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CHEMICAL ABUNDANCES IN PLANETARY NEBULAE: BASIC DATA AND CORRELATIONS BETWEEN ELEMENTS

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ABSTRACT

All the individual determinations of chemical abundances in planetary nebulae obtained with linear detectors have been considered to form a critical compilation of the "best" abundances of He, C, N, O, and Ne. The data base refers to all the galactic planetary nebulae observed in the last 20 years, up to the end of 1989, for which the abundance of at least two of the above elements have been obtained. Only a few objects have been excluded: the five known planetary nebulae of halo population and three more objects whose abundances have been recognized to be significantly different in the inner and in the outer nebular regions, something which is interpreted to mean a quite peculiar evolutionary status relative to the chemically homogeneous nebulae. For the resulting 209 planetary nebulae, average chemical abundances have been evaluated separately for nebulae of type I and of types II–III of Peimbert. For the first, they are He/H = 0.137, C/H = 8.72, N/H = 8.60, O/H = 8.66, and Ne/H = 8.05. For the second, they are He/H = 0.103, C/H = 8.82, N/H = 8.07, O/H = 8.66, and Ne/H = 7.99, in the usual units.

The data have been used to explore the reality of various possible relationships between pairs of the above elements. The observed correlations and anticorrelations are seen to broadly follow the expectation of the theory of stellar nucleosynthesis for intermediate-mass stars. The data are consistent with the possibility that the enrichment of nitrogen in type I PNs is due mostly to the ON cycle, while that in PNs of type II–III is due mostly to the CN cycle. The importance of improvements in the theoretical predictions of abundances in the hydrogen-rich envelope at the tip of the AGB evolution is underlined, as is the opportunity to confirm some "extreme" observed abundances, to exploit at best this powerful tool of analysis of stars of intermediate mass.

Subject headings: abundances — nebulae: planetary — stars: evolution

1. INTRODUCTION

The importance of the chemical abundances of the planetary nebulae as a tool to investigate the evolution of the stars of intermediate mass as well as the chemical enrichment of the interstellar medium, and, as a consequence, the chemical evolution of the galaxies, is well known.

The stellar evolutionary theory predicts that each single star in the mass range between 0.7–0.8 $M_{\odot}$ and 8–9 $M_{\odot}$, the precise value depending on the initial chemical composition (Iben & Renzini 1983), evolves from the main sequence through the red giant branch (RG), the horizontal branch (HB), and the asymptotic giant branch (AGB) undergoing mass loss and various mixing episodes which dredge up material processed in the nucleus into the hydrogen-rich envelope. The upper limit of 8–9 $M_{\odot}$ might be lowered to 5–6 $M_{\odot}$ if the so-called convective overshooting process is fully active (e.g., Bressan 1990). The real effectiveness of this mechanism is, however, still controversial (Renzini 1987, 1990).

In any case, the above range of masses refers to an enormous number of stars, i.e., from the stars of very low mass which did not yet evolve appreciably from the main sequence up to all the stars which at the present epoch of the universe did already evolve toward their advanced stages of evolution, with the exclusion of only those which end their life as supernovae of Type II.

During the last phases of the AGB evolution, the mass-loss rate is believed to become much larger than that expected on the basis of the observed rate in the previous RG evolution. The larger rate comes from the need to explain the observed masses of the nebulae, considering the relatively short evolutionary times spent in the last phases of the AGB evolution. This phase is called the superwind phase.

The changes in the chemical composition of the hydrogen-rich envelope during the evolutionary sequence depend on the initial mass, chemical composition, and rotational behavior.

It should then become possible to follow the chemical behavior of the envelope of each progenitor star from the main sequence to the tip of the AGB, at the moment of the main ejection of the envelope. Its chemical composition at this stage should reflect that of the nebular material of the proto–planetary nebula and subsequently of the PN. The latter phase is assumed to start when the nebula becomes visible in the optical, i.e., when the temperature of the remnant central star, evolving to the left in the H-R diagram, reaches some 30,000 K.

The most recent quantitative theoretical effort to predict the chemical composition of the stars at the tip of the AGB as a function of the initial mass of the progenitor in the main sequence for solar chemical abundance was made by Renzini & Voli (1981). Comparisons of these theoretical predictions with the chemical abundances observed in the nebulae have been performed by several authors, including Kaler (1983a), Peimbert & Torres-Peimbert (1983, hereafter PTP83), Cerruti-Sola & Perinotto (1983), Pottasch (1984a), and Perinotto (1987).

Meanwhile, new observational data have been secured, while it has become clear that the predictions of Renzini and

Voli need to be revised to incorporate improvements in the theory subsequently recognized to be relevant to the subject (cf. § 4).

The purpose of the present work is to make a critical compilation of the best observations of chemical abundances of galactic planetary nebulae to provide a basis for the comparison with the present and hopefully the future theoretical predictions. The compilation is presented in § 2. The data are then used to make an updated list of PNs of Type I (§ 3), to produce mean values of the chemical abundances for different groups of PNs (§ 4) and to examine the correlations between various elements (§ 5). A discussion in terms of the present theoretical predictions of chemical abundances in planetary nebulae follows in § 6, and the conclusions are presented in § 7.

2. A NEW COMPILATION OF CHEMICAL ABUNDANCES OF PNs

2.1. *Basic Properties*

The following basic criteria have been used in the compilation:

1. All the galactic objects considered to be planetary nebulae (i.e. with no strong arguments for exclusion from this class) have been considered, with the exception of the five known halo PNs and of A30, A57, and A78 which have been found to be so far the only ones chemically dishomogeneous, being helium-rich near to the star and hydrogen-rich in the outermost regions of the nebula. An interesting explanation for their behavior has been offered by Iben et al. (1983).
2. Only works based on observations obtained with linear detectors have been taken into account.
3. Only relatively recent papers were considered, in order to minimize the use of atomic data somewhat different from the ones presently accepted. The resulting earliest papers date from the late 1970s, while the search for the literature was completed up to the end of 1989.
4. Only the elements He, C, N, O, and Ne have been considered. This because (1) they are the most abundant elements, after hydrogen, and so (2) they have been studied in many PNs; (3) they are little affected by depletion in dust and thus the gaseous abundance remains well indicative of the total element content; (4) their abundance is likely to be more accurate than that of the other elements for an observational fact and for a theoretical reason. The first is that the intensities of their most relevant spectroscopic lines are, as a rule, stronger than those of the other elements and therefore are better observed. The second is that their atomic data, needed to derive the abundances, are more complete and likely accurate than those of the other elements.

In addition, the elements He, C, N, O, and Ne are important because the theory of stellar evolution predicts just for some of these elements very large changes in chemical composition and almost no changes for other of these elements (cf. § 4.1).

2.2. *The Techniques for Chemical Abundances*

Before entering more into details concerning the compilation, it is worth recalling that there are various procedures to derive chemical abundances in PNs (cf. Seaton 1960; Osterbrock 1974, 1989; Aller 1984; Harrington 1989). Here I simply recall that the techniques consists of (1) a detailed photoionization model, (2) simplified procedures with Te and Ne constant in the whole nebula or in two separate zones, and (3) a combination of the first two.

The method of the detailed photoionization model is the most satisfactory from a physical point of view, but it requires information often not easily available in addition to a substantial computational effort. Moreover, there are other difficulties with its use (Harrington 1989). So far it has been applied only to NGC 7662 (Harrington et al. 1982) and to NGC 3918 (Clegg et al. 1987). In the latter study, the derived chemical abundances are considered to be accurate to within 10% for He, 40% for C, N, O, and Ne, 60% for Mg, Si, S, and Ar, and to within a factor of two for Fe. Method (2) ignores various poorly known quantities, including the distance of the object, which are instead required for method (1), and is computationally very simple. It has been applied to about 200 PNs. Method (3) has been used in about 90 PNs essentially by Aller and collaborators (Aller & Czyzak 1983; Aller & Keyes 1987). Then essentially all our determinations of abundances in PNs are based on methods (2) and (3). I will comment on their accuracy in the next subsection.

2.3. *The Adopted Abundances*

The adopted chemical abundances are the simple averages of the data from the individual sources after having disregarded the values differing by more than a factor of 2 from the mean of the other determinations. In particular cases, the analysis made in a specific paper was considered quite superior to those of the other articles. In these cases the adopted abundances are simply those given by the "best" study.

The abundance of carbon deserves a comment. It is known that there is a systematic difference between the values obtained using the optical (faint) recombination lines and those obtained from the UV collisionally excited (strong) lines, the latter abundances beeing smaller (e.g., Barker 1982; Kaler 1986). Since these latter values are considered to be more correct, only determinations of the carbon abundance from the UV lines have been accepted. When the latter were not available, the determinations from the optical lines have been accepted if they were obtained through a procedure of calibration via the UV lines, of the type suggested by Kaler (1981), which seemed to give reasonably correct values.

The adopted chemical abundances are reported in Table 1, where full reference to the original authors is given, as well as the specifications of the single best article adopted in specific objects (see above) and of the cases where the carbon abundance is obtained from optical lines, via the above-mentioned procedure. In each PN, the sources which contain a determination of the abundance of carbon have been marked in any case.

Table 1 contains (with the exclusions above mentioned) all the galactic PNs where at least two of the following abundance ratios have been obtained: He/H, O/H, C/O, N/O, and Ne/O. This applies to 209 PNs.

The accuracy of the adopted abundances presented in Table 1 is of course better for the objects more extensively studied. The accuracy attainable from the use of procedures (2) and (3) has been discussed, e.g., by Pottasch (1984b). Judging from this and from the dispersion around the average values of the

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TABLE 1

CHEMICAL ABUNDANCES IN PLANETARY NEBULAE

Name	PK	He:H	O:H * 10-4	C:O	N:O	Ne:O	Sources
NGC 40	120+ 9 1	> 0.044	7.9	1.3	0.32	0.025	6,24,67
650	130-10 1	0.121	7.1	1.7	0.48	0.43	6*,41,59
1535	206-40 1	0.097	3.2	0.69	0.13	0.24	1,6,19+*,33,40, 78
2022	196-10 1	0.114	5.2	0.65	0.15	0.21	6+*,40,78
2346	215+ 3 1	0.155	3.8	-	0.45	0.34	6*,40,59
2371-2	189+19 1	0.124	5.6	3.2 :	0.54	0.29	6*,40,41,46,59 68,78
2392	197+17 1	0.090	3.8	0.55	0.50	0.17	5*,15,40,78
2438	231+ 4 2	0.103	-	-	0.34	-	46
2440	234+ 2 1	0.135	5.0	0.72	1.3	0.20	5*,33,40,41,55 59,61*,67,76*
2452	243- 1 1	0.111	6.7	-	0.70	0.21	6,78
2474	164+31 1	-	-	-	1.2	-	46
2610	239+13 1	0.110	-	-	< 0.38	-	46
2792	265+ 4 1	0.107	6.0 :	-	0.13 :	0.16	78
2818	261+ 8 1	0.162	3.2	0.47	0.97	0.31	26*,59
2867	278- 5 1	0.114	4.5	1.5	0.36	0.17	11*,33,67
3132	272+12 1	0.128	9.5	-	0.51	0.38 :	40,78+
3211	286- 4 1	0.117	8.5	-	0.18	0.16	78
3242	261+32 1	0.091	4.4	0.59	0.21	0.21	6,15,18+,40,41, 61,67,78
3587	148+57 1	0.090	3.7	-	0.28	-	40,41,46
3918	294+ 4 1	0.107	5.0	1.6	0.30	0.24	23+*,67,78,80
4361	294+43 1	0.121	4.0	0.1	0.14	0.25	1+,13,15,41,46, 78
5307	312+10 1	0.102	4.4	-	0.13	0.23	78
5315	309- 4 2	0.125	6.1	1.6	1.1	0.33	67,78,79+
5873	331+16 1	0.114	3.5	3.0 *	0.56	0.17	33*
5882	327+10 1	0.122	7.2	0.72*	0.32	0.19	33*,40,67
6058	64+48 1	0.114	3.5	-	0.31	0.40	47,67
6153	341+ 5 1	0.13	10.	0.80	2.0	0.25	40,70+
6210	43+37 1	0.107	4.5	1.6	0.096	0.22	6,15,25,31+,40, 41,67
6302	349+ 1 1	0.225	5.0	0.20	1.7	0.40	5+,66,67
6309	9+14 1	0.109	9.5	1.4	0.13	0.14	6+,40,43
6369	2+ 5 1	0.132	2.9	-	0.41	0.14	7
6439	11+ 5 1	0.135	4.5	-	0.64	0.24	7,40
6445	8+ 3 1	0.23	2.5	-	1.2	-	4,46
6537	10+ 0 1	0.24	1.6	-	1.8	-	45
6543	96+29 1	0.118	5.6	1.4 :	0.16	0.25	6+*,40,41,67,72*
6563	358- 7 1	0.15 :	1.5	-	1.8	-	47
6565	3- 4 5	0.111	5.9	1.1	1.0	0.24	9+,40
6567	11- 0 2	0.110	2.6	-	0.15	0.22	7,15,40,67
6572	34+11 1	0.120	4.3	1.5	0.30	0.22	15,30*,31*,40, 67,78,79*
6578	10- 1 1	0.103	6.3	-	0.25	0.25	7,47,67
6620	5- 6 1	0.115	6.9	-	0.65	0.22	7
6629	9- 5 1	0.115:	4.1	-	0.14	0.14	7,40,43
6644	8- 7 2	0.117	3.2	2.3	0.18	0.20	9*,15,40,43
6720	63+13 1	0.118	6.4	1.2	0.31	0.25	15,16*,29*,31*, 39,40,46,67,78
6741	33- 2 1	0.123	6.7	1.2 :	1.1	0.33	5*,8*,41,67
6751	29- 5 1	0.105	3.7	-	0.59	0.19	6,43,67
6765	62+ 9 1	0.123	15.	-	0.42	-	46,47
6778	34- 6 1	0.155	2.2	4.5	1.5	1.1	6*,40,41
6781	41- 2 1	0.129	4.3	-	0.51	0.16	7,40

TABLE 1—*Continued*

Name	PK	He:H	O:H * 10-4	C:O	N:O	Ne:O	Sources
6790	37- 6 1	0.130	3.6	1.8	0.20	0.15	6*,31*,45,67,74*
6803	46- 4 1	0.130	5.0	1.1	0.48	0.32	6*,15,40,67,78
6804	45- 4 1	0.138	3.2	-	-	0.16	7
6807	42- 6 1	0.113	3.0	-	0.28	0.25	7,40,41
6818	25-17 1	0.105	4.9	1.1	0.29	0.33	6*,31*,40,43,67
6826	83+12 1	0.107	2.9	4.5	0.10	0.24	6*,31*,40,41,67
6833	82+11 1	0.109	1.2	0.77*	0.66 :	0.29	7,15,40,41,44*
6853	60- 3 1	0.121	4.1	1.4	0.70	0.54	17*,46,69*
6879	57- 8 1	0.099	4.1	-	0.19	0.22	7,40,50,
6881	74+ 2 1	0.116	5.6	-	0.62	0.17	7,45,50,67
6884	82+ 7 1	0.119	6.9	1.2	0.25	0.11	6*,15,40,67,78
6886	60- 7 2	0.133	4.7	1.4	0.64	0.32	5*,40,41,43,67
6891	54-12 1	0.113	3.7	1.3	0.13	0.24	7,31*,40,43,67
6894	69- 2 1	0.100	3.9	-	0.49	0.24	7,40,46,47
6905	61- 9 1	0.105	4.6	0.98	0.22	0.30	6*
7008	93+ 5 2	0.135	-	-	1.4	-	43,44*,45
7009	37-34 1	0.112	5.5	0.51	0.33	0.25	14*,15,21*,31*, 36*,40,62,67,78
7026	89+ 0 1	0.109	5.1	2.4	0.49	0.37	6*,31*,40,41,67
7027	84- 3 1	0.113	7.0	1.6	0.47	0.21	15,31*40,60*,77, 78
7293	36-57 1	0.136:	7.8	-	0.40	< 0.54	38,46,59+
7354	107+ 2 1	0.126	4.0	-	0.83	0.18	7,41,43,67
7662	106-17 1	0.100	3.6	1.7	0.17	0.19	6,20,21,31,37+*, 40,43,56,57,67, 78
IC 351	159-15 1	0.105	4.3	-	0.30	0.22	15,40,78
418	215-24 1	0.086	5.8	1.3	0.13	0.091	2*,6*,15,33,34*, 40,67,78,81*
972	326+42 1	-	6.8 :	-	0.26	-	46,47
1297	358-21 1	0.117	6.1	3.1 :	0.52 :	0.25	10*,33
1454	117+18 1	0.063	5.9	-	0.36	-	47
1747	130+ 1 1	0.099	5.6	1.8	0.36	0.20	6*,41,67
2003	161-14 1	0.113	3.4	2.0	2.4	0.17	6*,15,40,41,55*
2149	166+10 1	0.099	3.4	0.79*	0.94	0.14	15,44*,67,78
2165	221-12 1	0.122	2.9	1.6	0.76 :	-	33,40,55*
2448	285-14 1	0.103	3.5	1.0	0.27	0.24	78,80*
2501	281- 5 1	0.108	5.1	1.2	0.31	0.37	32*,78
2553	285- 5 1	0.105	6.3	1.3 *	0.30	0.22	33*
2621	291- 4 1	0.119	5.0	6.3 *	1.4	0.21	33*
3568	123+34 1	0.096	3.5	0.83	0.14	0.23	35*,40,41
4191	304- 4 1	0.110	6.3	-	0.18	0.25	33
4406	319+15 1	0.141	5.3	-	0.48	-	40,46
4593	25+40 1	0.099	3.2	-	0.047	0.17	15,40,41
4634	0+12 1	0.087	4.1	0.32	0.032	0.24	6*
4673	3- 2 3	0.145	5.2	-	0.54	0.27	7
4732	10- 6 1	0.112	1.9	-	0.33	0.20	7,40,41
4776	2-13 1	0.085	6.6	-	0.12	0.17	6
4846	27- 9 1	0.092	3.8	2.6	0.15	0.20	6*,15,40
4997	58-10 1	0.117	1.1	0.41	-	-	27*,41
5117	89- 5 1	0.115	4.1	1.9	0.27	0.27	6*,41
5217	100- 5 1	0.099	4.2	1.3	0.22	0.20	6*,15,31,40,41, 78
A 50	78+18 1	0.089	-	-	0.40	-	46
A 77	97+ 3 1	-	2.6	-	0.04	-	45
BD+30	64+ 5 1	0.043	5.2 :	> 2.8	0.37 :	0.32 :	15,67,78,79
BV-1	119+ 0 1	0.174	3.0	-	1.5	-	51
Cn 2-1	356- 4 1	0.100	11.5	-	0.40	0.33	7,82
Cn 3-1	38+12 1	0.038	17. :	3.8 :	0.77 :	0.65 :	6*,15
H 1-11	2+ 8 1	0.10	3.7	-	-	-	82
H 1-18	357+ 2 4	0.174	5.1	-	1.8	0.24	7
H 1-20	358+ 3 6	0.12	10.	-	0.35	-	82
H 1-23	357+ 1 1	0.141	5.8	-	0.66	0.15	7

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TABLE 1—*Continued*

Name	PK	He:H	O:H * 10-4	C:O	N:O	Ne:O	Sources
H 1-32	355- 2 3	0.11	3.8	-	0.10	-	82
H 1-40	359- 2 3	0.11	3.4	-	-	-	82
H 1-44	358- 3 1	0.10	4.7	-	0.62	-	82
H 1-55	1- 4 1	-	32.	-	0.23	-	71
H 1-56	1- 4 2	0.10	5.3	-	0.08	-	82
H 1-59	3- 4 3	0.100	4.3	-	0.11	0.18	7
H 1-60	4- 4 1	0.10	> 4.3	-	-	-	82
H 2-15	3+ 5 1	0.14	> 5.3	-	-	-	82
H 2-18	6+ 4 1	0.126	3.3	-	1.5 :	0.15	7
H 2-24	4+ 1 1	0.14	> 0.4	-	-	-	82
H 2-26	356- 3 1	0.15	> 2.7	-	-	-	82
H 2-37	2- 3 2	0.11	> 4.2	-	0.36	-	82
Hb 8	3-17 1	0.19	> 2.7	-	0.19	-	82
Hb 12	111- 2 1	0.105	2.5	1.2 :	0.092	0.16	6*,74*
He 2-5	264-12 1	0.095	2.1	-	0.15	0.11	33
He 2-7	264- 8 1	0.085	2.4	2.0 *	0.40	0.17	33*
He 2-131	315- 3 1	-	4.7	0.30	0.38	0.31	2*,67
He 2-250	0- 3 1	0.13	15.	-	0.48	-	82
He 2-277	358- 0 2	-	1.4	-	0.32	-	65
Hf 2-2	5- 8 1	0.18	1.1	19. :	0.21	> 0.36	48
Hu 1-1	119- 6 1	0.092	5.7	-	0.19	0.21	6,15,40,41
Hu 1-2	86- 8 1	0.158	1.3	0.92	2.1	0.40	6*,40,41,59
Hu 2-1	51+ 9 1	0.096	2.5	2.0	0.12	0.11	6*,15,31*,53*
Hu 4	--	0.126	4.8	-	0.58	0.19	7
Hu 5	--	0.145	6.6	-	1.7	0.18	7
Hu 6	--	0.110	5.1	-	0.88	0.20	7
J 320	190-17 1	0.113	1.7	2.6	0.21	0.32	6*,15,40,41
J 900	194+ 2 1	0.096	3.2	4.1	0.16	0.25	6*,41,43
K 3-60	98+ 4 1	0.129	4.3	-	0.44	0.21	7
K 3-61	96+ 2 1	0.115	4.9	-	2.4	0.17	7
K 3-67	--	0.110	1.8	-	0.77	0.23	7
K 3-68	--	0.098	1.3	-	0.28	0.31	7
M 1-1	130-11 1	0.117	1.8	-	0.35	0.28	6,15
M 1-4	147- 2 1	0.094	2.7	-	0.28	0.17	7,40,45,47
M 1-5	184- 2 1	0.100	4.4	-	0.082	0.13	15
M 1-7	189+ 7 1	0.102	5.1	-	0.67	0.15	45,73
M 1-8	210+ 1 1	0.152	3.9	-	0.56	0.28	59
M 1-9	212+ 4 1	0.194	0.31	-	1.6	0.094	75
M 1-13	232- 1 1	0.121	6.6	-	0.50	0.27	45,59+
M 1-14	235- 1 1	> 0.088	3.2	11. *	0.13	0.10	44*,78
M 1-17	228+ 5 1	0.113	4.5	-	0.51	0.20	59
M 1-25	4+ 4 1	0.13	> 8.7	-	0.18	-	82
M 1-29	359- 1 1	0.14	5.2	-	0.32	-	82
M 1-30	355- 4 2	> 0.11	28. :	-	0.19	-	82
M 1-35	3- 2 1	0.162	3.0	-	2.1	0.15	7
M 1-38	2- 3 5	0.01	3.6	-	0.31	-	82
M 1-42	2- 4 2	0.170	4.7	-	1.7	0.28	7
M 1-44	4- 4 2	> 0.050	1.6	-	0.79 :	-	7
M 1-67	50+ 3 1	0.060	3.0	-	0.40	-	15
M 1-74	52- 4 1	0.108	5.4	1.9	0.20	0.28	6*,15
M 1-75	68- 0 1	0.186	6.2	-	1.7	0.28	7
M 1-78	93+ 1 1	0.095	1.17	-	0.47	-	7
M 1-79	93- 2 1	0.18	4.2	-	0.45	-	45
M 1-80	107- 2 1	0.091	3.9	1.9 *	0.51	0.13	7,44*
M 2-2	147+ 4 1	0.10 :	2.7	-	0.33	0.22	7
M 2-6	353+ 6 2	0.095	3.6	-	0.13	0.16	7
M 2-9 S/N	10+18 2	0.069	2.4	-	0.16	0.12	15
M 2-10	354+ 4 1	0.098	5.4	-	0.50	0.22	7
M 2-16	357- 3 2	0.13	6.0	-	0.44	-	82
M 2-21	0- 2 4	0.12	3.1	-	0.29	0.19	7
M 2-22	357- 4 2	0.14	3.4	-	0.9 :	-	82
M 2-23	2- 2 4	0.100	2.5	-	0.19	0.16	7
M 2-24	356- 5 2	0.13	0.67 :	-	0.68 :	-	82

TABLE 1—*Continued*

Name	PK	He:H	O:H * 10-4	C:O	N:O	Ne:O	Sources
M 2-27	359- 4 2	0.12	7.8	-	0.55	-	82
M 2-29	4- 3 1	0.13	0.28	-	0.37	-	82
M 2-30	3- 4 8	0.120	5.6	-	0.20	0.21	7
M 2-33	2- 6 1	0.093	4.2	-	0.095	0.19	7
M 2-36	3- 6 1	0.12	5.8	-	0.55	-	82
M 2-50	97- 2 1	0.042	1.7	-	0.18	0.21	15
M 2-55	116+ 8 1	0.137	4.9	-	0.53	0.37	46,59
M 3-1	242-11 1	0.147	1.7	3.7 *	0.48	0.33	33*
M 3-3	221+ 5 1	0.125	3.5	-	1.8	0.31	59
M 3-7	357+ 3 1	0.107	2.6	-	0.46	0.12	7
M 3-8	358+ 4 1	0.098	5.0	-	0.11	0.20	7
M 3-10	358+ 3 1	0.11	7.3	-	0.16	-	82
M 3-15	6+ 4 2	0.107	2.6	-	0.46	0.12	7
M 3-20	2- 2 2	0.098	5.0	-	0.106	0.20	7
M 3-33	9-10 1	0.09	> 3.0	-	-	-	82
M 3-35	71- 2 1	0.112	> 2.5	-	-	-	15
M 3-36	358+ 7 1	0.10	> 4.7	-	-	-	82
M 3-38	356+ 4 2	0.14	> 2.1	-	-	-	82
M 3-42	357+ 3 4	0.12	10.	-	1.96	-	82
M 3-43	0- 1 1	0.14	> 9.9	-	-	-	82
M 3-45	359- 1 3	0.10	2.8	-	0.26	-	82
M 3-46	359- 2 4	0.15	11.	-	0.59	-	82
M 3-48	359- 4 1	0.14	> 1.8	-	-	-	82
M 3-50	357- 6 1	0.13	> 8.9	-	-	-	82
M 4-3	357- 7 1	0.095	4.8	-	0.40	0.17	7
M 4-6	358+ 1 1	0.13	> 2.9	-	-	-	82
M 4-14	43- 3 1	-	2.2	-	0.32	-	40
Me 1-1	52- 2 2	0.126	4.7	-	0.73	0.25	7,40
Me 2-1	342+27 1	0.102	5.4	1.2	0.30	0.28	12
Me 2-2	100- 8 1	0.156	1.9	-	1.7 :	0.24	7,15,40,41,59
Mz 3	331- 1 1	0.18 :	-	-	1.26 :	-	22,24a
PB 6	278+ 5 1	0.183:	5.2 :	-	1.7 :	0.23 :	78
PC 12	0+17 1	0.09	6.6	-	0.09	-	82
Pe 2-11	2- 1 1	0.16	> 1.8	-	-	-	82
Sn 1	13+32 1	0.092	3.8	-	0.047	0.24	15,40,41
SwSt 1	1- 6 2	0.107	5.9	0.67	0.069	-	28*,64*
Vy 1-2	53+24 1	0.096	7.5	0.23*	0.15	0.20	15,40,43,44*
IRAS 15154-5258		0.40	11.3	-	-	-	54
IRAS 16455-3455		0.112	4.3	-	-	-	54
SUN	--	0.100	8.3	0.56	0.12	0.18	52

COL. 5.—An asterisk denotes C abundance from optical lines scaled via the procedure of Kaler 1981.

SOURCES.—A plus sign indicates that the chemical abundances only from that source have been adopted, except for carbon (see next comment); an asterisk indicates that the source provides information on the abundance of carbon and this was used to form the adopted C/O. (1) Adam & Koppen 1984; (2) Adams & Seaton 1982; (4) Aller et al. 1973; (5) Aller & Czyzak 1981; (6) Aller & Czyzak 1983; (7) Aller & Keyes 1987; (8) Aller et al. 1985; (9) Aller et al. 1988; (10) Aller et al. 1986; (11) Aller et al. (AKRO) 1981; (12) Aller et al. (AKC) 1981; (13) Aller et al. 1979; (14) Barker 1983; (15) Barker 1978; (16) Barker 1982; (17) Barker 1984; (18) Barker 1985; (18a) Barker 1987; (19) Barker 1989; (20) Benvenuti & Perinotto 1981; (21) Bohlin et al. 1978; (22) Calvet & Peimbert 1983; (23) Clegg et al. 1987; (24) Clegg et al. 1983; (24a) Cohen et al. 1978; (25) Danziger 1975; (26) Dufour 1984; (27) Flower 1980; (28) Flower et al. 1984; (29) Flower 1982; (30) Flower & Penn 1981; (31) French 1983; (32) Goharji & Adams 1984; (33) Gutierrez & Moreno 1988; (34) Harrington et al. 1980; (35) Harrington & Feibelman 1983; (36) Harrington et al. 1981; (37) Harrington et al. 1982; (38) Hawley 1978; (39) Hawley & Miller 1977; (40) Kaler 1978a; (41) Kaler 1978b; (43) Kaler 1980; (44) Kaler 1981; (45) Kaler 1983b; (46) Kaler 1983c; (47) Kaler 1985a; (48) Kaler 1988; (50) Kaler et al. 1987; (51) Kaler et al. 1988; (52) Lambert 1978; (53) Lutz 1981; (54) Manchado et al. 1989; (55) Marionni & Harrington 1981; (56) Pequignot 1980; (57) Pequignot et al. 1978; (59) Peimbert & Torres-Peimbert 1987; (60) Perinotto et al. 1980; (61) Perinotto & Benvenuti 1981a; (62) Perinotto & Benvenuti 1981b; (64) Pacheco et al. 1987a; (65) Pacheco et al. 1987b; (66) Pottasch et al. 1985; (67) Pottasch et al. (PPmOJK) 1986; (68) Pottasch et al. 1981; (69) Pottasch et al. 1982; (70) Pottasch et al. (PDM) 1986; (71) Price 1981; (72) Pwa et al. 1984; (73) Sabbadin et al. 1984; (74) Seaton 1983; (75) Shibata & Tamura 1985; (76) Shields et al. 1981; (77) Shields 1978; (78) Torres-Peimbert & Peimbert 1977; (79) Torres-Peimbert & Pena 1981; (80) Torres-Peimbert et al. 1981; (81) Torres-Peimbert et al. 1980; (82) Webster 1988.

various independent determinations on the individual objects, it is possible to say the following.

The adopted abundances of He/H should be in general accurate to within a 15%, those of O/H, C/H, N/H, and Ne/H should be better than a factor of 2, while the ratios between each two of the last four abundances should be correct to within 50%.

3. TYPE I PLANETARY NEBULAE

To analyze the data on the chemical abundances of PNs, it is appropriate to consider the classification scheme in four types proposed by Peimbert (Peimbert 1978; PTP83).

According to this classification, type I contains PNs with either He/H $\geq$ 0.125 or log (N/O ≥ -0.3. These PNs have been recognized to be morphologically filamentary and not central symmetric, but instead bipolar or biaxial; to have very strong forbidden lines of quite different excitation, from [O I] to [Ne V] and with kinematics and Galactic distribution resembling those of Population I stars. Type II contains the PNs (not He-N rich) in the solar neighborhood with an average height over the Galactic plane of $|Z| = 150$ pc. These PNs have been later subdivided into IIa [log (N/H) + 12 ≥ 8.0] and IIb [log (N/H) + 12 < 8.0] by Faundez-Abans & Maciel (1986). They are considered to resemble stars of intermediate Population I. Type III contains the PNs, not belonging to the halo, with an high velocity ($|\Delta V| > 60$ km s^{-1}). Type IV refers to the halo PNs, i.e., to those which are at high distance from the Galactic plane or belong to a globular cluster.

The PNs of type II and III are similar in chemical composition and thus may be considered together as disk PNs.

To my knowledge, the more extended list the type I PNs is the one given by PTP83. They list 29 objects with their abundance of He/H, N/O, O/H, and C/O. To these, one should add NGC 7293, M1-13 and M1-17 listed as Type I PNs by Peimbert & Torres-Peimbert (1987, hereafter PTP87).

From the present analysis it is found that 102 PNs meet the requirements for beeing classified as of type I. This includes, as occurred in the list of PTP83, objects where only one of the two quantities He/H or N/O is available. These 102 PNs are listed for convenience in Table 2. Note that in Table 2 there are entries not present in Table 1. That is because in Table 1 I have listed only the PNs with at least two abundances known (among the ones above indicate in § 2.2), while in Table 2 all the PNs are listed, for which at least one of the quantities He/H or N/O is known and satisfies the type I definition. That means that Table 2 contains in fact all the PNs which at present can be classified as type I PNs.

By comparing Table 2 with the list of PTP83, one sees that the following objects considered to be of type I by PTP83 are not in Table 2: NGC 650, 5189, 6629, and 6894. For NGC 650, 6629, and 6894, this is due to improved chemical abundances resulting in different values of He/H and/or N/O from those listed by PTP83. In the case of NGC 5189, I have omitted it because apparently the abundances of this object are not yet available. A comment is due for Mz 3. The chemistry of this object was studied by Cohen et al. (1978) with improvements by Calvet & Peimbert (1982). The abundances both of He/H and of N/O are very uncertain. The object has been therefore listed in Table 2 but has been omitted from the subsequent analysis.

With the present much larger number of type I PNs, it will be interesting to explore other characteristics of these objects, as their morphology and their spectroscopic and kinematical behavior, for a deeper understanding of this important class of PNs.

4. ABUNDANCES OF GROUPS OF PNs

It is convenient to give the averages abundances of the most abundant elements separately for type I and type II–III PNs. This is done in Table 3. In forming the averages, uncertain values or upper/lower limits have been omitted. Furthermore the following PNs have been excluded from the averages, because their abundances are too different from the mean of the others. Among PNs of type I: Cn 3-1 and IRAS 15154-5258 for He/H; NGC 6153 and M3-42 for N/H; M1-9 for Ne/H; and among type II–III: H1-55 for C/H, N/H, O/H. A part from this, all the objects listed in Table 1 (i.e., with the chemical abundances of at least two elements reasonably well known) have been used in forming the averages for type II–III PNs. In case of the PNs of type I, all the objects listed in Table 2 have been used. Therefore also Vy 1-1 and Vy 2-2, for which only the abundance of helium is reasonably well known, have been included.

It must be noted that among the PNs listed in Table 1, and therefore with two abundance ratios measured (among He/H, O/H, C/O, N/O, Ne/O), 91 have been classified of type I and the remaining 118 of type II–III. However in only 103 of the latter PNs, both He/H and N/O have been measured. As a consequence, some among the remaining (118 − 103) = 15 PNs (6 of which are lacking of He/H and 9 of N/O), might be of type I, with the unavailable ratio matching the request for type I. However, the probability for this to occur is very low.

In fact the probability for any PN to be of type I is equal to 91/209, i.e., about 44%. Moreover among the type I PNs listed in Table 2, 80 have both He/H and N/O measured. Of these, 13 are rich only in He, 29 only in N/O, and 38 are rich both in He/N and N/O. Therefore the probability for a type I PN to be such for being overabundant only in He, is of $13/80 * 100 = 16\%$. And the probability for a type I PN to be such for being overabundant only in N/O, is of $29/80 * 100 = 36\%$.

As a consequence, the expected number of type I PNs among the above nine objects, classified as of type II–III from He/H and lacking of N/O is of $9 * 0.44 * 0.36 = 1.4$. Similarly, the expected number of PNs of type I, among the six above objects, classified to be of type II–III from N/O and lacking of He/H, is of $6 * 0.44 * 0.16 = 0.4$. It is then fully justified to consider all these 15 PNs to be of type II–III.

The average abundances are presented both as simple numbers with their standard deviation and in the usual log (A/H) + 12 notation. The three meaningful digits of the logarithmic notation reproduce the original numbers to the second meaningful digit, which is internally consistent with their standard deviation.

The determination of the abundance of He deserves a comment. It has been recently recognized that the role of the collisional excitation of the metastable $2\,^3S$ level of He I in contributing to the formation of the He I "recombination" lines is larger than previously assumed (Ferland 1986). The problem has been further studied by PTP87 and by Clegg (1987). This particular effect was not taken into account by the authors whose abundances enter in the present compilation, with the exception of the study of 13 PNs of type I by PTP87.

Owing to this effect, an abundance of He should be lowered by some 10% (cf. Clegg 1989). On the other hand, one has to bear in mind that, particularly in the PNs of lower ionization, the abundance of He is underestimated because the neutral He is not counted. All in all, is has been decided not to apply here any correction to the He abundance for the mentioned effect.

Looking at the averages abundances given in Table 3, it is evident that (1) the average abundance of neon is similar in PNs of type I and of types II–III and is close to the solar value; (2) the average abundance of oxygen again is identical in the two groups of PNs and is definitely below the solar value by a factor 1.8; (3) helium and nitrogen are enhanced in type I PNs relatively to types II–III (following the definition) by factors

TABLE 2

PLANETARY NEBULAE OF TYPE I

Name	PK	He:H	O:H * 10-4	C:O	N:O	Ne:O	Sources
NGC 2346	215+ 3 1	0.155	3.8	-	0.45	0.34	
2371-2	189+19 1	0.124	5.6	3.2 :	0.54	0.29	
2392	197+17 1	0.090	3.8	0.55	0.50	0.17	
2440	234+ 2 1	0.135	5.0	0.72	1.3	0.20	
2452	243- 1 1	0.111	6.7	-	0.70	0.21	
2474	164+31 1	-	-	-	1.2	-	
2818	261+ 8 1	0.162	3.2	0.47	0.97	0.31	
3132	272+12 1	0.128	9.5	-	0.51	0.38:	
5315	309- 4 2	0.125	6.1	1.6	1.1	0.33	
5873	331+16 1	0.114	3.5	3.0 *	0.56	0.17	
6153	341+ 5 1	0.13	10.	0.80	2.0	0.25	
6302	349+ 1 1	0.225	5.0	0.20	1.7	0.40	
6369	2+ 5 1	0.132	2.9	-	0.41	0.14	
6439	11+ 5 1	0.135	4.5	-	0.64	0.24	
6445	8+ 3 1	0.23	2.5	-	1.2	-	
6537	10+ 0 1	0.24	1.6	-	1.8	-	
6563	358- 7 1	0.15 :	1.5	-	1.8	-	
6565	3- 4 5	0.111	5.9	1.1	1.0	0.24	
6620	5- 6 1	0.115	6.9	-	0.65	0.22	
6741	33- 2 1	0.123	6.7	1.2 :	1.1	0.33	
6751	29- 5 1	0.105	3.7	-	0.59	0.19	
6778	34- 6 1	0.155	2.2	4.5	1.5	1.1	
6781	41- 2 1	0.129	4.3	-	0.51	0.16	
6790	37- 6 1	0.130	3.6	1.8	0.20	0.15	
6803	46- 4 1	0.130	5.0	1.1	0.48	0.32	
6804	45- 4 1	0.138	3.2	-	-	0.16	
6833	82+11 1	0.109	1.2	0.77 *	0.66 :	0.29	
6853	60- 3 1	0.121	4.1	1.4	0.70	0.54	
6881	74+ 2 1	0.116	5.6	-	0.62	0.17	
6886	60- 7 2	0.133	4.7	1.4	0.64	0.32	
7008	93+ 5 2	0.135	-	-	1.4	-	
7293	36-57 1	0.136:	7.8	-	0.40	< 0.54	
7354	107+ 2 1	0.126	4.0	-	0.83	0.18	
IC 1297	358-21 1	0.117	6.1	3.1 :	0.52 :	0.25	
2003	161-14 1	0.113	3.4	2.0	2.4	0.17	
2149	166+10 1	0.099	3.4	0.79:*	0.94	0.14	
2165	221-12 1	0.122	2.9	1.6	0.76 :	-	
2621	291- 4 1	0.119	5.0	6.3 :*	1.4	0.21	
4406	319+15 1	0.141	5.3	-	0.48	-	
4673	3- 2 3	0.145	5.2	-	0.54	0.27	
A 4	144-15 1	-	-	-	0.67	-	46
A 24	214+14 1	-	-	-	> 2.7	-	46
A 35	303+40 1	-	-	-	0.8	-	46
A 71	85+ 4 1	-	-	-	2.4 :	-	46
A 82	114- 4 1	-	-	-	0.53	-	46
BV-1	119+ 0 1	0.174	3.0	-	1.5	-	
Cn 3-1	38+12 1	0.038	17. :	3.8 :	0.77 :	0.65 :	
CRL 618	--	-	-	-	0.79	-	22
H 1-18	357+ 2 4	0.174	5.1	-	1.8	0.24	
H 1-23	357+ 1 1	0.141	5.8	-	0.66	0.15	
H 1-44	358- 3 1	0.10	4.7	-	0.62	-	
H 2-18	6+ 4 1	0.126	3.3	-	1.5 :	0.15	
H 2-24	4+ 1 1	0.14	> 0.4	-	-	-	
H 2-26	356- 3 1	0.15	> 2.7	-	-	-	
Hb 8	3-17 1	0.19	> 2.7	-	0.19	-	
Hf 2-2	5- 8 1	0.18	1.1	19. :	0.21	> 0.36	
Hu 1-2	86- 8 1	0.158	1.3	0.92	2.1	0.40	
Hu 4	--	0.126	4.8	-	0.58	0.19	

TABLE 2—*Continued*

Name	PK	He:H	O:H * 10-4	C:O	N:O	Ne:O	Sources
Hu 5	--	0.145	6.6	-	1.7	0.18	
Hu 6	--	0.110	5.1	-	0.88	0.20	
Jn 1	104-29 1	-	-	-	0.67	-	46
K 3-60	98+ 4 1	0.129	4.3	-	0.44	0.21	
K 3-61	96+ 2 1	0.115	4.9	-	2.4	0.17	
K 3-67	--	0.110	1.8	-	0.77	0.23	
M 1-7	189+ 7 1	0.102	5.1	-	0.67	0.15	
M 1-8	210+ 1 1	0.152	3.9	-	0.56	0.28	
M 1-9	212+ 4 1	0.194	0.31	-	1.6	0.094	
M 1-13	232- 1 1	0.121	6.6	-	0.50	0.27	
M 1-17	228+ 5 1	0.113	4.5	-	0.51	0.20	
M 1-25	4+ 4 1	0.13	> 8.7	-	0.18	-	
M 1-29	359- 1 1	0.14	5.2	-	0.32	-	
M 1-35	3- 2 1	0.162	3.0	-	2.1	0.15	
M 1-42	2- 4 2	0.170	4.7	-	1.7	0.28	
M 1-44	4- 4 2	> 0.050	1.6	-	0.79 :	-	
M 1-75	68- 0 1	0.186	6.2	-	1.7	0.27	
M 1-79	93- 2 1	0.18	4.2	-	0.45	-	
M 1-80	107- 2 1	0.091	3.9	1.9 :*	0.51	0.13	
M 2-10	354+ 4 1	0.098	5.4	-	0.50	0.22	
M 2-22	357- 4 2	0.14	3.4	-	0.9 :	-	
M 2-24	356- 5 2	0.13	0.67 :	-	0.68 :	-	
M 2-27	359- 4 2	0.12	7.8	-	0.55	-	
M 2-36	3- 6 1	0.12	5.8	-	0.55	-	
M 2-55	116+ 8 1	0.137	4.9	-	0.53	0.37	
M 3-1	242-11 1	0.147	1.7	3.7 :*	0.48	0.33	
M 3-3	221+ 5 1	0.125	3.5	-	1.8	0.31	
M 3-38	356+ 4 2	0.14	> 2.1	-	-	-	
M 3-42	357+ 3 4	0.12	10.	-	1.96	-	
M 3-43	0- 1 1	0.14	> 9.9	-	-	-	
M 3-46	359- 2 4	0.15	11.	-	0.59	-	
M 3-48	359- 4 1	0.14	> 1.8	-	-	-	
M 3-50	357- 6 1	0.13	> 8.9	-	-	-	
M 4-6	358+ 1 1	0.13	> 2.9	-	-	-	
Me 1-1	52- 2 2	0.126	4.7	-	0.73	0.25	
Me 2-2	100- 8 1	0.156	1.9	-	1.7 :	0.24	
PB 6	278+ 5 1	0.183:	5.2 :	-	1.7 :	0.23 :	
Pe 2-11	2- 1 1	0.16	> 1.8	-	-	-	
PW 1	158+17 1	-	-	-	1.5 :	-	46
Sh 2-71	36- 1 1	-	-	-	6.8 :	-	46
Vy 1-1	118- 8 1	0.139	-	-	-	-	41,44
Vy 2-2	45- 2 1	0.143	-	-	-	-	43
Ym 29	205+14 1	-	-	-	1.1	-	46
IRAS 15154-5258		0.40	11.3	-	-	-	

Sources: The sources are given only for the objects with the data of only one column of abundances available. For the correspondence between a source number and its reference, see the notes to Table 1. For the other PNs the sources are those in Table 1.

Stars (*): Carbon abundance derived from optical lines via calibration through UV lines (cf. Kaler 1981).

TABLE 3

CHEMICAL ABUNDANCES IN GALACTIC PNs[a]

	Type I		Type II–III		
ELEMENTS	Simple Values	log Notation	Simple Values	log Notation	SUN log Notation
He/H	0.137 ± 0.029 (85)	11.14	0.103 ± 0.015 (105)	11.01	11.0
C/H	$(5.27 \pm 2.93) * 10^{-4}$ (15)	8.72	$(6.56 \pm 3.67) * 10^{-4}$ (103)	8.82	8.67
N/H	$(3.94 \pm 2.60) * 10^{-4}$ (64)	8.60	$(1.17 \pm 1.14) * 10^{-4}$ (99)	8.07	7.99
O/H	$(4.64 \pm 2.24) * 10^{-4}$ (75)	8.66	$(4.57 \pm 2.45) * 10^{-4}$ (103)	8.66	8.92
Ne/H	$(1.11 \pm 0.56) * 10^{-4}$ (55)	8.05	$(9.71 \pm 5.78) * 10^{-5}$ (80)	7.99	7.92

[a] In parentheses, below the average abundance, is the number of PNs. Objects with uncertain abundances or lower/upper limits have been omitted (see also text).

1.3 and 3.4, respectively; (4) carbon is similar in the two groups of PNs, apparently a bit higher (factor 1.25) in types II–III, and close to the solar value.

Clearly C/O is below the solar value in both classes of objects. This has been noticed in several studies (e.g., Torres-Peimbert & Peimbert 1977; Perinotto, Panagia, & Benvenuti 1980; French 1983). While a general discussion on the possible interpretation of the observed behavior of the chemical abundances is deferred to § 6, here I simply remind that the underabundance of oxygen has been explained with the existence of various PNs with central stars older than the Sun or with the theory of stellar evolution underestimating a lowering of oxygen during the evolution of the progenitors of the PNs.

It is clear that the first explanation cannot hold because the underabundance of oxygen refers also to type I PNs, which are believed to represent stars more massive than the Sun while, on the other hand, neon is instead solar both in PNs of type I and in PNs of type II–III. Therefore, the second possibility, involving the theory of stellar evolution, should be carefully explored.

5. CORRELATIONS BETWEEN CHEMICAL ELEMENTS

The study of the correlations between the abundances of different chemical elements is clearly a powerful tool for understanding the evolution of the central stars of planetary nebulae (cf. Kaler 1985a). Indeed, one of the main motivations of the present work has been to provide the largest set of relatively accurate data, to allow comparison with the prediction of the evolutionary theory (see § 1).

To this aim, the data of Table 1 have been examined for the existence of correlations between the abundances of He, C, N, O, and Ne. This was done separately for different groups of PNs. To justify these groups, it is to be remembered that the definition of type I PNs includes objects with enhanced abundance of He/H or of N/O. PNs enhanced in both of these quantities are, therefore, in a sense, more strictly of type I than those enhanced in only one of the two quantities. To account for this, I call PNs of type I (−/+) those of type I according to the original definition, PNs of type I (−) those which are enhanced in only one of the two above quantities and of type I (+) those which are enhanced both in He/H and in N/O.

All the data of Table 1 have been considered, except for Mz 3, excluded for the reasons given in § 1.

The relationships between abundance ratios have been examined separately for (1) all the PNs of Table 1 (evidently having entries in the specific abundances) (2) the PNs of type I (−/+) (3) the PNs of type I (−), (4) the PNs of type I (+); and (5) the PNs of type II–III.

A number of these relationships are plotted in Figures 1–16.

From these figures it is first of all clear that the dispersion of the data are always much larger than the expected errors, which, I remind the reader, have been evaluated to be of a 15% for He/H, of a factor of 2 for A/H (A = C, N, O, Ne) and of a 50% for A/B (A, B = C, N, O, Ne) (cf. § 2.3).

Looking at the individual Figures, we have the results summarized in Table 4, where the evidence for a correlation is indicated as follows: no (not existent), vf (very feeble), f (feeble), y (clear), m (marked). The meaning of the designations 'vf' is that there is just an indication that a correlation might exist. In these cases more observations would be needed to confirm or deny the reality of the correlation. A '+' or a '−' in parenthesis designates a positive or negative correlation, respectively.

No effort was made to define mathematically the character of the correlations (when present), in particular to establish to which level of probability they are linear or not and to calculate the corresponding correlation coefficients. In fact the dispersion of the data points is often high, so that a qualitative discussion was considered adequate.

6. DISCUSSION

Before a comparison with the theoretical predictions is attempted, one should clearly consider the possible existence of radial gradients of chemical abundances in the Galaxy. The

TABLE 4

CORRELATIONS BETWEEN CHEMICAL ABUNDANCES IN PNs[a]

ELEMENTS	TYPES					FIGURE
	I–II–III	I(−/+)	I(−)	I(+)	II–III	
He/H, C/H	no	vf(−)	no	f(−)	no	1
He/H, N/H	vf(+)	no	no	no	vf(+)	2
He/H, Ne/H	no	no	no	no	vf(+)	3
He/H, C/O	no	no	no	f(−)	no	4
He/H, N/O	y(+)	no	vf(−)	f(+)	f(+)	5
O/H, N/H	y(+)	m(+)	m(+)	y(+)	y(+)	6
O/H, Ne/H	m(+)	m(+)	m(+)	m(+)	m(+)	7
O/H, C/O	no	no	no	f(−)	no	8
O/H, N/O	no	no	no	f(−)	f(+)	9
N/H, Ne/H	y(+)	f(+)	f(+)	f(+)	y(+)	10
N/H, N/O	m(+)	y(+)	y(+)	f(+)	y(+)	11
Ne/H, C/H	no	vf(+)	f(+)	f(+)	no	12
Ne/H, N/O	no	no	no	no	vf(+)	13
N/O, Ne/O	vf(+)	no	no	no	vf(+)	14
Ne/O, C/O	no	no	no	vf(+)	no	15
C/N, O/N	y(+)	y(+)	y(+)	f(+)	y(+)	16

[a] The evidence for a correlation is designated as no (not present), vf (very feeble), f (feeble), y (clear), m (marked). A (+) or (−) indicates positive or negative correlation, respectively. The following pairs of abundances do not show meaningful correlations: (He/H, O/H); (O/H, C/H); (He/H, Ne/O); (O/H, Ne/O); (N/H, C/H); (N/O, C/O).

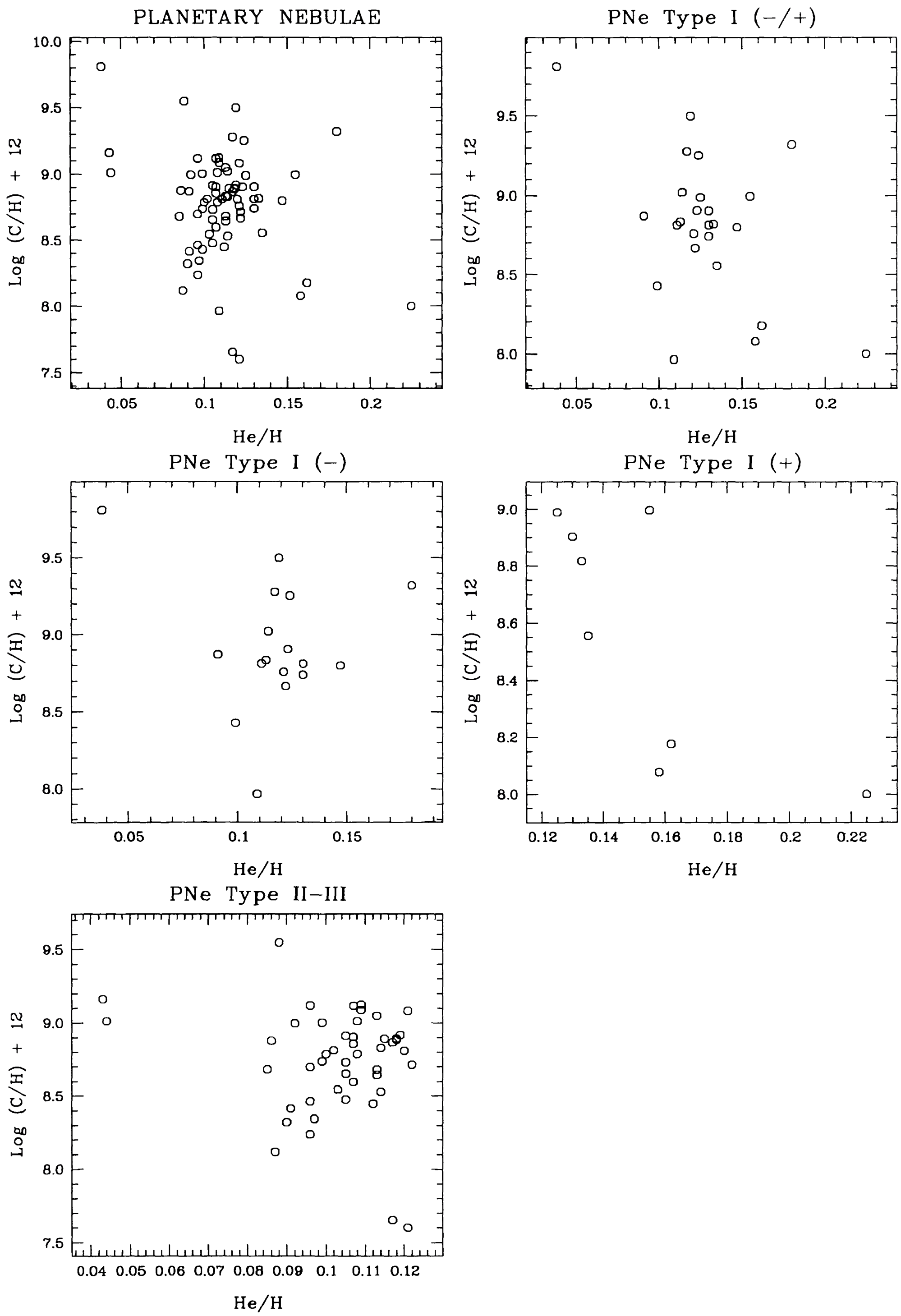

FIG. 1.—Abundances of carbon vs. helium for the galactic PNs in Table 1 separately for (*a*) all PNs of types I–II–III, (*b*) only PNs of type I (−/+), (*c*) only PNs of type I (−), (*d*) only PNs of type I (+), and (*e*) only PNs of types II–III.

matter is still controversial. According to Kaler (1985b), the vertical gradients in the Galaxy are more important in PNs than radial or horizontal gradients. However, the recent radial gradient in O/H found by Faundez-Abans & Maciel (1986) for type II Galactic PNs seems rather convincing. The matter might be further investigated using the present data base of chemical abundances, but this is beyond the purposes of the present paper.

It is to be noted, however, that the effects of radial galactocentric gradients of chemical composition in PNs, although apparently not negligible relative to the abundances produced by the stellar nucleosyntesis, should to a first approximation

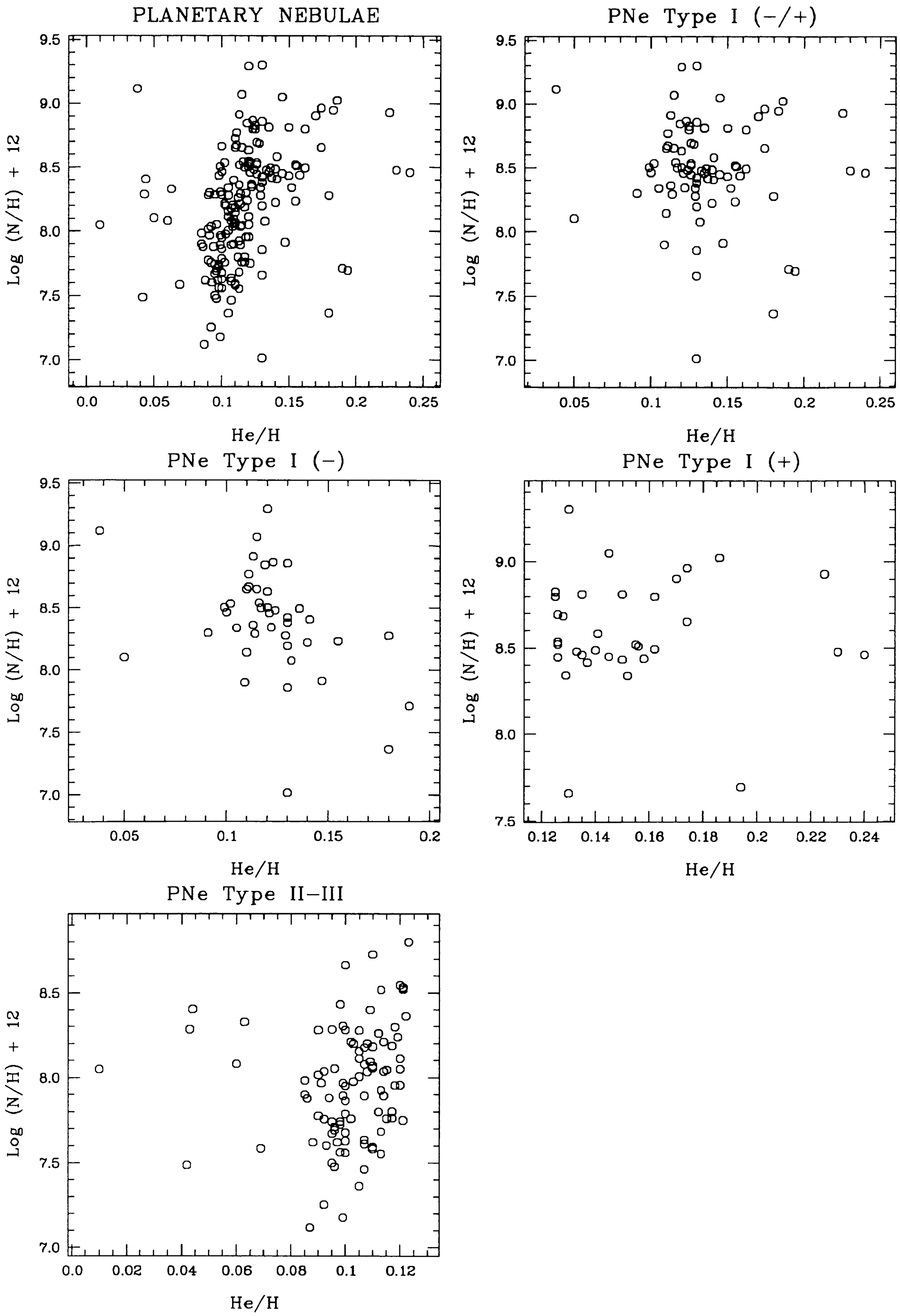

FIG. 2.—Same as in Fig. 1 for N/H vs. He/H

affect the progenitors in each mass interval in the same way. If so, they should produce a scatter in the chemical abundances over the values from the stellar nucleosyntesis, with not much disturbance on the latter.

It is now appropriate to recall the present status of the theory on the predictions of the chemical abundances in the ejected envelope of an intermediate-mass star at the tip of its AGB evolution.

6.1. *Theoretical Predictions*

It has been noted (see the Introduction) that the theory of stellar evolution predicts a number of "mixing" processes be-

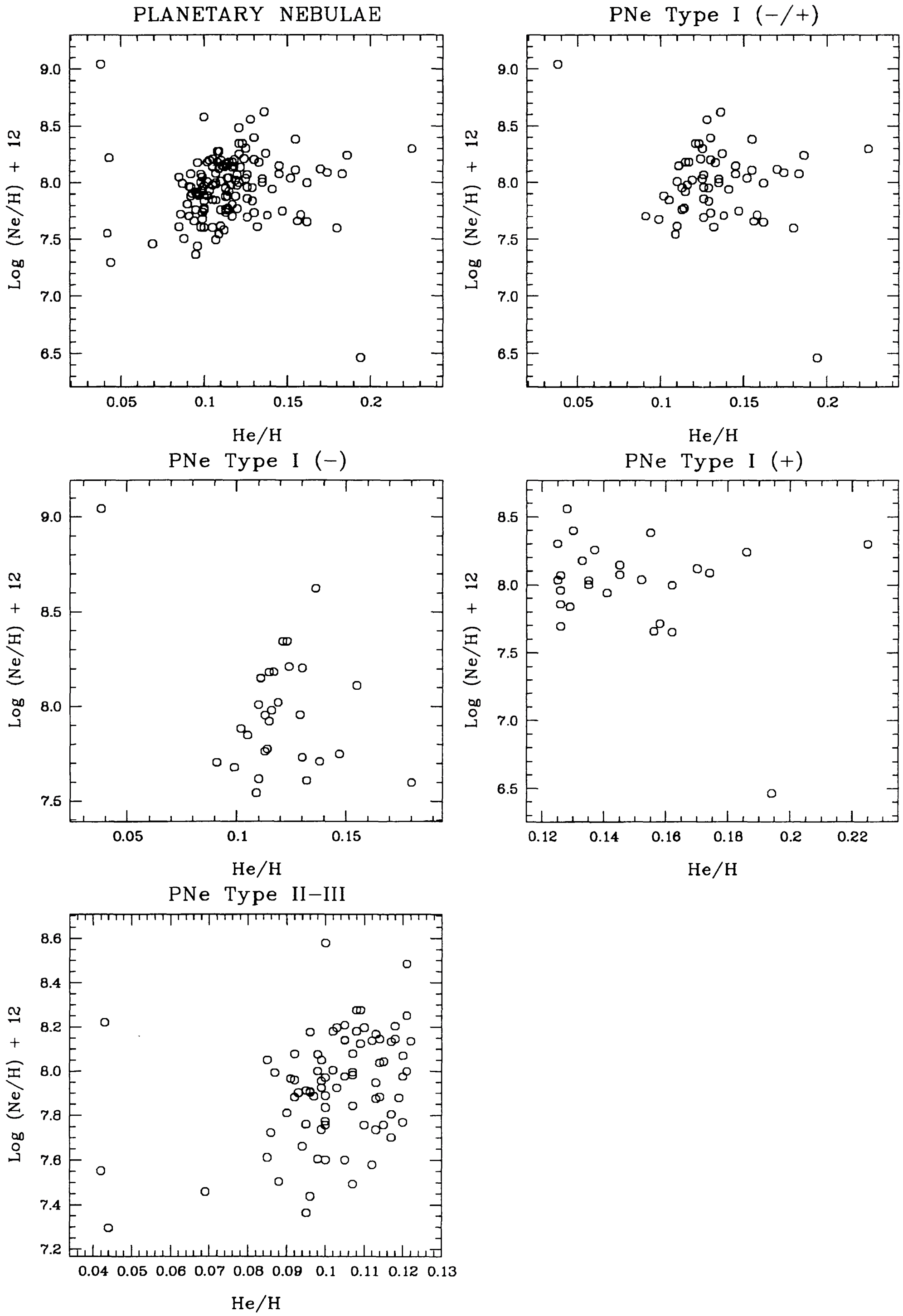

FIG. 3.—Same as Fig. 1 for Ne/H vs. He/H

tween the envelope and the stellar interior during the life-time of the intermediate-mass star before the ejection of the H-rich envelope (cf. Iben & Renzini 1983). In the so-called first dredge-up process, occurring for all the intermediate stars during the RG phase, the main changes in chemical composition of the envelope concern N which is enhanced by a factor 2, irrespective of the initial mass of the progenitor, and C which is lowered by some 30%. In the second dredge-up, occurring to stars in the main sequence more massive than 2.5 $M_{\odot}$, He is enhanced and N is also enhanced by a further factor close to 2 (for the most massive progenitors), while C is again lowered by a small quantity. In the third dredge-up process, occurring

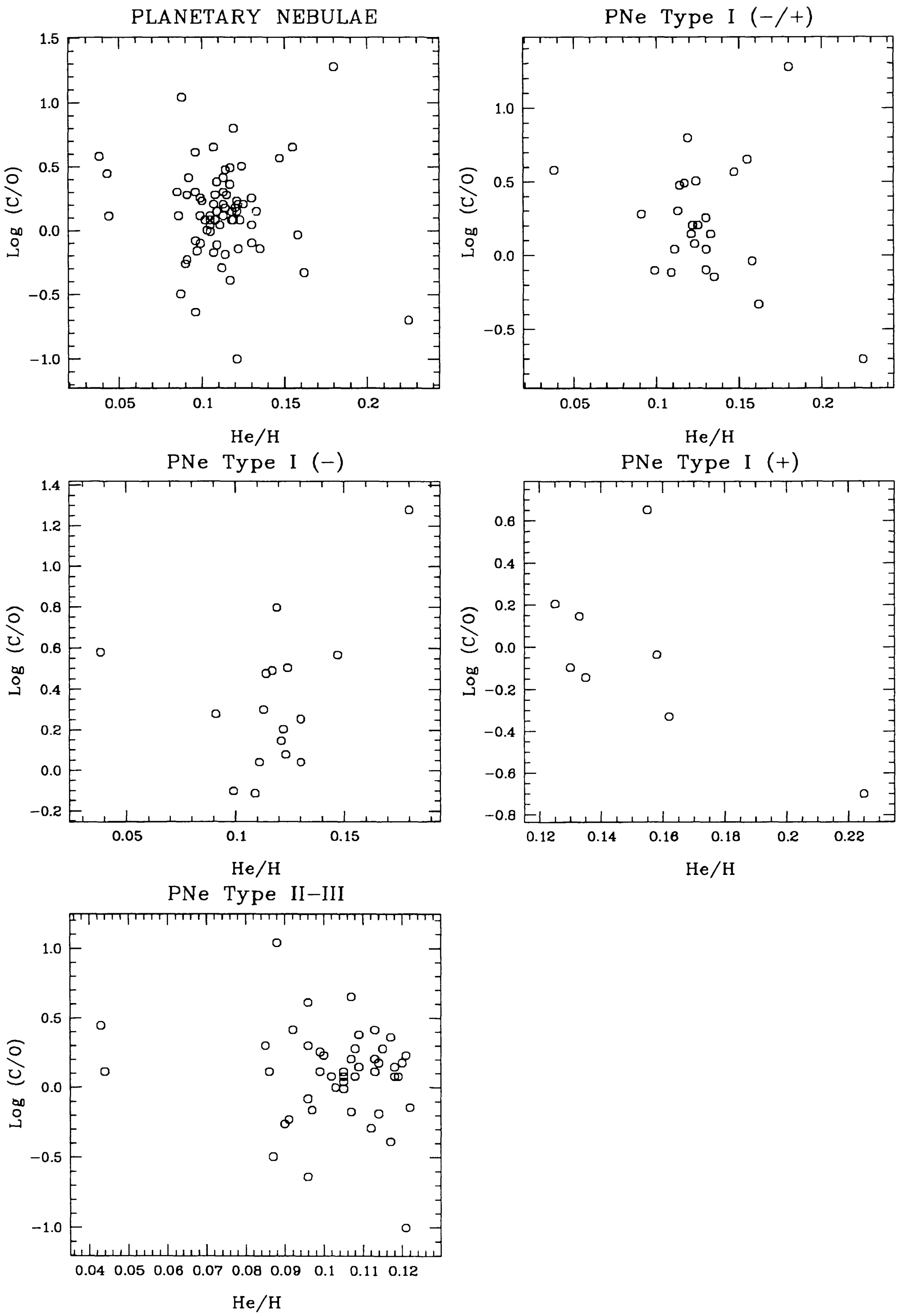

FIG. 4.—Same as Fig. 1 for C/O vs. He/H

along the AGB phase, nitrogen is lowered by a small amount while C/O may be enhanced by a factor up to 50 or so for the most massive stars. In the so-called EB process (burning at the base of the envelope), N/O may be enhanced by a similar factor of 60 for the most massive progenitors. Other mixing processes expected to be produced by rotational driven instabilities have not been yet adequately investigated.

Predictions have been made by Becker & Iben (1980) and by Renzini & Voli (1981). The last authors have predicted the abundance ratios of He/H, C/O, and N/O in the H-rich enve-

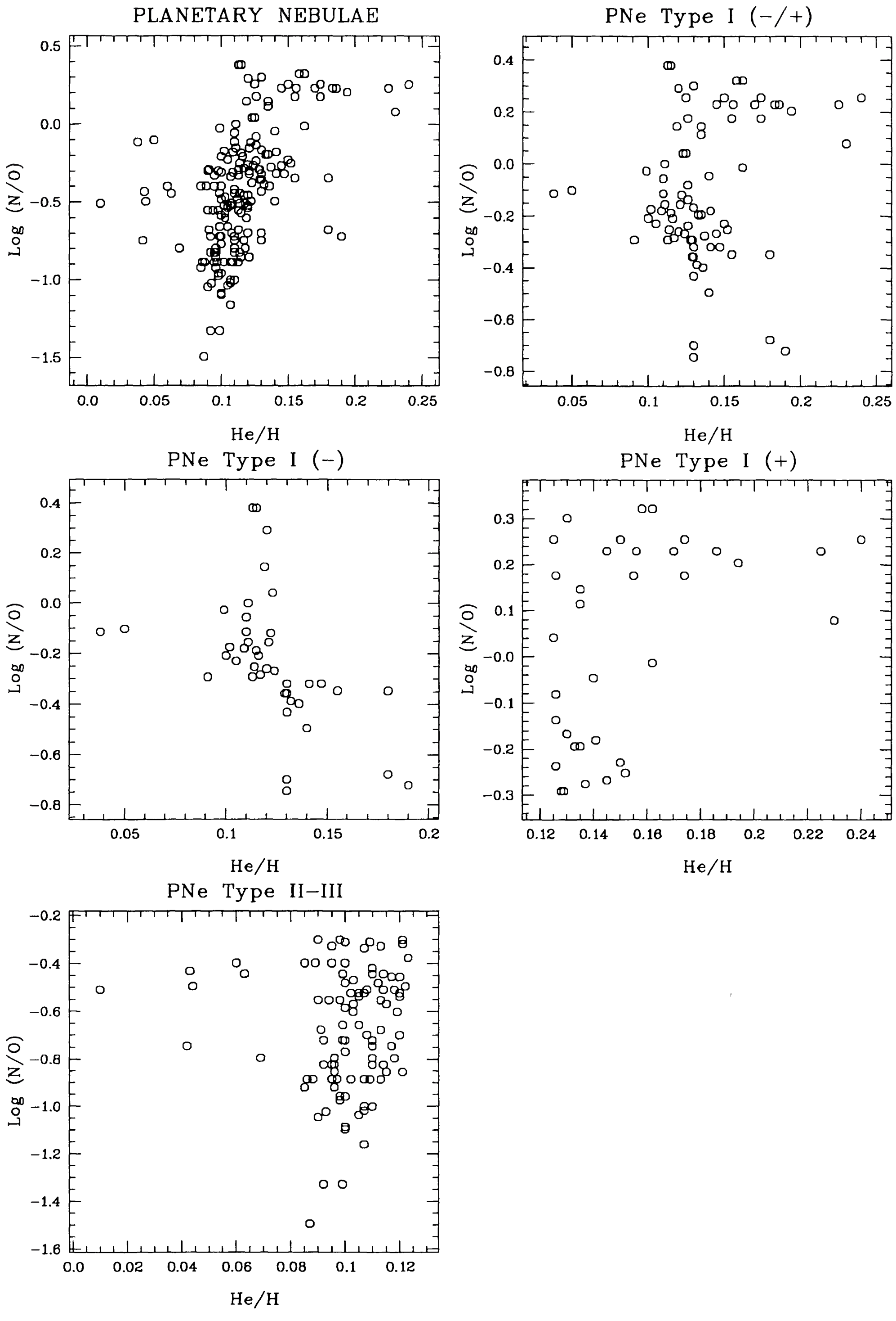

FIG. 5.—Same as Fig. 1 for N/O vs. He/H

lope at the moment of its ejection, as function of the initial mass of the progenitor for solar initial abundances, considering the above mentioned four processes.

A detailed comparison of the observed abundances with the above theoretical predictions cannot however be easily made. This is because the third dredge-up process was considered to occur only for the most massive stars (>2.5 $M_{\odot}$) at the time of the Renzini and Voli work, while it was later found that it occurs also for smaller masses. And because is has also been later recognized that the third dredge-up process may also not

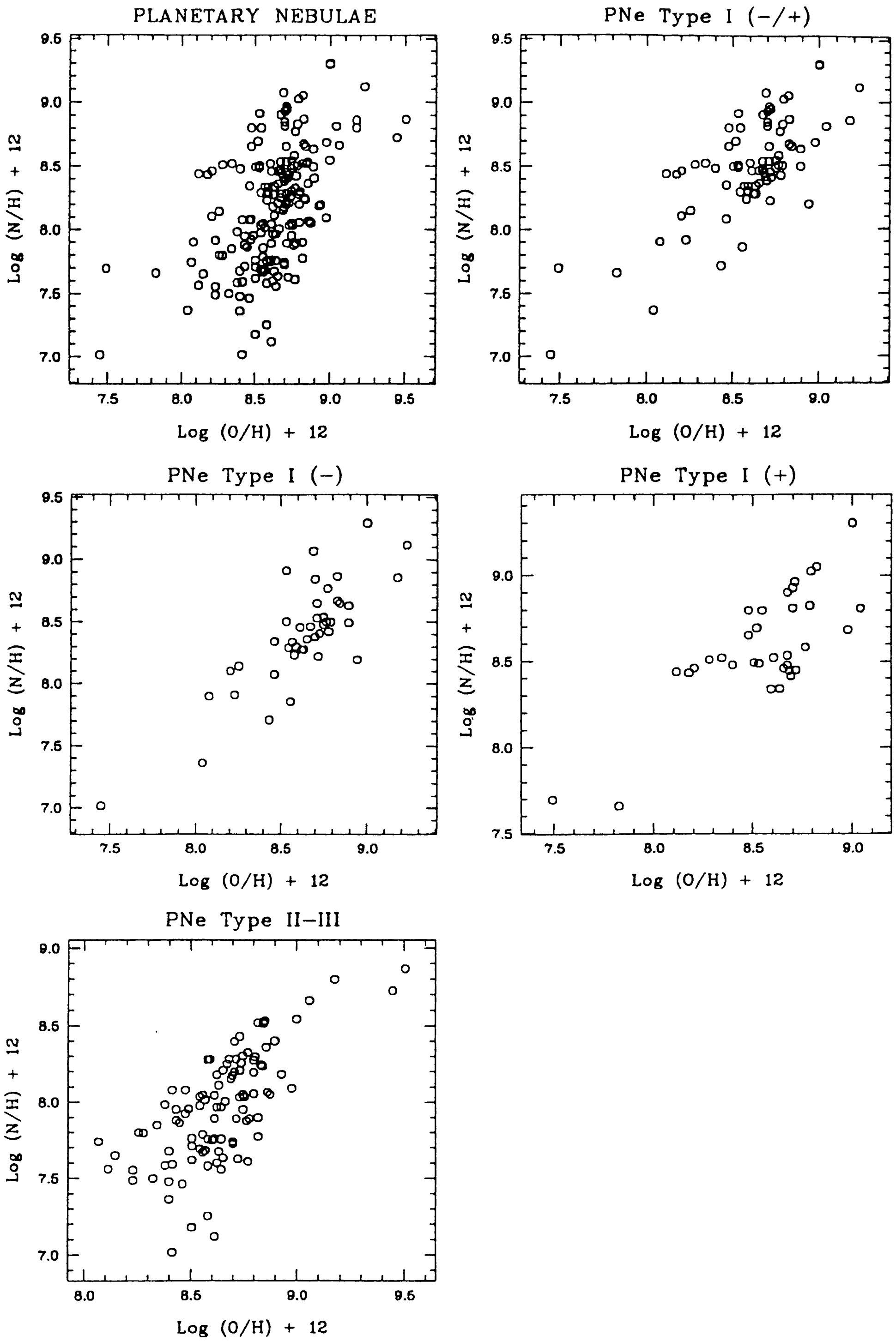

FIG. 6.—Same as Fig. 1 for N/H vs. O/H

occur at all, the ejection possibly occurring before the on-set of this process, due to a mechanism driven by the radiation pressure (cf. Renzini 1990).

In the following an effort is made, however, to understand the basic observational facts along the lines of the available theoretical predictions.

6.2. *The Observed Abundances and Comparison with the Theory*

The strongest correlation, applying to all kinds of the considered PNs, is that between Ne/H and O/H (Fig. 7). It is a positive, apparently rather linear relationship, known for some

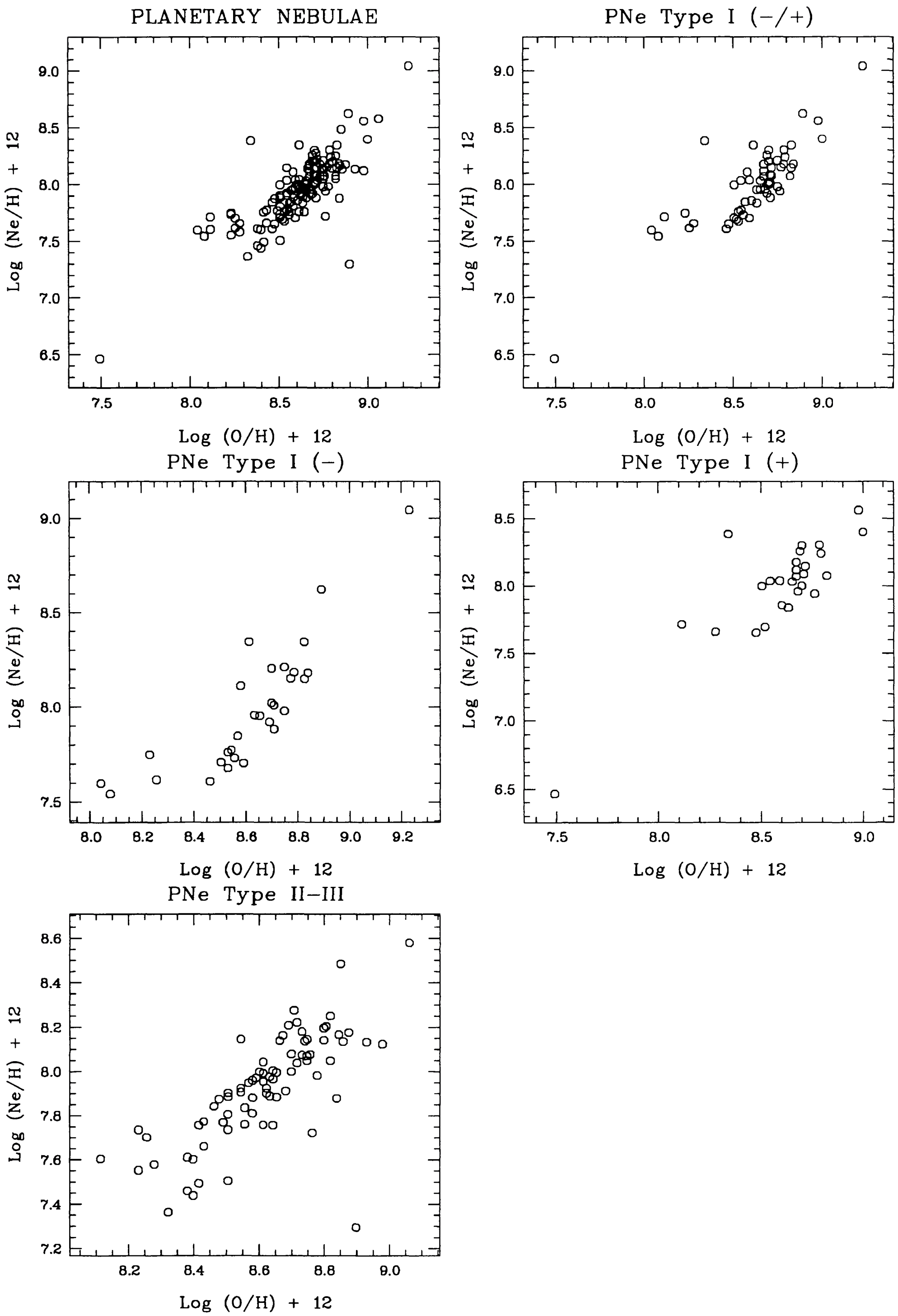

FIG. 7.—Same as Fig. 1 for Ne/H vs. O/H

time (Kaler 1978a), which has been recently extensively studied by Henry (1989a, b) in 171 PNs, 84 of which are located in the Galaxy, and the others in the Large and the Small Magellanic Clouds and in M31. This correlation clearly suggests that the ratio of the concentrations of these elements has not been appreciably modified by nucleosynthesis during the lifetime of the progenitor stars, with respect to the original ratio established by the preceeding stellar population. This of course as far as the observed abundances reflect, as they should, the chemical history of the stellar core. This hypothesis is in fact maintained through all the subsequent discussion.

The tendency noticed by Henry (1989b) for type I PNs to

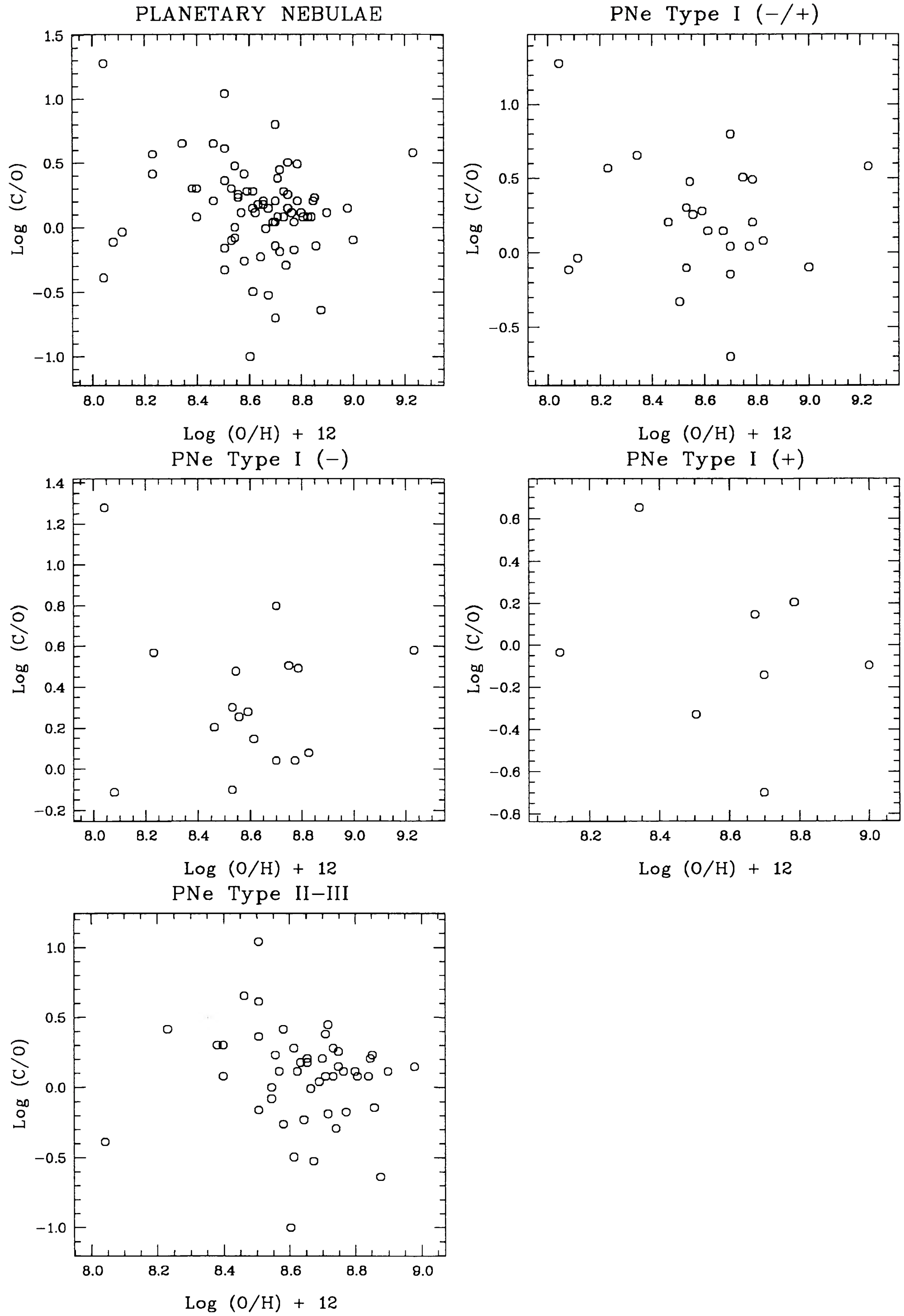

FIG. 8.—Same as Fig. 1 for C/O vs. O/H

deviate to the left of the linear relationship (Ne/H, O/H) at the lowest values of Ne/H, appears to be confirmed in the present richer sample of Galactic PNs. It occurs for an abundance of Ne a bit higher than that found by Henry, i.e., 7.7 instead 7.3, with no type I PNs in the present sample below 7.5. There is, however, a PN of type I (+), which would deny the reality of such tendency. It is interesting to confirm the abundances of this object.

Considering that during the evolution of a progenitor of a PN, Ne/H should not change, the above relationship means that also O/H has not been modified substantially. On the other hand, we have seen (§ 5) that the mean value of O/H is,

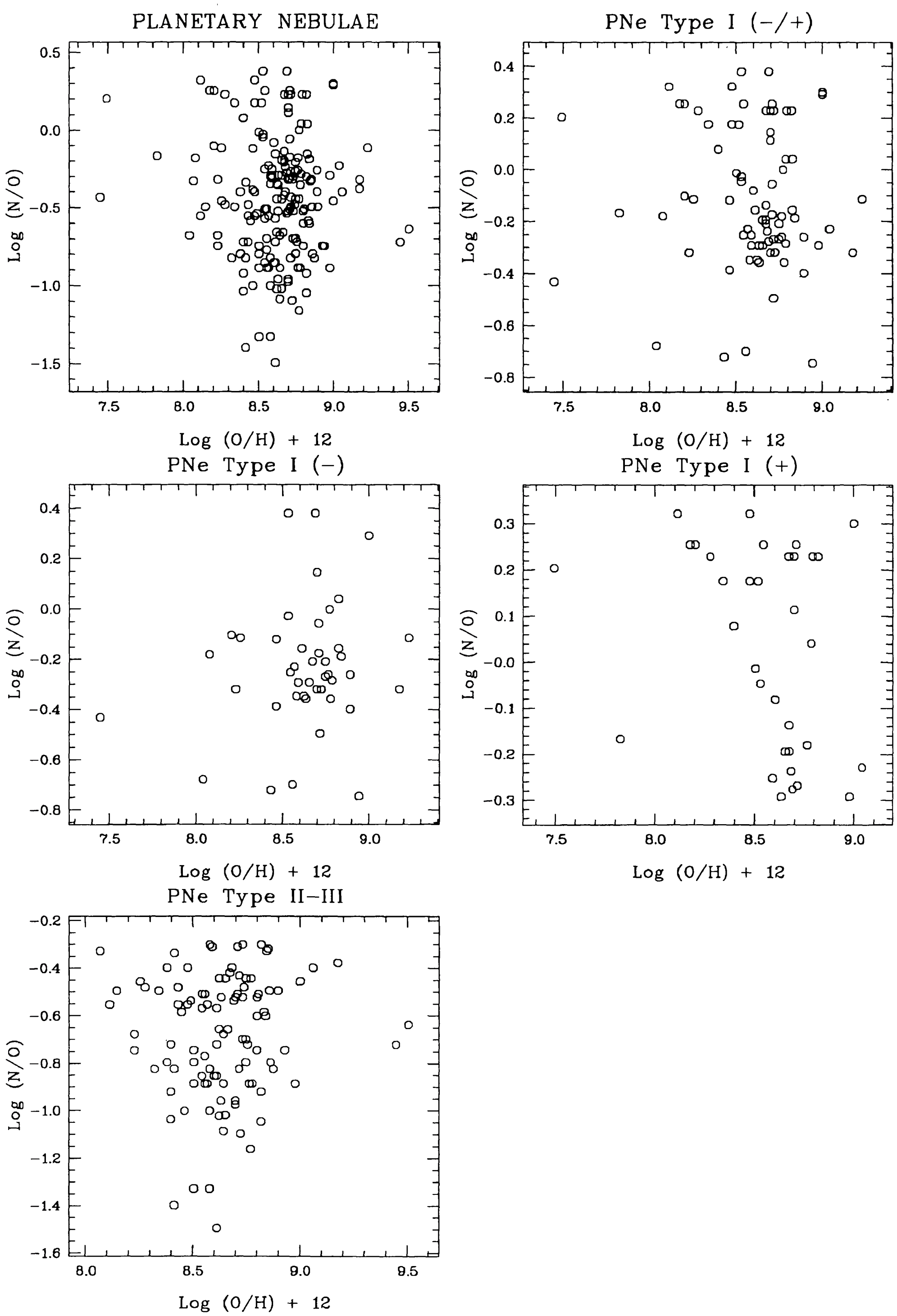

FIG. 9.—Same as Fig. 1 for N/O vs. O/H

in PNs, smaller than in the Sun by a factor of 1.8, while Ne is solar.

It appears, then, that O/H has been reduced in central stars of PNs by this amount. This might be consistent with the above linear relationship (Ne/H, O/H) in PNs, but it is difficult to reconcile with the mean ratio of Ne/O in H II regions being the same as in PNs (Henry 1989b). The point requires a deeper study.

Another relevant relationship is that of N/H or N/O with He/H (Figs. 2 and 5). This positive relationship is more evident in the (N/O, He/H) plot than in the (N/H, He/H) plot. This can be referred to the higher accuracy of the determina-

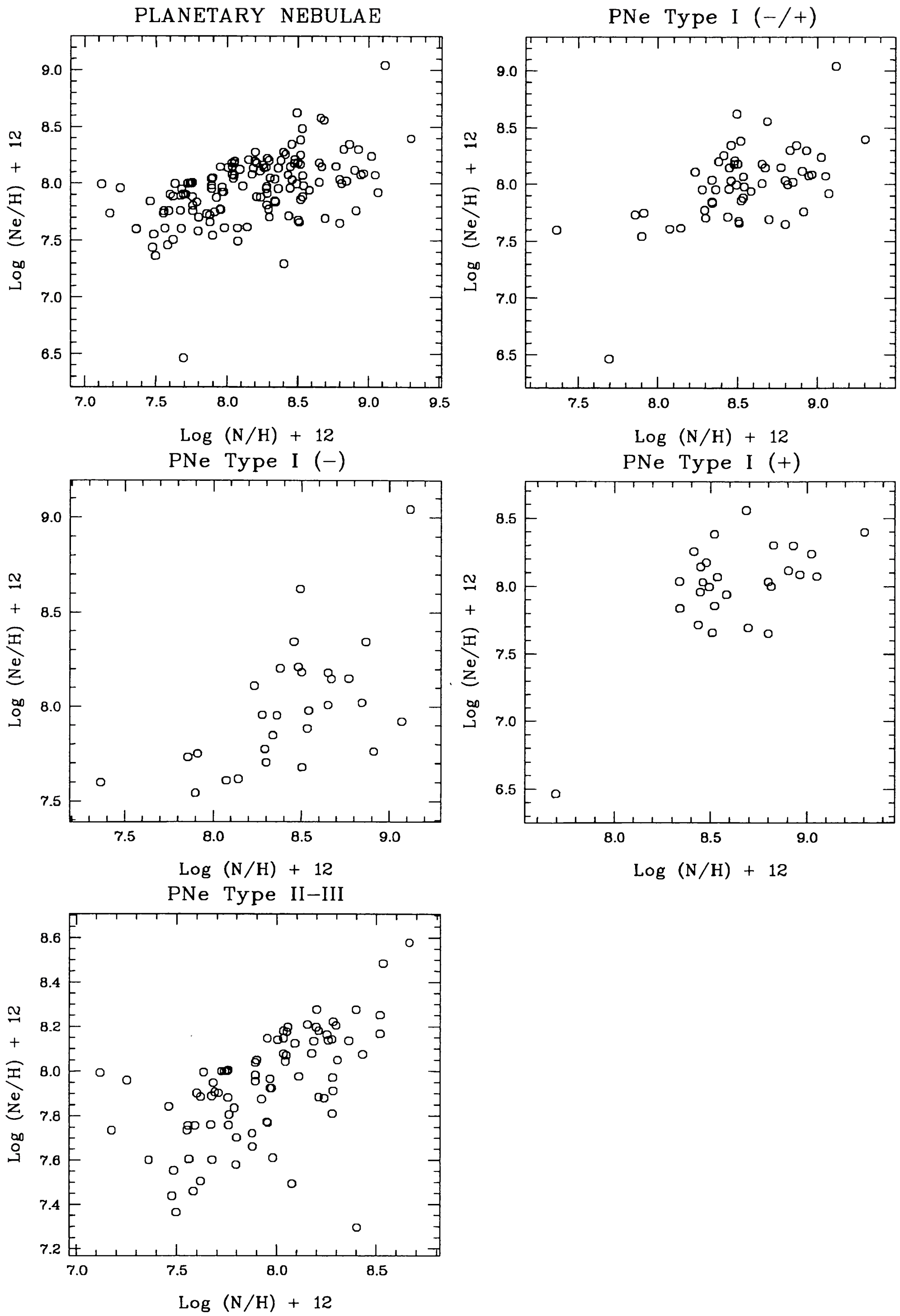

FIG. 10.—Same as Fig. 1 for Ne/H vs. N/H

tions of N/O relative to those of N/H. This correlation was first discussed by Kaler (1979) and most recently by Henry (1990), who has studied various relationships in a sample of 192 PNs, 84 of which belonging to the Galaxy. Moreover, Kaler & Jacoby (1989) have discussed the relationship between N/O and the mass of the central star.

The present richer sample confirms the trends found in the previous studies. In Figs. 2 and 5, as well as in other figures where He/H is plotted, there are a few PNs with very low He/H. They are low-excitation objects, where the abundance of helium has been certainly underestimated. A few other objects do have quite high He/H. This looks correct.

The action of the first and the second dredge-up processes appear consistent with the above trend, while the third dredge-

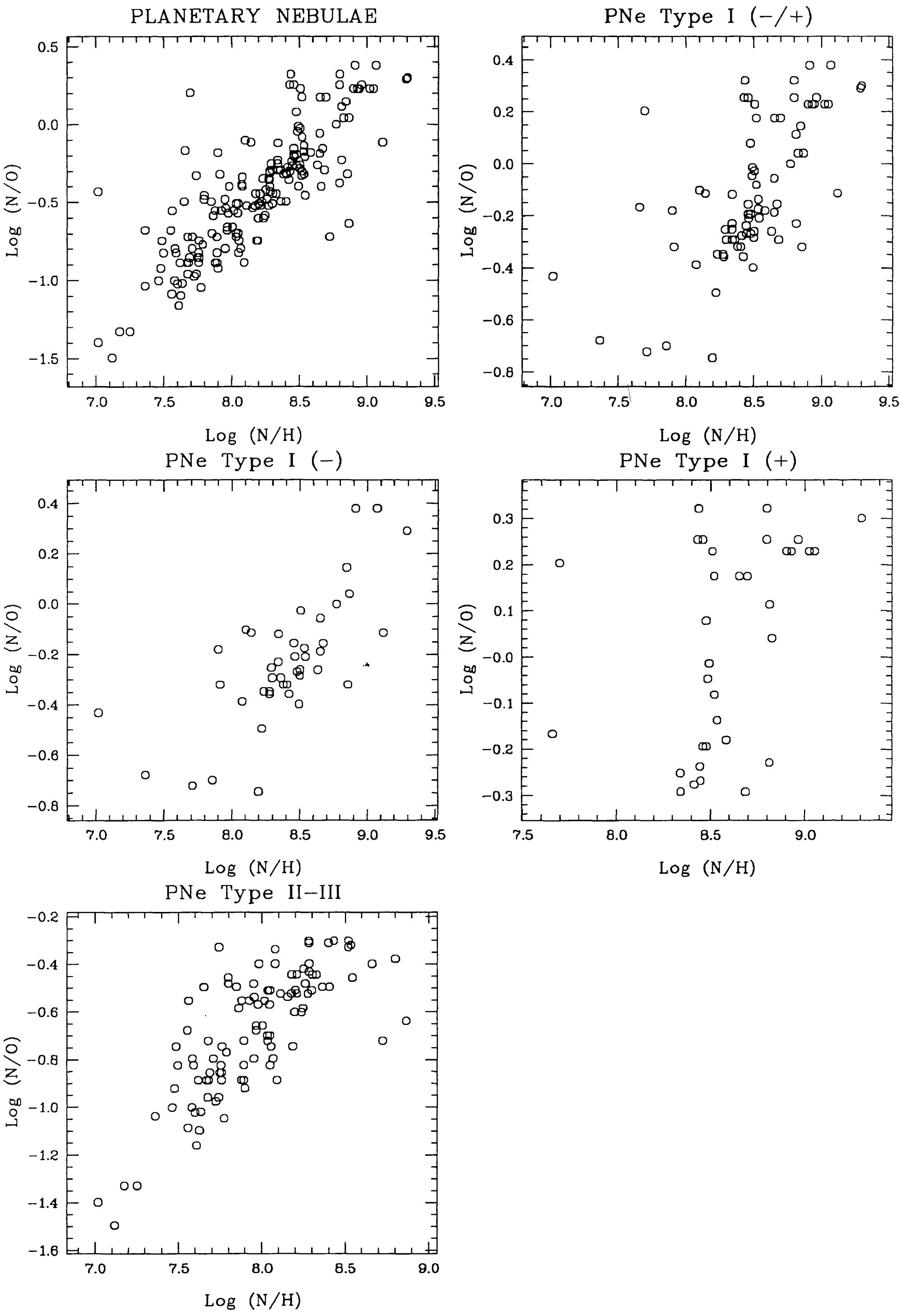

FIG. 11.—Same as Fig. 1 for N/O vs. N/H

up plus the EB process would predict a very high N/O which is not observed.

Consider now the following relationship: (N/H, O/H), (N/O, O/H), and (N/O, N/H) (Figs. 6, 9, and 11, respectively). The first represents a clear positive correlation in all kinds of the considered PNs. The second shows a feeble anticorrelation in type I (+) PNs and a feeble correlation in PNs of types II–III. The third one again a tight positive correlation in all kinds of PNs, except those of type I (+), where no correlation is indicated, while, strangely enough, the correlation is instead clear in PNs of type I (−).

What may be the meaning of this behavior? It is evident that in PNs of type II–III, the variation of N/H is larger than the corresponding variation of O/H while the two variations are

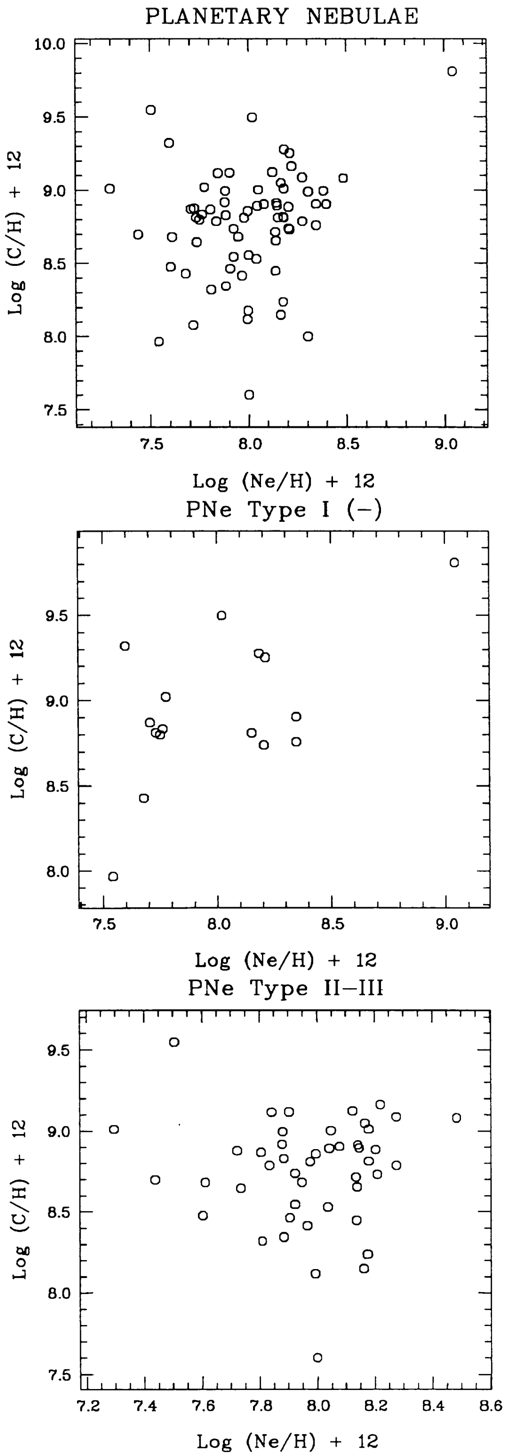

FIG. 12.—Same as Fig. 1 for C/H vs. Ne/H

similar in PNs of type I (+). That explains why N/O can correlation with N/H in PNs of types II–III, while no correlation is present in type I (+) PNs. The behavior of the PNs of type I (−) is, in this case, much closer to that of type II–III PNs than to that of the PNs of type I (+). This in fact justifies a separation of these two groups of PNs.

The anticorrelation between N/O and O/H in type I PNs has been mentioned by various authors (as PTP83; Aller 1983; and Peimbert 1985). The last author suggests that it may indicate the action of the ON cycle in the most massive PNs, i.e., the production of nitrogen at expenses of oxygen. On the other hand, the correlation between N/O and O/H in type II–III

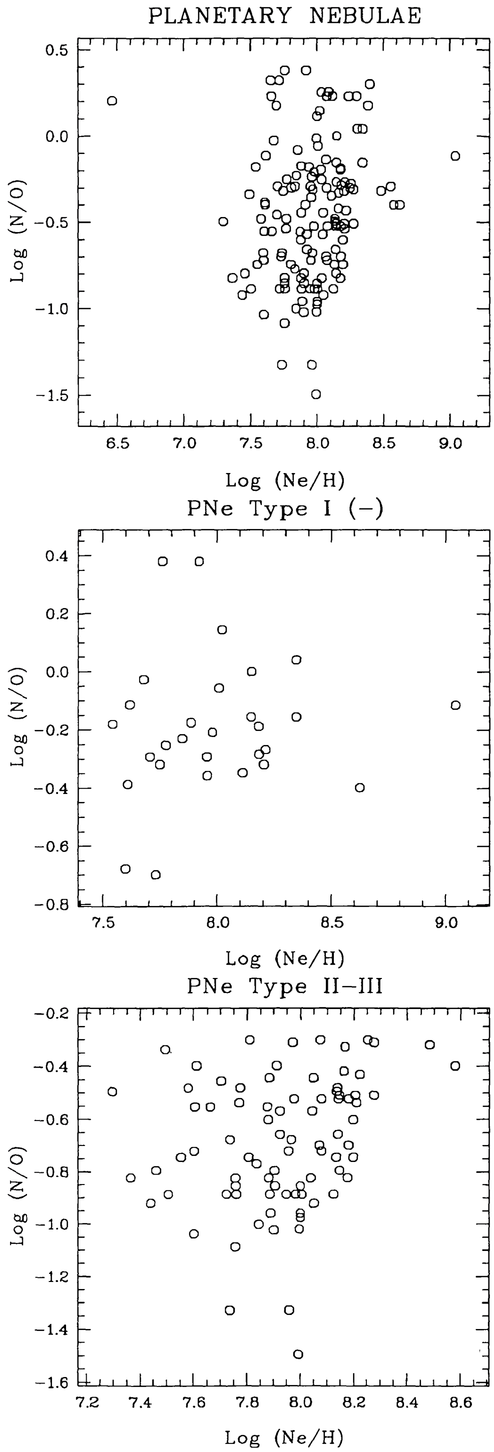

FIG. 13.—Same as Fig. 1 for N/O vs. Ne/H

PNs, apparently not seen before and not seen in the sample of Henry (1990), but seen here, supports the general view recently illustrated by Henry (1990) that in type II–III PNs the ON cycle was not active and therefore the production of nitrogen is to be attributed to the CN cycle of the CNO bi-cycle.

Coming to carbon, there is no correlation between He/H and C/H or C/O (Figs. 1 and 4). The general trend of the points in the diagrams, excluding as discussed above the clearly unacceptable very low values of He/H, is, however, consistent with the prediction of the theory, at least in the sense that a rather large variation of C/O is predicted for a moderate variation of He/H, due to the action of the third dredge-up process (see the plots of the theoretical curves reported, e.g., by Kaler 1985b). The role the EB process appears here not in contradic-

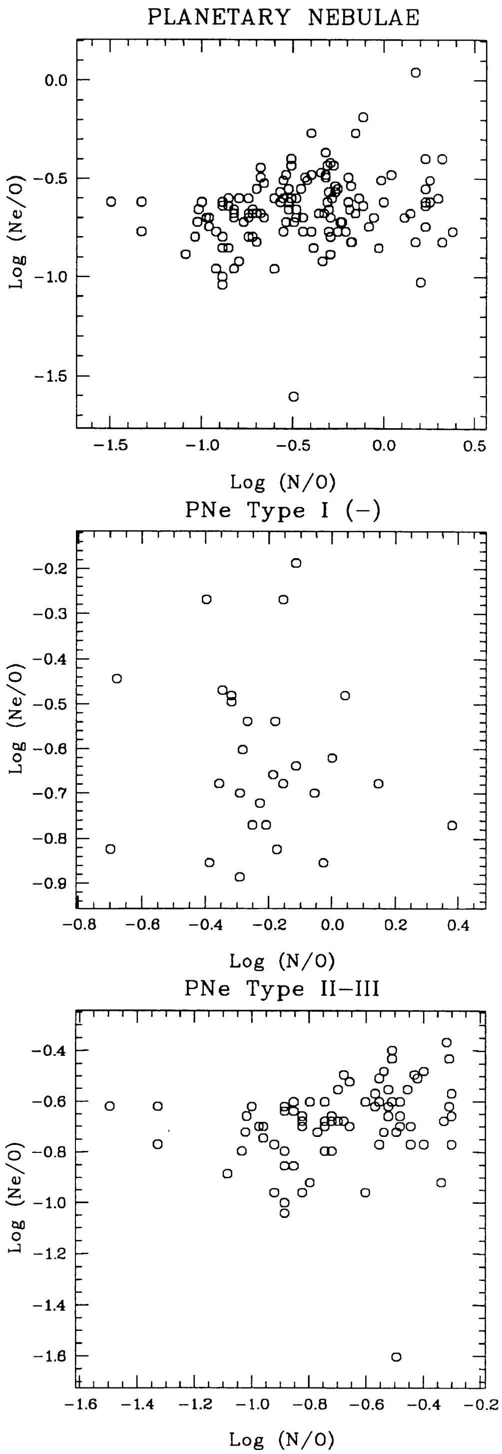

FIG. 14.—Same as Fig. 1 for Ne/O vs. N/O

tion with the observed data, whose scatter is, however, very large.

An anticorrelation of C/O with He/H is apparently indicated in PNs of type I (+). This might be expected in fact from the two processes just mentioned for the most massive stars with He/H in the range between 0.12 and 0.18 or more.

Finally C/N correlates positively with O/N in all kinds of the considered PNs (Fig. 16). One notices that PNs of type I have smaller values both of C/N and of O/N than PNs of types II–III.

From the diagrams plotted in Figure 16, it would be easy to see how many objects of the different kinds of C/O > 1 or

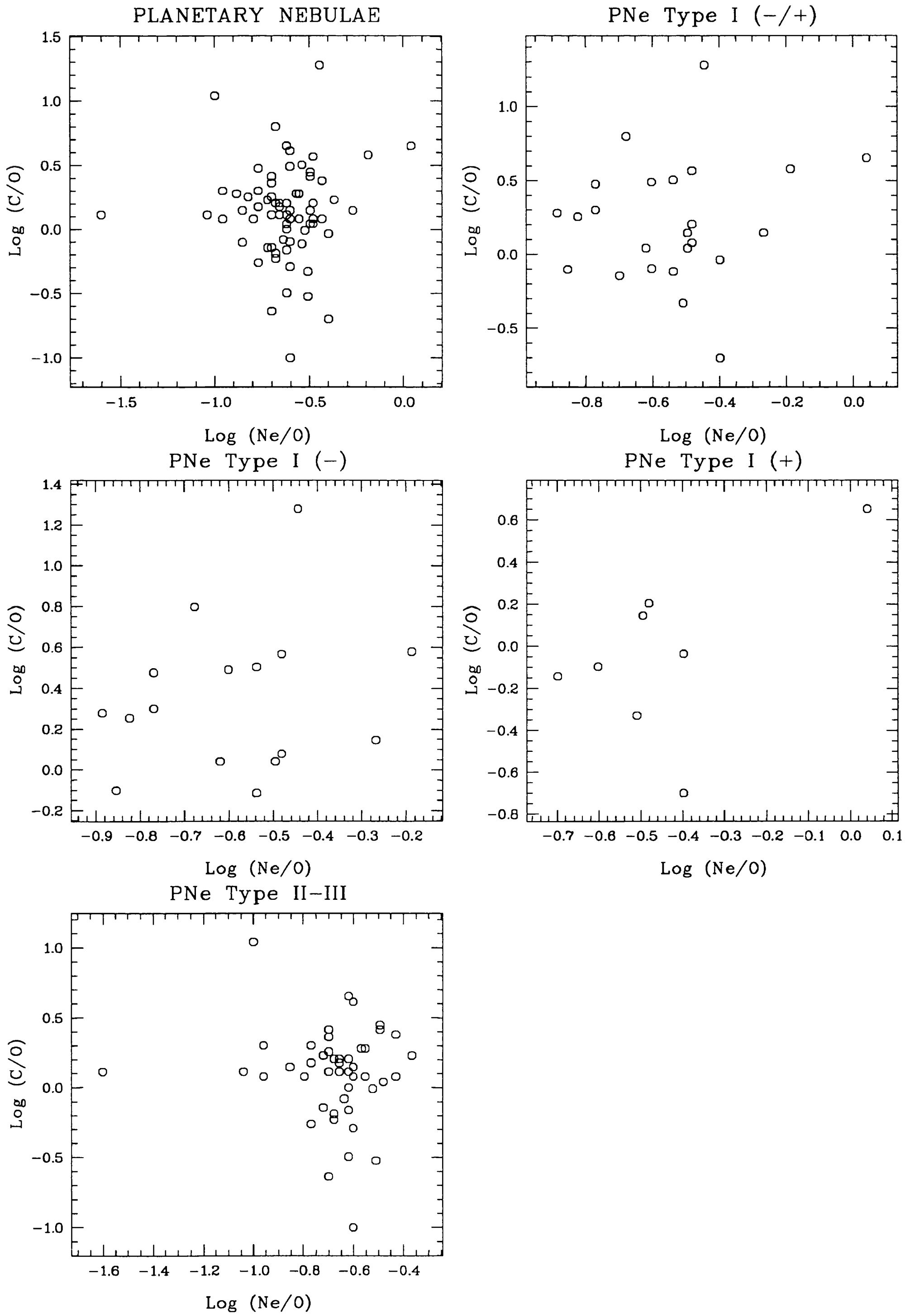

FIG. 15.—Same as Fig. 1 for C/O vs. Ne/O

C/O < 1, by plotting lines with C/O = 1. The same information comes, of course, also from a simple inspection of Table 1. One then finds that the PNs of type I and the PNs of types II–III do have about the same fraction (about 75%) of objects with C/O > 1.

7. CONCLUSIONS

Using a new compilation of abundances of He/H, C/H, N/H, O/H and Ne/H in 209 Galactic planetary nebulae, all the possible relationships between pairs of elements have been investigated.

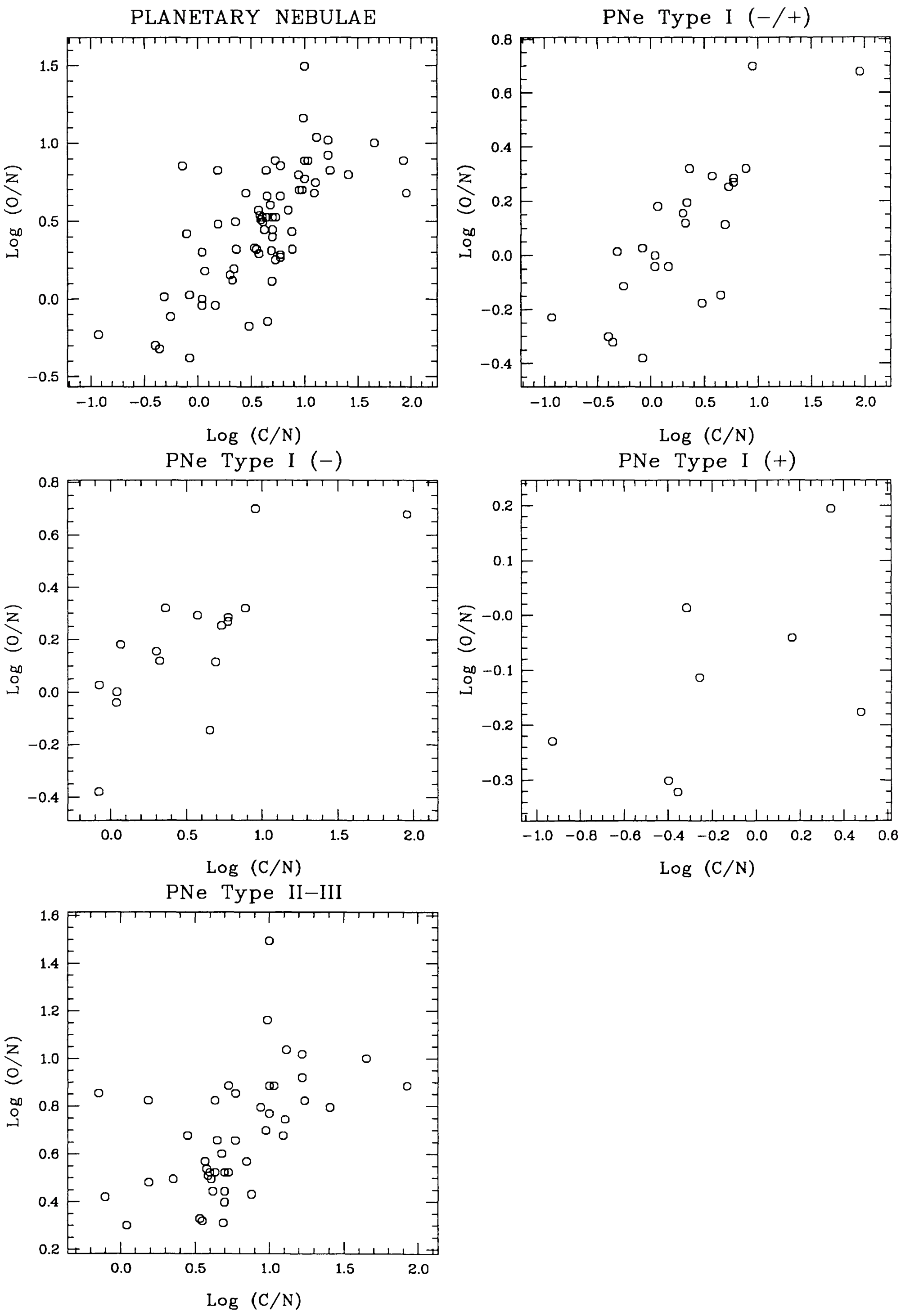

FIG. 16.—Same as Fig. 1 for O/N vs. C/N

The results indicate a reasonable qualitative agreement with most expectations of the theory of stellar nucleosynthesis for intermediate-mass stars, supporting the view that this kind of study is one of the most promising for a better understanding of the late phases of stellar evolution of intermediate-mass stars.

On the other hand, aspects have been underlined which deserve further attention. The data are consistent with the possibility that the enrichment of nitrogen in type I PNs is due mostly to the ON cycle, while that in PNs of types II–III mostly to the CN cycle.

The analysis must be pursued further on the theoretical side, to overcome the difficulties and incompleteness recognized to affect the presently available predictions of chemical abundances in PNs, and on the observational side, in particular carefully examining the most "extreme" objects.

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