891	54-12°2	10.68±.01			296± 4		5.6± .3		
7008W	93+ 5°1	10.82±.03	19±14	600±170	337±22	102 ± 6			3
7008B				644±195		105 ± 3	1.6±1.0		4
7354	107+ 2°1	11.51±.01[b]				34 ± 1	2.7± .7		
NGC 7662	106-17°1	9.99±.01				46.7±.2	3.6± .2		
IC 4776	2-13°1	10.67±.05			345±14				
A 35	303+40°1	11.30±.05[b]			111±30			430±40	5
J 900	194+ 2°1		78± 8	473± 16		35 ± 2		33± 3	
Vy 1-2	53+24°1	11.53±.01					3.9± .6	24± 4	
Vy 2-2	45- 2°1	11.54±.01[a]			272±17		4.6±1.1	11± 2	
Vy 2-3	101-13°1	12.00±.02[a]			370±30	6 ± 8		29±14	

[a]First photoelectrically measured Hβ flux.

[b]Replaces value in Kaler (1978).

NOTE: 1. 2.1 times fainter than given by Collins, Daub and O'Dell (1961)
2. 2.2 times fainter than given by Collins, Daub and O'Dell (1961)
3. whole nebula
4. bright know NW of central star with 40" aperture
5. I(λ6584)[NII]/I(Hα) = 1.22

TABLE 2

HELIUM-TO-HYDROGEN RATIOS

Nebula (1)	c (2)	t (3)	log N_e (4)	He^+/H^+ (5)	He^{2+}/H^+ (6)	He/H (7)
NGC 6309	0.07	1.35	3.62	0.044 ± 0.036	0.061 ± 0.007[a]	0.105 ± 0.037
NGC 6629	0.89	0.85	3.26	0.143 ± 0.030		0.143 ± 0.030
NGC 6644	0.41	1.22	3.86	0.094 ± 0.009	0.018 ± 0.001[a]	0.112 ± 0.009
NGC 6751	0.86	1.0	<3	0.131 ± 0.020		0.131 ± 0.020
NGC 6778	0.30	1.17	3.40	0.148 ± 0.009	0.004[a]	0.152 ± 0.009
NGC 6807	0.27	1.17	3.6	0.103 ± 0.015		0.103 ± 0.015
NGC 6818	0.26	1.27	3.58	0.058 ± 0.006	0.042 ± 0.003	0.100 ± 0.007
NGC 6886	1.13	1.29	4.00	0.112 ± 0.010	0.039 ± 0.001[a]	0.151 ± 0.010
NGC 6891	0.30	1.00	3.40	0.120 ± 0.007		0.120 ± 0.007
NGC 7008	0.96	1.25	3.53	0.041 ± 0.027	0.099 ± 0.003	0.140 ± 0.027
NGC 7354	1.81	1.2[b]	3.8	0.083 ± 0.022	0.035 ± 0.001	0.118 ± 0.022
NGC 7662	0.19	1.3	3.69	0.077 ± 0.044	0.041	0.118 ± 0.004
J900	0.83	1.20	3.76	0.061 ± 0.004	0.033 ± 0.002	0.094 ± 0.004
Vy 1–2	0.06	0.93	3.90	0.077 ± 0.013	0.020 ± 0.001[a]	0.097 ± 0.014
Vy 2–2	1.48	1.49	3.00	0.140 ± 0.035	0.033[a]	0.143 ± 0.035

[a] $I(\lambda4686)$ from KC, Barker (1978*b*), Ahearn (1978), or AC.

[b] T_e estimated.

columns give the nebula's name, the Perek-Kohoutek (1971) number, and the logarithm of the Hβ flux (calibrated to Capriotti and Daub's 1960 Hβ flux for NGC 7027; see Kaler 1978*a*). Columns (4) through (9) then give relative intensities of various emission lines on the scale $I(H\beta) = 100$. The two red lines, Hα and λ6584 [N II], were observed by means of three new red filters. Two, centered at λ6563 and λ6584, were used to observe the lines, and one in a line-free region at λ6503 was used to subtract the underlying continuum. Each of the two line filters pass both lines. The transmission characteristics were calibrated by observing two planetaries: IC 418, which has a strong and accurately known [N II]/Hα intensity ratio, and NGC 3242 for which [N II] is practically absent. The results are corrected for air temperature and radial velocity. The last column gives references to notes.

From the data of Table 1 we can compute additional helium-to-hydrogen ratios needed in the O/H calculation and which will be needed in § IV. These ratios are derived by the method outlined by Kaler (1978*a*) and are shown in Table 2. The first four columns give the nebula's name, the extinction constant c, the electron temperature times $10^{-4}t$, and the log of the electron density N_e. Values of He^+/H^+, He^{+2}/H^+, and He/H are given in columns (5), (6), and (7). For some nebulae, $I(\lambda4686)$ was taken from the work of others; see Kaler (1978*a*). For NGC 7008, c is calculated from the Hα/Hβ ratio in Table 1.

The compilation of O/H ratios is given in column (2) of Table 3. For six of these objects, indicated by footnote a, N_e is well over 10^4 and is inaccurately known, making O/H unreliable. These are presented as "half-weight objects," as are A35, M1–64, and NGC 6818. For the last object the AC data violated criterion (2) above, and O/H is quite uncertain. The electron temperature has not been measured for six objects (indicated by footnote b). For these, T_e was estimated from the ionization level of the nebula (see Kaler 1978*b*). This procedure is reasonably reliable, but the O/H for these nebulae is still clearly not as good as it is for the others.

Because of the mix of data, errors on individual O/H ratios are hard to estimate. The corrected line intensities are certainly good to better than ±10%. The [O III] electron temperatures are generally well-determined, and even an error as large as 1000 K, which is unlikely, produces an error in O^{2+}/H^+ of only about ±25%. The largest sources of error lie in the occasional lack of the [N II] temperature, and in the sensitivity of the O^+/H^+ ratio to N_e when it is high, mentioned above. Since most of the oxygen is usually in O^{2+}, these effects are not usually important. Generally, the O/H ratios of Table 3 should be correct to within about ±20%. In any case, since the work described below involves averages of individual O/H ratios, random errors, at least, can be evaluated by the averaging process itself.

Column (3) contains values of He/H, where the AC data are averaged into those presented in Table 1 and by Kaler (1978*a*, 1979). AC is given equal weight with TPP and Barker (1978*b*) and double the weight of the interference filter photometry since AC observed three He I lines. Column (4) shows N/O ratios in cases where they will be needed later, taken from Kaler (1979), or calculated from AC or Kondratyeva (1978).

The last column of Table 3 contains the radial velocity of the nebula with respect to the local standard of rest, v_r(LSR), where the basic solar motion given by Mihalas and Routly (1968) was used. Heliocentric radial velocities were taken from Perek and Kohoutek (1971), Bohuski and Smith (1974), and Acker (1975). These data are used in the next section.

III. GALACTIC OXYGEN DISTRIBUTION

The oxygen-to-hydrogen ratios are plotted against $|v_r(\text{LSR})|$ from Table 3 in Figure 1. The nebulae are

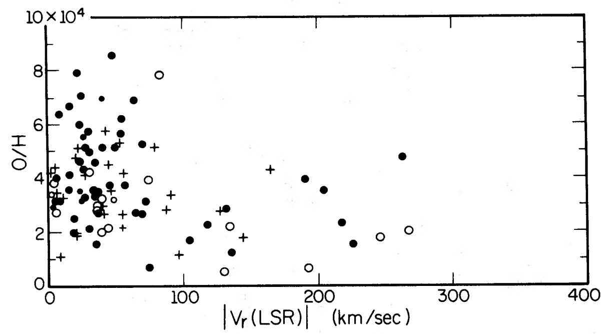

FIG. 1.—Values of O/H plotted against the absolute radial velocity of the nebula measured with respect to the local standard of rest, $|v_r(\mathrm{LSR})|$. *Filled circles:* $|Z| < 400$ pc; *crosses:* $400 < Z < 1000$ pc; *open circles:* $|Z| \geq 1000$ pc.

divided into three groups, depending upon distance from the galactic plane, $|Z|$: $|Z| < 400$ pc, $400 < |Z| < 1000$ pc, and $|Z| \geq 1000$ pc, each plotted according to the legend in Figure 1. This figure shows a number of salient points. First, and most important, is a sudden drop in O/H, as $|v_r(\mathrm{LSR})|$ increases, at about 85 km s^{-1}. Above 85 km s^{-1} there is only one nebula out of 20 with O/H $> 4 \times 10^{-4}$, whereas below this value 45% of the nebulae have O/H $> 4 \times 10^{-4}$. A χ^2 test shows that the random probability of obtaining this distribution is less than 0.005. Second, the objects with $|Z| > 1$ kpc are also generally confined below O/H $= 4 \times 10^{-4}$. Third, the nebulae with $|Z| < 400$ pc have the highest maximum O/H. The maximum O/H for each $|Z|$-group is progressively higher as $|Z|$ decreases. Finally, the behavior of O/H versus $|v_r(\mathrm{LSR})|$ is qualitatively the same for each of the two groups with $|Z| < 1000$ pc.

The variation with $|Z|$ can be seen better in Figure 2 where O/H is plotted directly against this parameter. Values of $|Z|$ are taken from Kaler (1978*a*) or are given in column (2) of Table 4. For the optically thin nebulae, they are calculated from the system used by Cahn and Kaler (1971) as given by Cahn (private communication). For the thick nebulae they are computed on the assumption of constant luminosity on the

TABLE 3
O/H AND V_{LSR}

Nebula	10^4 O/H	He/H	N/O	v_r(LSR) km/s	Nebula	10^4 O/H	He/H	N/O	v_r(LSR) km/s	Nebula	10^4 O/H	He/H	N/O	v_r(LSR) km/s
(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)
NGC 40	3.6			-14	NGC 6853	5.14	.122	.56	-40	Hb 8	2.04[c]			-267
650	7.96	.113	.26	-21	6857	1.16[bc]			---	He2-108	1.12			-8
1535	2.87	.099	.12	-20	6884	4.68	.113	.26	-23	He2-138	3.77			-45
2346	2.13	.137	.65	29	6886	5.18	.120	.32	-22	Hu 1-1	4.23	.094	.20	-56
2392	3.16	.092	.47	71	6891	2.74	.120	.14	55	Hu 1-2	1.95	.167	1.5	20
2438	6.93	.103	.28	63	7009	3.59	.112	.39	-39	Hu 2-1	3.7			32
2440	5.13	.146	2.5	49	7026	5.72	.104	1.2	-29	J 320	1.79	.108	.11	246
2452	5.69	.115		54	7027	6.00	.111	.54	23	J 900	3.51	.099	.20	36
3132	6.70	.126	.44	-16	7293	3.3	.19	.88	-26	M 1-5	2.70			64
3211	5.07	.152	.17	-29	7354	3.37[b]	.118	.13	-34	M 1-14	2.24		.14	117
3242	4.23	.103	.15	- 2	7662	3.43	.123	.18	- 5	M 1-17	2.79[c]		2.8	87
3587	3.25	.086	.31	10	IC 351	3.88	.098	.22	4	M 1-33	2.56[c]			18
3918	6.42	.108	.24	-22	418	8.38			47	M 1-64	3.49[bc]			- 2
5307	2.76	.097	.23	39	1747	5.25	.103		-69	M 1-64	1.56[bc]			34
5315	4.2[a]	.127		-35	2003	4.28	.107	.28	-30	M 1-67	2.31[c]			217
5882	4.60	.116	.24	23	2149	2.03			-39	M 1-74	4.62[a]			24
6210	4.56	.099	.14	-22	2165	3.06	.113		38	M 2-9	5.19			79
6302	2.76	.22	.70	-41	2448	2.80	.095	.26	-34	M 2-23	1.52[c]		.33	225
6445	5.17	.22	.96	27	2501	7.1[a]	.108		23	M 2-27	3.97[c]		1.3	190
6543	5.35	.118	.12	-53	3568	2.90	.092	.07	-35	M 2-50	2.81	.073	.21	-127
6567	2.89	.122	.30	131	4406	5.78	.141	.35	-45	M 3-20	2.78[c]			64
6572	3.19	.109	.41	5	4593	3.29			40	Me 2-2	1.80	.162	2.0	-144
6629	4.12	.143		23	4634	3.21[c]			-24	Pb 4	2.66	.129		----
6644	3.54	.112	.25	204	4732	1.21			-135	Ps 1	0.65	.090	.28	-130
6720	4.07	.114	.28	- 6	4776	4.16[c]			27	Sn 1	3.93	.084	.13	- 74
6741	6.21	.136	.74	-54	4846	4.37	.087	.22	163	Vy 1-1	2.22	.139		- 44
6751	7.13	.112	.09	-23	5117	4.90[a]			-15	Vy 1-2	7.89	.097		- 83
6778	1.70	.143	2.4	104	IC 5217	3.42	.096	.30	-90	Vy 2-2	0.71	.143		- 73
6790	3.80	.099	.20	56	A 35	3.93[bc]			- 6	Vy 2-3	3.22[abc]			- 48
6803	4.36	.127	.60	27	BB 1	0.62	.099	2.4	192					
6807	2.28[a]	.103		-54	BD +30	2.00			-17					
6818	4.51[d]	.104		- 5	Cn 2-1	4.75[c]		.59	-263					
6826	3.13	.104	.13	7	Cn 3-1	2.4			19					
6833	1.19	.097	.53	-96	Ha 4-1	2.2	.115	.28	-134					

[a] O/H approximate because of high Ne.
[b] T_e estimated.
[c] He/H not measured but no He II line.
[d] Borderline for O^{3+} correction.

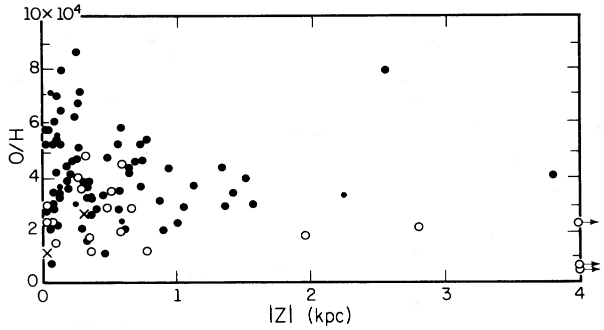

FIG. 2.—Values of O/H plotted against the absolute distance of the planetary from the galactic plane, $|Z|$. *Filled circles:* $|v_r(\mathrm{LSR})| \leq 85$ km s^{-1}; *open circles:* $|v_r(\mathrm{LSR})| > 85$ km s^{-1}; X: $|v_r(\mathrm{LSR})|$ unknown.

scale of Cudworth (1974) divided by 1.45. In this figure the nebulae are divided into two velocity groups at 85 km s^{-1}. There are only two objects out of 16 with $|Z| \geq 1$ kpc for which O/H $> 4 \times 10^{-4}$, whereas below $|Z| = 1$ kpc 40% are above O/H $= 4 \times 10^{-4}$. A χ^2 test shows only a probability of 0.03 for obtaining this distribution by chance.

These two figures very clearly show a difference in oxygen abundance between the galactic halo and the disk. The halo contains objects with low O/H, whereas the disk objects range from low to high values. The sharp cutoff on the velocity plot appears to be real. The same phenomenon is seen by Kaler (1980) when the central star temperature or nebular excitation is plotted against $|v_r(\mathrm{LSR})|$. A more gradual drop in O/H is seen on the $|Z|$-plot. It must be kept in mind, however, that random and systematic errors in the distances may mask the true behavior in $|Z|$. The data are consistent with a contraction of the galactic halo to a disk of a thickness of less than 1 kpc. During the contraction, the O/H level has gradually been built up probably through production of oxygen by supernova explosions. More data should be obtained to confirm the reality of the distinct division at 85 km s^{-1}.

TPP suggested that the planetaries provide evidence for a radial gradient in O/H within the galactic disk. Such a gradient is known to exist from studies of diffuse nebulae; see § I. Figure 3 shows O/H plotted against distance from the galactic center, as projected onto the plane R, with $2\frac{1}{2}$ times as many points as TPP had available. The nebulae are divided into three population groupings. Population II, or halo, includes those objects for which either $|v_r(\mathrm{LSR})| > 85$ km s^{-1} or $Z \geq 1000$ pc; Population I, disk, consists of those with both $|v_r(\mathrm{LSR})| < 85$ km s^{-1} and $400 \text{ pc} < |Z| < 1000$ pc; and Population I′ (extreme disk) contains those nebulae with both $|Z| < 400$ pc and $|v_r(\mathrm{LSR})| < 85$ km s^{-1}. The criterion in R for population assignment used by Kaler (1978*a*) has been dropped. Values of R and the population types are given either by Kaler (1978*a*) or in Table 4, where the latter also includes corrections to the former.

TABLE 4

PARAMETERS FOR NEBULAE NOT IN OR CORRECTED FROM KALER (1978)

Nebula (1)	Z_{kpc} (2)	R_{kpc} (3)	Population (4)
NGC 40	0.31	11.0	I′
NGC 2346	0.10	11.1	I′
NGC 2438	...	...	I′[a]
NGC 6629	0.10	8.9	I′
NGC 6751	0.26	7.9	I′
NGC 6778	0.35	7.7	II
NGC 6790	0.17	8.9	I
NGC 6807	0.59	7.3	I
NGC 6818	0.68	8.2	I
NGC 6853	0.02	9.9	I′
NGC 6857	0.01	9.9	...
NGC 6891	0.40	9.1	I′
NGC 7293	0.12	9.9	I′
NGC 7354	...	...	...
IC 418	0.25	10.4	I′
IC 1747	...	...	I′[a]
IC 2149	0.29	11.5	I′
IC 2165	...	...	I[a]
IC 4593	1.41	8.5	II
IC 4776	0.63	7.4	I
A35	0.24	9.8	I′
BD +30	0.05	9.8	I′
Cn 2–1	0.23	5.9	II
Cn 3–1	0.60	8.0	I
Hb 8	2.8	1.1	II
He 2–108	0.46	8.1	I
He 2–138	0.34	8.6	I′
Hu 2–1	0.29	9.1	I′
J900	...	...	I′[a]
M1–5	0.08	12.3	I′
M1–14	0.07	11.8	II
M1–17	0.66	15.6	II
M1–33	0.36	5.3	I′
M1–64	1.12	9.1	II
M1–65	0.33	7.2	I′
M1–67	0.03	7.9	
M2–9	0.72	8.0	II
M2–23	0.10	6.1	II
M2–27	0.26	8.1	II
M3–20	0.07	14.3	I
Vy 1–1	1.00	8.0	II
Vy 1–2	2.45	9.1	II
Vy 2–2	0.06	15.7	II
Vy 2–3	2.2	...	II

[a] Population type changed from Kaler (1978*a*) because of change in the velocity criterion or the dropping of the criterion in R.

The dominating feature of Figure 3 is again the population separation. Of the Population I and I′ points, half have O/H above 4×10^{-4}, but only four out of the 32 Population II nebulae have O/H $> 4 \times 10^{-4}$. The probability of obtaining this distribution by chance is less than 0.001. The Population I′ points also range to higher values of O/H than do the Population I points, a feature already seen in Figure 2 and discussed above. An apparent radial gradient is perceived in Figure 3 primarily because the majority of nebulae with $R > 11$ kpc are halo objects, and thus have low O/H. If the halo nebulae are excluded, the remaining disk objects are at least consistent with the negative radial gradient found from diffuse nebulae, in

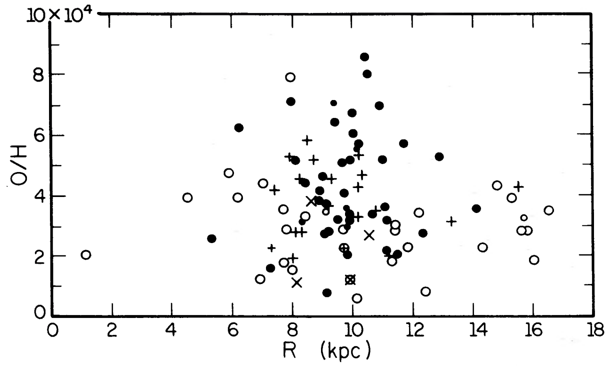

FIG. 3.—Values of O/H plotted against distance from the galactic center projected onto the plane, *R*. *Filled circles:* Population I′ (both $|v_r(\text{LSR})| < 85$ km s^{-1}, $|Z| < 400$ pc); *crosses:* Population I (both $|v_r(\text{LSR})| < 85$ km s^{-1}, $400 < |Z| < 1000$ pc); *open circles:* Population II (either $|v_r(\text{LSR})| \geq 85$ km s^{-1} or $|Z| \geq 1000$ pc); X: unknown population, no measured radial velocity.

that for $R \leq 11$ kpc 55% of the objects have O/H $> 4 \times 10^{-4}$, whereas the figure is 45% for $R > 11$ kpc.

The diffuse nebulae of course represent the current state of the interstellar medium, whereas the planetaries are produced by stars with a variety of ages. This fact coupled with errors in the distances will tend to smear any radial gradient that may be present.

IV. THE ENRICHMENT OF GALACTIC OXYGEN

Since the planetaries represent a variety of population types and a variety of stellar ages, we should be able to use them to determine how O/H has varied with time in our Galaxy. This procedure will work providing that we can identify planetaries as belonging to stars of specific ages, and with the assumption that O/H in the ejected envelope is not largely altered during the stars' lives by internal processes. In § IV*a* below we will consider how planetaries can be grouped

TABLE 5

MEAN O/H FOR AGE GROUPS

Age - Population Group	10^4 O/H	Remarks
1a) Old Halo - Globular Cluster	0.56 (1)	
1b) Old Halo - $\|Z\|$ > 4 kpc	1.12±0.55(3)	Includes Ps-1 in above row
2a) Intermediate Halo $\|v_r(\text{LSR})\|$ >85 km/s, $\|Z\|$ < 4 kpc	2.61±0.26(17)	
2b) Intermediate Halo 1 kpc ≤ $\|Z\|$ < 4 kpc	3.44±0.50(11) 3.00±0.25(10)	 Excludes the high point Vy 1-2
3) Old Disk, Pop I, I' He/H < 0.10	3.61±0.24(7)	
4a) Intermediate Disk, Pop I 0.10 < He/H ≤ 0.12 R < 11 kpc	 4.41±0.33(6) 4.54±0.51(3)	 Low excitation
4b) Intermediate Disk, Pop I' 0.10 ≤ He/H ≤ 0.12, Low excitation, R < 11 kpc	4.42±0.71(6)	
5a) Young Disk, Pop I' 0.10 ≤ He/H < 0.12, High excitation, R < 11 kpc	5.79±0.71(6) 5.36±0.69(5)	 Excludes NGC 650
5b) Young Disk, Pop I' 0.12 < He/H < 0.16, R < 11 kpc	5.31±0.31(8) 4.96±0.45(9)	 Includes NGC 2346
5c) Young Disk, Pop I, I' He/H > 0.16	3.30±0.68(4)	
Diffuse Nebulae (7 < R < 11 kpc) PTPR and Hawley (1978a)	4.40±0.88(9) 3.61±0.47(8)	All nebulae Excludes the high point IC 5146
	4.81±0.33(3)	Mean of 3 highest diffuse nebulae excluding IC 5146
Solar (Ross and Aller 1976) (Lambert 1978)	6.9±1.1 8.3±1.7	

according to the age of the progenitor star. Section IV*b* will discuss effects of stellar evolution on the O/H ratios, and § IV*c* will consider problems and inconsistencies in the procedures.

a) Age Groups and the Variation of ⟨O/H⟩

Table 5 shows the progenitor stars of the planetaries divided into five age groupings, from oldest to youngest. We may discriminate among the ages of the stars by their distances from the galactic plane, by the helium content of the nebulae, and by the degree of ionization of the nebulae which indicates the stars' temperatures. Table 5 presents, in successive columns, the mean O/H (⟨O/H⟩) for each group, the mean error of the mean, the number of planetaries in the group (in parenthesis), and remarks. The nebulae in Table 3 designated as half-weight are not included in the averages. The explanation of the age groups follows, but note at the outset that, except for the last subgroup, the values of ⟨O/H⟩ increase with decreasing age of the object, or rather that ⟨O/H⟩ has increased steadily with the age of the Galaxy.

The oldest stars should be those in the extreme, or *old halo*, for which $|Z|$ is large, here above 4 kpc. Of these objects, the oldest should be found in globular clusters. Unfortunately, extreme halo planetaries are very rare. There are only three (Ps–1, BB–1, and Ha 4–1; see, for example, Hawley and Miller 1978), and only one (Ps–1) in a globular cluster (M15). This one nebula, however, does show the lowest O/H of all the nebulae considered here. Since one should not place a large reliance on one object, group 1 (the oldest) is subdivided into 1*a* (Ps–1) and 1*b* (all three planetaries, including Ps–1). The three together have about twice the O/H as Ps–1 alone, but with a large error which nearly includes Ps–1's value.

The second oldest identifiable grouping is the general collection of halo objects, excluding the above three, or the *intermediate halo*. Two separate criteria can be used here. Group 2*a* includes objects with $|v_r(\text{LSR})| > 85$ km s^{-1}, and 2*b* is made up of those with 4 kpc $> |Z| \geq 1$ kpc. Only two objects overlap the two subgroups. Two entries are given for 2*b*. The nebula Vy 1–2 (see Fig. 2) has an anomalously high O/H, which is ignored in the second entry. Probably this latter figure more nearly reflects the initial O/H for the group. In either case, the averages for the two subgroups are similar and are more than twice that for the old halo.

The planetaries of the next three groups are disk objects, and as such must be younger than the above. In order to avoid any possible effects of the radial gradient (see § I), planetaries with $R > 11$ kpc are generally not considered for the disk groups. Group 3, called *old disk*, consists of the nebulae that have Population I characteristics, $|Z| < 1000$ pc, $|v_r(\text{LSR})| < 85$ km s^{-1}, but which have a helium content appropriate to the halo (He/H < 0.10; see Kaler 1978*a*). These might be expected to be among the earliest disk objects, in that the stars formed before there was a significant buildup of helium in the Galaxy. The entry in Table 5 includes nebulae irrespective of R. There are only three objects in the sample with $R < 11$ kpc, and ⟨O/H⟩ for these is identical to that of the whole set.

Groups 4 and 5 have higher helium and thus constitute on the whole a later disk population. Helium is up either because the Galaxy became enriched by the time of the birth of the star, or because helium has been enriched by nuclear processes in the star itself. In the latter case, the star must be fairly massive (see Kaler, Iben, and Becker 1978), and again of a younger population. Here we may also discriminate age on the basis of nebular excitation. Kaler (1980) showed that the highest excitation nebulae, and consequently those with the hottest central stars, are confined to the galactic plane; the halo contains no high-excitation objects. High excitation in a nebula thus indicates a progenitor of higher mass, and therefore of smaller age.

Group 4 is called the *intermediate disk*, and it probably represents an average of the disk over much of its lifetime, in that it includes both old and young stars. It is a transition between groups 3 and 5, the latter consisting of only young objects. Group 4 is characterized by having a helium abundance in the range $0.10 \leq$ He/H ≤ 0.12, which is typical of disk objects (Kaler 1978*a*). As with group 2, two separate criteria are used. Group 4*a* consists only of Population I nebulae, which are rather removed from the central plane (400 pc $< |Z| <$ 1000 pc). Discrimination on the basis of excitation makes no difference here. The second entry for group 4*a* shows ⟨O/H⟩ for the low-excitation objects only (see below) with practically the same result as found for the whole set. Group 4*b* contains only the extreme disk objects (Population I′, $|Z| < 400$ pc), and since this region is where one would expect to find the truly young stars, only the set of low-excitation nebulae, those with He^{2+}/He < 0.2, were chosen. This value is the maximum that Kaler (1980) finds for the lower mass stars of the galactic halo, and thus the higher mass, and younger, stars are excluded from the group. Groups 4*a* and 4*b* give substantially the same result. In both cases, ⟨O/H⟩ is higher than it is for group 3, and clearly above the halo values.

Group 5 is referred to as the *young disk*. Here, three criteria are used, each of which should ensure that only the youngest stars are chosen. Group 5*a* consists of Population I′ nebulae of moderate helium, but of the high excitation which should earmark the more massive progenitors. The second entry excludes the highest value of the set, that for NGC 650. Group 5*b* contains only nebulae for which helium is clearly enriched ($0.12 <$ He/H < 0.16), where the anomalous Vy 2–2 is excluded. BI show that these nebulae must be produced by high-mass and consequently young stars. The second entry for this group includes NGC 2346 for which $R = 11.1$ and whose exclusion would be marginal. The calculations by BI do not explain He/H ratios greater than about 0.16. Consequently, these objects are placed in their own group, 5*c*.

It is of interest to compare the ⟨O/H⟩ for planetaries in Table 5 to that of diffuse nebulae and the Sun. All the nebulae in groups 4 and 5 are between 8 and 11 kpc from the galactic center. The average O/H for diffuse nebulae with $8 < R < 11$ kpc from Hawley (1978) and PTPR (for $t^2 = 0$) is also given in Table 5. Three entries are given. The first, which includes all the nebulae, is consistent with ⟨O/H⟩ for the disk as defined by group 4. The agreement is not as good for the second entry, for which the one anomalously high point IC 5146 (Hawley 1978) is excluded. Comparison with diffuse nebulae may present problems because a variable amount of their oxygen may be tied up in grains. An average of the three nebulae with the highest oxygen content (excluding IC 5146) is thus also presented. Note that this last value falls between the entries for groups 4 and 5, and is within the errors of all but the first entry for group 5*a*.

Finally, the solar O/H is presented from Ross and Aller (1976) and from Lambert (1978). The former value agrees within the errors with the first entry for group 5*a*, and nearly does so with the second entry, but Lambert's value is higher than any of the nebular entries. It is not surprising, however, that the agreement is not better between the nebular and solar values because entirely different procedures, sets of lines, and *f*-values are used, each with different systematic errors. On the whole, it appears that ⟨O/H⟩ for the youngest sets of planetaries is consistent with those measures in the Sun and in diffuse nebulae.

b) *The Effect of Stellar Evolution, and Conclusions Regarding Galactic* O/H

The overall trend in ⟨O/H⟩ in Table 5 is clear. The oxygen abundances in planetaries increase steadily as the age of the group decreases, converging on the value defined by the diffuse nebulae and the Sun. More important than absolute external comparisons, however, is the consistent relative increase among the sets of planetaries, because these constitute a collection of similar objects which are all treated in the same way.

Before we can draw any conclusions about the enrichment of galactic oxygen, however, we must consider the role played by stellar nuclear processing in perturbing the initial O/H ratios. The average mass of the stars increases with decreasing age. If a change in O/H by the star is related to its mass, at least, part of the correlation in Table 5 could be due to internal stellar processes.

For lower mass stars, O/H changes appear unimportant. Becker and Iben (1979) show that O/H is not changed significantly at the surface for stars as low as 3 $M_\odot$ through the first two dredge-up phases, and Iben (private communication) shows that a 1 $M_\odot$ low-metal star is also unaffected. The halo stars have core masses of about 0.5 $M_\odot$ (Kaler 1980), and Gingold (1974) shows that stars of this size do not significantly mix processed material with the outer layer even through the thermal pulsing stage. Sweigart and Mengel (1979) demonstrate that meridional circulation can produce changes in surface abundances. These circulation currents can dip into the oxygen-depleted zone for the low-metal stars of the halo. However, the effect would be seen in an increased N/O ratio, which is only marginally detected; see below.

However, an increase in O/H is predicted by Becker (1979) and BI for high-mass stars. Enrichments of up to 35% are possible following the first thermal pulse. From the mean He/H ratios of group 5 and BI, groups 5*a* and 5*b* have mean initial stellar masses of about 2 $M_\odot$ and 4 $M_\odot$, respectively. From Becker (1979), a 3 $M_\odot$ star shows only about a 3% O/H enrichment, and a 4 $M_\odot$ star about 15%. But from Table 5, group 5*b* has a *lower* ⟨O/H⟩ than does 5*a*, which indicates that oxygen enrichment here is not very important.

Stellar evolution effects can be looked at still more closely by considering the N/O ratios of the nebulae. If nuclear burning affects O/H, we would expect it to affect N/O as well. Becker and Iben (1979) and BI show that in high-mass stars N/O enrichment correlates with He/H enrichment, and Becker (1979) shows that O/H should also correlate with He/H. In low-mass stars, oxygen depletion in CNO burning, whether by convective dredging or meridional circulation, should also show up in increased N/O. Thus if we take only nebulae with low N/O, we should eliminate effects of nuclear burning on O/H.

In order to provide this test, simplified versions of Table 5 are presented in Tables 6*a* and 6*b*, which also show comparisons among the groups. The numbers in parenthesis in column (2) again give the number of nebulae in the group. In the compilation of Table 6, judicious choices were made among the various entries in Table 5, explained below. One major problem is that we do not know the appropriate O/H for the old halo. Consequently, both groups 1*a* and 1*b* (old halo) are again presented, and comparisons are drawn against both of them. The entry for group 2 (intermediate halo) is the mean of all objects in 2*a* and 2*b*, less the anomalous Vy 1–2. That for group 3 is simply copied from Table 5. The value presented for group 4 is the mean of all the nebulae in 4*a* and 4*b*. If only the low-excitation entry in 4*a is* averaged with that of 4*b*, the same value results. The entry for group 5 excludes 5*c*. Since theory does not explain the observed He/H for these objects, ⟨O/H⟩ is suspect. In any case, ⟨O/H⟩ for 5*c* is clearly out of line with that for groups 4 and 5*a*, *b*. The entry in Table 6*a* is the mean for the nebulae in 5*a* and 5*b*, excluding NGC 650 and NGC 2346, which are the extreme high and low points. If they are included, the average is nearly the same, although with a higher error.

Table 6*a* shows the results for nebulae without regard to N/O, and Table 6*b* shows the averages of the various groups for nebulae with N/O ≤ 0.3; see Table 2. In order to qualify, the nebula had to have log T_* > 4.65; below this value there may be difficulty in establishing N/O; see Kaler (1979). An exception was made for Ps–1; see the next subsection. The only clear

TABLE 6

⟨O/H⟩ FOR AGE GROUPS AND COMPARISONS

Group (1)	$10^4\langle O/H\rangle$ (2)	$\frac{\langle O/H\rangle(n)}{\langle O/H\rangle(n-1)}$ (3)	$\frac{O/H(n)}{O/H(1b)}$ (4)	$\frac{\langle O/H\rangle(n)}{O/H(1a)}$ (5)
	a) ALL N/O			
1*a*) Old halo, globular cluster	0.56 (1)			
1*b*) Old halo, $\|Z\| > 4$ kpc	1.12 ± 0.55 (3)			
2) Intermediate halo..............	2.82 ± 0.20 (25)	2.5 ± 1.2 (1*b*) 5.0 (1*a*)	2.5 ± 1.2	5.0
3) Old disk......................	3.61 ± 0.24 (7)	1.28 ± 0.13	3.2 ± 1.6	6.4
4) Intermediate disk..............	4.41 ± 0.37 (12)	1.22 ± 0.13	3.9 ± 1.9	7.9
5) Young disk....................	5.33 ± 0.31 (13)	1.21 ± 0.12	4.8 ± 2.4	9.4
	b) NEBULAE WITH N/O < 0.30			
1*a*) Old halo, globular cluster	0.56 (1)			
1*b*) Old halo, $\|Z\| > 4$ kpc	1.38 ± 0.82 (2)			
2) Intermediate halo..............	3.28 ± 0.22 (12)	2.4 ± 1.5 (1*b*) 5.9 (1*a*)	2.4 ± 1.5	5.9
3) Old disk......................	3.69 ± 0.27 (6)	1.13 ± 0.11	2.7 ± 1.6	6.6
4) Intermediate disk..............	4.41 ± 0.50 (8)	1.20 ± 0.16	3.2 ± 1.9	7.9
5) Young disk....................	5.62 ± 0.64 (5)	1.27 ± 0.21	4.2 ± 2.4	10.0
Diffuse nebulae	4.8 ± 0.3			
Solar..............................	7.6 ± 1.8			

change occurs for group 2, which consists of low-mass halo stars. The ratio (group 2) ⟨O/H⟩(N/O ≤ 0.3)/⟨O/H⟩(N/O > 0.3) = 1.30 ± 0.28, which implies a slight O/H reduction due to processing, but which is not really statistically significant. The change for group 5 is not significant and results mostly because of the dropping of nebulae for which N/O is unknown. From comparison of Tables 6*a* and 6*b*, then, it seems most likely that O/H is not seriously affected by nuclear processes in the parent star.

If such is the case, then we can interpret the change in ⟨O/H⟩ with group as an evolutionary effect of the Galaxy. The last three columns of Table 6 give ratios of ⟨O/H⟩ between various groups. Column (3) shows the comparison between adjacent groups, $\langle O/H\rangle(n)/\langle O/H\rangle(n-1)$, where n is the group number. Columns (4) and (5) give the ratios of ⟨O/H⟩ for each group with ⟨O/H⟩ for groups 1*b* and 1*a*, respectively. Also, the third entry for the diffuse nebulae and the average of the two solar entries in Table 5 are given in Table 6. In the last row of Table 6*a*, we see that the total increase in O/H over the lifetime of the Galaxy represented by available planetaries is between factors of 5 and 10, and that the ⟨O/H⟩ for the youngest objects is in line with that for diffuse nebulae and the Sun. These results regarding galactic enrichment are, not surprisingly, essentially the same as those already found by Peimbert (1973), Hawley and Miller (1978), and Torres-Peimbert and Peimbert (1979). What is new here is that we can see the steady enrichment of oxygen through all the various age groups presented. Column (3) of Table 6 shows that the largest increase occurs in the early stages of the formation of the Galaxy, between the old halo and the intermediate halo. Thereafter, the percentage rate of increase between adjacent groups appears to be roughly constant. It is interesting to note that the ratio of ⟨O/H⟩ for the intermediate halo nebulae to that of the young disk nebulae is similar to the ratio of the mean O/H found by Sneden, Lambert, and Whitaker (1980) for 12 metal-poor dwarf stars to that of the Sun.

c) *Problems and Inconsistencies*

There are clearly difficulties in the above analysis which must be kept in mind. First is the small number of nebulae in each group. The only set with a substantial number is group 2. The ratios in column (3) of Table 6 are not in general that much larger than the errors. The increase in O/H between any two adjacent groups might in fact not be truly present; it is the overall trend in the ratios among all the groups that is important here, and the significant ratios for nonadjacent groups. Obviously, it is important to increase the number of well-observed nebulae.

Second, groups 4*b* and 5*a* are discriminated from one another on the basis of excitation, where the high-excitation objects come from the more massive and younger stars. Yet in group 4*a*, the low-excitation nebulae have somewhat higher ⟨O/H⟩ than do the high-excitation objects. There are, however, only three nebulae in each excitation subgroup.

Third, half of the group 5*b* sample are in the low-excitation category. For consistency, all of these high-helium objects, which presumably came from high-mass stars, should also be of high excitation. However, the high-excitation group alone gives nearly the same ⟨O/H⟩ as do all the nebulae together.

Fourth, we must consider the possibility of systematic error in the calculation of O/H. Group 5*a*, composed entirely of high-excitation objects, also exhibits the highest O/H. Perhaps the He^{2+}/He^{+} ratio overcorrects for the O^{3+} and O^{4+} contribution. However, recall that in group 4*a* the high-excitation objects actually have lower ⟨O/H⟩ than do those of low excitation. In addition, ⟨O/H⟩ for the two excitation sets of group 5*b* (less NGC 2346) are about the same.

Fifth is the problem of group 5*c* in Table 5. These extreme helium objects seem to show a deficiency of oxygen, which implies that O/H can be noticeably changed by the star. Becker (1979) shows that O/H first increases through 5 $M_{\odot}$, then decreases. Perhaps O/H for 5*c* is near normal and that for 5*b* is enriched. But the theory cannot account for such high helium as in 5*c* in any case, and the comparison between low and high N/O objects seems to show that the observed O/H reflects that of the stars' galactic origins for the other groups.

Finally ⟨O/H⟩ for group 1 in Table 6*b* is unreliable. Ps–1 is of low excitation, and Kaler (1979) showed that for these objects N/O does not appear to equal the observed quantity N^{+}/O^{+}. However, log T_{*} for Ps–1 is a lower limit, N/O is probably an upper limit, and N/O is already <0.3, and the analysis of group 2 shows that CNO burning is probably not important here anyway.

V. SUMMARY AND CONCLUSIONS

The oxygen abundances of planetary nebulae are dependent on the radial velocities of the nebulae, their distances from the galactic plane, and consequently on population type. Planetaries with high radial velocity and large distance from the galactic plane have O/H almost always less than 4×10^{-4}, whereas those with low $|Z|$ or radial velocity have O/H ratios which range up to twice as large. The distribution of O/H with LSR radial velocity shows a distinct cutoff at 85 km s^{-1}, similar to that found in central star temperature by Kaler (1980). Generally, planetaries with $|Z| > 1$ kpc have low O/H. The drop in O/H is more gradual with increasing $|Z|$ than it is with increasing $|v_r(\mathrm{LSR})|$. If a sharp cutoff exists for O/H versus $|Z|$, it may currently be masked by random and systematic errors in the distances to the planetaries. These results are qualitatively similar to those found by Kaler (1970). The radial O/H gradient in the disk is not readily seen. The planetaries do exhibit an apparent O/H gradient because the nebulae farthest from the galactic center are predominantly halo objects which have low O/H.

When the planetaries are divided into age groups, it is clearly seen that ⟨O/H⟩ for each group increases with decreasing age. The available evidence, particularly the fact that there is little difference in O/H between nebulae with high and low N/O, suggests that processing by individual stars is not important, and that we are seeing the enrichment of galactic oxygen. From the time of the early halo to the present, O/H has increased by between factors of 5 and 10, depending upon which old halo group is adopted, which is consistent with earlier studies. The galactic O/H ratio is characterized by a rapid buildup in the halo followed by a slower rate of increase between the other adjacent age groups. Since those age groups can only be relatively dated, the true behavior of the enrichment rate cannot yet be ascertained.

However, the problem of the effects of individual stellar evolution cannot yet be entirely ignored. A case in point is that the nebulae with highest helium (He/H > 0.16) have O/H which appears to be significantly less than for those nebulae for which $0.12 < \mathrm{He/H} \leq 0.16$. More extensive observations to increase the number and distribution of observed nebulae, and advances in the theory of stellar evolution, are needed to resolve the difficulties fully.

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REFERENCES

Acker, A. 1975, *Astr. Ap.*, **40**, 415.
Ahern, F. J. 1978, *Ap. J.*, **223**, 901.
Aller, L. H., and Czyzak, S. J. 1979, *Ap. Space Sci.*, **63**, 397 (AC).
Barker, T. 1978*a*, *Ap. J.*, **220**, 193.
———. 1978*b*, *Ap. J.*, **219**, 914.
Becker, S. A. 1979, Ph.D. thesis, University of Illinois.
Becker, S. A., and Iben, I., Jr. 1979, *Ap. J.*, **232**, 831.
———. 1980, *Ap. J.*, in press (BI).
Bohuski, T. J., and Smith, M. G. 1974, *Ap. J.*, **193**, 197.
Cahn, J. H., and Kaler, J. B. 1971, *Ap. J. Suppl.*, **22**, 319.
Capriotti, E. R., and Daub, C. T. 1960, *Ap. J.*, **132**, 677.
Collins, G. W., Daub, C. T., and O'Dell, C. R. 1969, *Ap. J.*, **133**, 471.
Conti, P. S., Greenstein, J. L., Spinrad, H., Wallerstein, G., and Vardya, M. S. 1967, *Ap. J.*, **148**, 105.
Cudworth, K. M. 1974, *A.J.*, **79**, 1384.
Gingold, R. A. 1974, *Ap. J.*, **193**, 177.
Harrington, J. P. 1969, *Ap. J.*, **156**, 903.
Hawley, S. A. 1978*a*, *Ap. J.*, **224**, 417.
———. 1978*b*, *Pub. A.S.P.*, **90**, 370.
Hawley, S. A., and Miller, J. S. 1978, *Ap. J.*, **220**, 609.
Kaler, J. B. 1970, *Ap. J.*, **160**, 887.
———. 1976*a*, *Ap. J. Suppl.*, **31**, 517.
———, 1976*b*, *Ap. J.*, **210**, 113.
———. 1978*a*, *Ap. J.*, **226**, 947.
———. 1978*b*, *Ap. J.*, **225**, 527.
———. 1979, *Ap. J.*, **228**, 163.
———. 1980, *Ap. J.*, in press.
Kaler, J. B., Iben, I., Jr., and Becker, S. A. 1978, *Ap. J.* (*Letters*), **224**, L63.
Kondratyeva, L. N. 1978, *Astr. Zh.*, **55**, 334.
———. 1979, *Astr. Zh.*, **56**, 345.
Lambert, D. L. 1978, *M.N.R.A.S.*, **182**, 249.
Mihalas, D., and Routley, P. M. 1968, *Galactic Astronomy* (San Francisco: Freeman).
Peimbert, M. 1973, *Mem. Soc. Roy. Sci. Liège*, **5**, 307.
Peimbert, M., Torres-Peimbert, S., and Rayo, J. F. 1978, *Ap. J.*, **220**, 516 (PTPR).
Perek, L., and Kohoutek, L. 1967, *Catalogue of Galactic Planetary Nebulae* (Prague: Czechoslovakian Acad. Sci.).
Ross, J. E., and Aller, L. H. 1976, *Science*, **191**, 1223.

Sabbadin, R. 1977, *Astr. Ap.*, **57**, 307.
Searle, L. 1971, *Ap. J.*, **168**, 327.
Seaton, M. J. 1968, *M.N.R.A.S.*, **139**, 129.
Shields, G. A., and Searle, L. 1978, *Ap. J.*, **222**, 821.
Smith, H. E. 1975, *Ap. J.*, **199**, 591.
Sneden, C., Lambert, D. L., and Whitaker, R. W. 1980, *Ap. J.*, in press.
Sweigart, A. V., and Mengel, J. G. 1979, *Ap. J.*, **229**, 624.
Talent, D. L., and Dufour, R. J. 1979, *Ap. J.*, **233**, 888.
Tinsley, B. M. 1979, *Ap. J.*, **229**, 1046.
Torres-Peimbert, S., and Peimbert, M. 1977, *Rev. Mexicana Astr. Ap.*, **2**, 181 (TPP).
———. 1979, *Rev. Mexicana Astr. Ap.*, in press.
Webster, B. L. 1976, *M.N.R.A.S.*, **174**, 513.

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