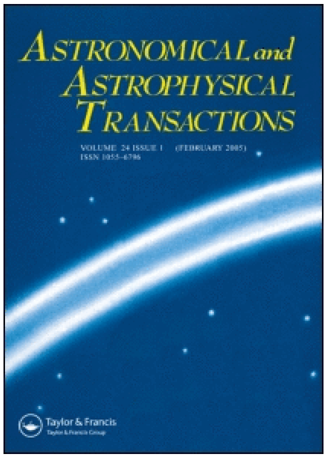

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THE CHEMICAL COMPOSITION OF PLANETARY NEBULAE: CORRELATIONS BETWEEN ELEMENTS

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The complete data on chemical abundances of 218 galactic planetary nebulae are analyzed. Correlation between abundances of different elements is suggested. The constraints on theory of evolution are discussed.

KEY WORDS planetary nebulae, chemical abundance.

1. INTRODUCTION

The knowledge of chemical abundances of planetary nebulae (PNe) plays an important role in solution of, at least, three complicated astrophysical problems: a) chemical enrichment of the interstellar medium, b) chemical evolution of intermediate-mass stars ($\sim$1–8 $M_\odot$), and c) chemical evolution of the Galaxy (and other galaxies as well).

For comparison of the observational data with theoretical predictions, one takes into consideration, as a rule, the following factors: a) the average values of chemical abundances in PNe, b) the estimations of the galactic radial gradients of abundances, c) correlations between different element abundances, d) the estimations of the galactic gradients of the electron temperature $T(e)$.

The correlations between abundances of several chemical elements (for PNe as well as HII regions) were investigated earlier by Kaler (1978, 1979), Peimbert and Torres-Peimbert (1983), Aller (1983), Torres-Peimbert (1984), Peimbert (1985), Perinotto (1987), Henry (1989a, b; 1990, hereafter H90), Clegg (1990), and Perinotto (1991, hereafter P91). Investigations of PNe are interesting because in PNe we see a chemical composition which reflects not only abundances of primary elements but is also consequences of the chemical evolution of a progenitor star whose mass can be estimated.

In order to compare theoretical predictions with PNe observational data, one has to make a correct subdivision of PNe into several groups, according to the mass of the parent stars, because objects with approximately equal initial masses are to be considered together. All the aforementioned authors used in their discussions the classification of PNe by Peimbert (1978). According to this classification, all PNe are subdivided into classes I–IV using the following four

Table 1 The criteria for defining the mass class of a planetary nebula

No	*Our criteria*	*Criteria used by Peimbert (1978)*
1	The mass of the central star	no
2	Zanstra temperature of the central star: TZ(HI) and TZ(HeII)	no
3	Chemical abundance of PN (N/O–He/H dependence)	Chemical abundance in PN (values of He/H and/or N/O)
4	The presence of molecular hydrogen	no
5	The dependence of TZ(HI)/TZ(HeII) on the radio surface brightness of PN	no
6	The dependence of electron density in PN on the nebula diameter	no
7	The dependence of low-frequency break in the radiospectrum of PN on the nebula diameter	no
8	The morphology of PN	The morphology of PN
9	The proper velocity of PN	The proper velocity of PN
10	Distance from the galactic plane	Distance from the galactic plane

basic criteria: i) the abundance criterion; for PN-I, $He/H > 0.125$ and/or $\log N/O > 0.3$; ii) two kinematic criteria; kinematics and galactic distribution of PNe-I resembling those of Population I stars, PNe-II having $Z \sim 150$ pc, where Z is the distance from the galactic plane (intermediate Population I), PNe-III do not belong to the halo but have a high velocity $V > 60$ km/s, PNe-IV belong to the halo; iii) the morphological criterion; PNe-I are filamentary, bipolar or biaxial; the others exhibit, basically, the central symmetry (Table 1).

All the statistical investigations of galactic planetary nebulae have two common shortcomings:

a) The subdivision of the nebulae into the classes (Peimbert, 1978) relies on only four criteria, this can lead to errors in class determinations. In particular, several PNe with log $(N/O) > -0.3$ may belong to the intermediate Population I subsystem if one takes into account the mass of the central star and the nebula as well as other PNe parameters which are not included in Peimbert's classification. Thus, a more precise subdivision of PNe into different groups is necessary.

b) Distances to the PNe belonging to all classes are determined using one and the same distance scale. This leads to essential errors in the distance estimates (particularly, for massive PNe) and, consequently, in estimations involving any distance scale.

Amnuel *et al.* (1989) proposed a new PNe classification as well as individual distance scale for each PN class. This allows to estimate more precisely many statistical properties of the PNe population.

Amnuel *et al.* (1989) subdivided all PNe into the following three classes according to the mass of the parent star and PN itself: the low-mass PNe (L–PNe)

Table 2 Distribution of PNe over the mass classes

Sample		*L-PNe*	*In-PNe*	*M-PNe*	*A-PNe*	*All*
FAM86	I	—	—	—	—	—
	II	21	20	1	3	45
H90	I	8	10	3	3	24
	II–III	23	25	4	1	53
P91	I	9	47	17	12	85
	II–III	55	48	3	5	111
ours		74	94	21	19	208

with the parent star mass between $\sim$0.8 and $\sim 2\,M_\odot$; the intermediate-mass PNe (In–PNe) with the parent star mass between $\sim$2 and $\sim 3\,M_\odot$; the massive PNe (M—PNe) with the parent star mass between $\sim$3 and $\sim 8\,M_\odot$. The class of anomalous PNe (A-PNe) was also included. A-PNe lie between In- and M-PNe in the main parameters, but in this case a PN is a consequence of a secondary ejection of small mass envelope (no more than $\sim 0.08\,M_\odot$ in mass) $>10^5$ yrs after ejection of the first envelope.

Amnuel *et al.* (1989) used ten criteria for the PNe subdivision and obtained a more precise subdivision of PNe into the mass classes (Table 1). The main criteria are connected with the estimations of the masses of PNe and their central stars (other criteria also depend, directly or indirectly, on these parameters). Using data on the radio emission of PNe, Amnuel *et al.* (1989) obtained separate distance scales for all the classes of PNe.

The type II PNe (according to Peimbert's classification) used by FAM86 and H90 actually represent a mixture of L-, In- and M-PNe (see Table 2). This (as well as using of a unique distance scale for all the PNe classes) leads to inaccuracy in the determinations of gradients and correlations. Moreover, among the type I PNe used by H90, the number of L-PNe actually exceeds that of M-PNe (Table 2).

Now we have at least three reasons for the revision of all statistical properties of PNe:

—more accurate subdivision of PNe into mass classes,

—more accurate determination of distance scales,

—recent observational data on chemical abundances of PNe.

Amnuel *et al.* (1990) proposed estimations of the galactic abundance and $T(e)$ gradients using data on 125 PNe. Now data on chemical abundances of at least 218 galactic PNe have been obtained (e.g. H90; P91).

In this paper I use new observational data on PNe chemical abundances and new subdivision of PNe into mass classes for the revision of the correlations between different elements in all the classes of PNe.

The results obtained here are compared with theoretical predictions. The interpretation of the results may be used for better understanding of some of the physical and chemical features of PNe as indicators of the evolution of intermediate-mass stars in the AGB-stage.

2. SELECTION OF PNe

I use for analysis the data on 218 galactic PNe for which at least He/H and(or) N/O have been determined. The estimates of He/H and N/O are available for 197 and 190 PNe, respectively. Also the abundances of O (182 PNe), C (81 PNe), Ne (146 PNe), S (98 PNe) and Ar (82 PNe) have been determined.

The values of abundances are compiled from Amnuel *et al.* (1989), H90, Perinotto (1991), Freitas Pacheco *et al.* (1991) and the papers quoted in these works.

Among the 218 PNe used, 74 belong to the L-type; 94, 21 and 19, belong to In-, M- and A-type, respectively. For 9 PNe the mass class was not determined because of the absence of reliable criteria. PN K648 (L-type) located in the globular cluster M15 was omitted from our analysis because of its peculiarity. In Table 2 I present the distributions of PNe mass classes for the samples of FAM86, H90 and P91.

For the determination of the mass class of 162 PNe, five or more criteria were used, and for 92 PNe, six or more criteria. Only for 53 PNe we used three or less criteria. This provides a more correct subdivision of PNe into the mass classes, but each class contains some objects with individual peculiarities; in particular, a PN can be typical of a given mass class in abundances of all the elements except N (for example, Mz 3, H 1–55, M 1–30), He (M 1–38, He 2–131, etc.), O (M 1–9, M 1–30), etc. If any PN deviated considerably ($>3\sigma$) from the dependence obtained by the least-squares method, the object was omitted from the analysis.

3. CORRELATIONS BETWEEN ELEMENTS

The existence (or absence) of correlations between element abundances in different PNe classes was investigated for 25 pairs of elements or their ratios. I have not found any reliable correlation between the following pairs: He/H-O/H, He/H–N/H, He/H–Ne/H, C/H–Ne/H, C/H–N/O, O/H–C/H, O/H–N/O, O/H–C/O, N/H–C/H, Ne/H–N/O and N/O–C/O.

The data obtained numerical are shown in Table 3. In all the samples (like in the galactic abundance gradient search), the PNe deviating $>3\sigma$ from the best-fit line were omitted. The dependences between the element abundances (and between the ratios of the abundance) were modelled by the form

$$\log y = a + b \log x,$$

where x and y are the ratios of the element abundance to the hydrogen one, or the ratios between different element abundances.

3.1. *The Correlation Between Nitrogen and Oxygen*

The correlations have been obtained for all the PNe classes (Table 3 and Figure 1). P91 concluded that in PNe II–III (Peimbert's classification) N/H varies more than O/H, while in PNe I the abundances of N/H and O/H vary approximately equally. This behavior was explained (see also H90) in terms of the assumption that in massive progenitor stars nitrogen arises mainly at the expence of oxygen

Table 3 Correlations between elements

X–Y		a	b	Δa	Δb	N	ρ
He/H–C/H	L-PNe	15.78	7.34	0.23	1.83	22	0.67
	In-PNe	10.11	1.39	0.23	0.55	34	0.41
	M-PNe	4.80	−4.56	0.13	0.62	7	−0.96
	A-PNe	12.26	3.66	0.12	2.04	6	0.67
He/H–Ar/H	L-PNe	9.44	3.18	0.16	0.99	23	0.58
	In-PNe	7.95	1.66	0.23	0.53	36	0.47
	M-PNe	6.75	0.00	0.22	0.88	12	0.00
	A-PNe	8.62	2.36	0.15	1.15	9	0.61
He/H–S/H	L-PNe	11.59	4.87	0.22	1.28	27	0.61
	In-PNe	9.04	2.24	0.28	0.70	41	0.46
	M-PNe	5.02	−2.29	0.35	2.01	11	−0.36
	A-PNe	9.34	2.54	0.16	1.18	9	0.63
He/H–C/O	L-PNe	4.10	4.11	0.27	1.95	23	0.42
	In-PNe	1.48	1.30	0.30	0.68	36	0.31
	M-PNe	−2.81	−3.23	0.16	0.58	8	−0.92
	A-PNe	2.79	2.89	0.16	2.58	6	0.46
He/H–N/O	L-PNe	−0.24	0.50	0.24	0.76	49	0.10
	In-PNe	1.99	2.57	0.25	0.36	78	0.63
	M-PNe	0.58	0.88	0.18	0.38	20	0.48
	A-PNe	0.16	0.42	0.22	0.82	16	0.13
C/H–N/C	L-PNe	7.79	−0.99	0.31	0.18	25	−0.75
	In-PNe	6.33	−0.80	0.31	0.19	36	−0.58
	M-PNe	11.08	−1.29	0.22	0.22	8	−0.93
	A-PNe	8.93	−1.06	0.20	0.64	6	−0.64
O/H–N/H	L-PNe	0.64	0.84	0.28	0.13	57	0.65
	In-PNe	0.41	0.91	0.32	0.13	83	0.60
	M-PNe	−0.21	1.01	0.20	0.22	20	0.72
	A-PNe	−1.88	1.19	0.22	0.38	16	0.64
O/H–Ne/H	L-PNe	−0.47	0.98	0.13	0.10	45	0.82
	In-PNe	−0.38	0.97	0.20	0.10	69	0.75
	M-PNe	0.62	0.86	0.12	0.25	17	0.67
	A-PNe	−11.01	2.19	0.19	0.73	11	0.71
O/H–Ar/H	L–PNe	5.52	0.10	0.19	0.16	23	0.13
	In–PNe	1.19	0.61	0.23	0.19	36	0.48
	M–PNe	−5.72	1.44	0.16	0.49	12	0.68
	A-PNe	−1.82	0.94	0.17	0.74	9	0.43
O/H–S/H	L-PNe	4.37	0.28	0.23	0.37	26	0.15
	In-PNe	−1.24	0.95	0.23	0.18	43	0.64
	M-PNe	−7.62	1.69	0.27	0.37	12	0.82
	A-PNe	7.17	−0.02	0.20	0.69	9	−0.01
N/H–Ne/H	L-PNe	5.70	0.28	0.19	0.11	42	0.38
	In-PNe	5.10	0.35	0.19	0.07	65	0.55
	M-PNe	5.45	0.30	0.14	0.17	17	0.43
	A-PNe	4.76	0.41	0.26	0.60	12	0.21
N/H–N/C	L-PNe	−10.40	1.21	0.35	0.26	25	0.69
	In-PNe	−8.01	0.90	0.23	0.10	36	0.84
	M-PNe	−15.55	1.80	0.38	0.60	8	0.78
	A-PNe	−9.15	1.03	0.16	0.39	6	0.80
N/H–N/O	L-PNe	−6.75	0.77	0.17	0.07	54	0.82
	In-PNe	−5.45	0.62	0.19	0.05	83	0.79
	M-PNe	−5.69	0.65	0.14	0.16	19	0.71
	A-PNe	−5.77	0.65	0.12	0.11	16	0.84
C/N–O/N	L-PNe	0.31	0.48	0.13	0.07	22	0.85
	In-PNe	0.06	0.58	0.18	0.08	37	0.79
	M-PNe	0.02	0.44	0.08	0.07	7	0.95
	A-PNe	0.09	0.51	0.12	0.24	6	0.73

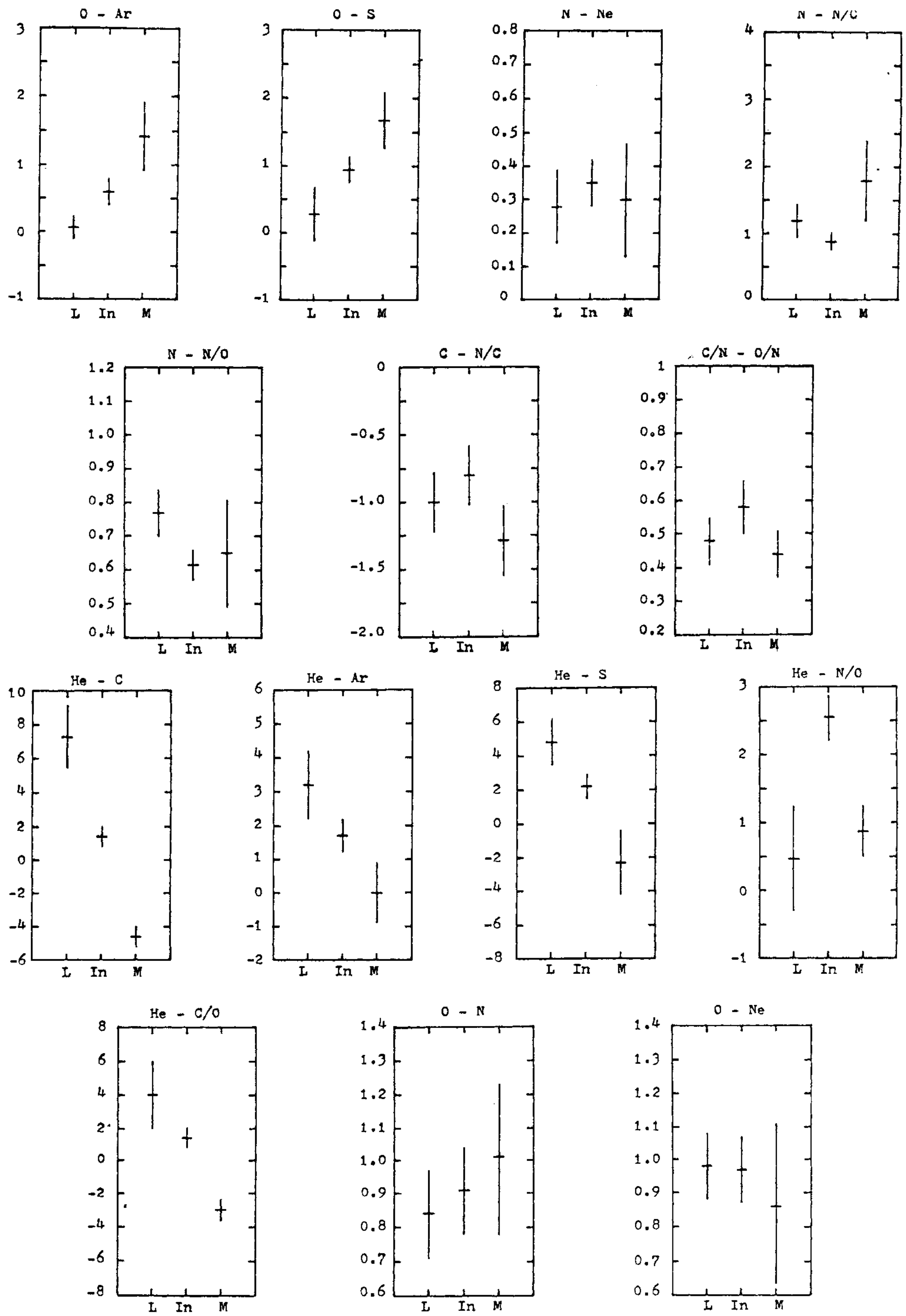

Figure 1 The slopes of values in the correlation between elements, i.e. the coefficients b in the approximation $\log Y = a + b \log X$ for different mass classes of PNe.

(the ON-cycle). H90 obtained a weak anticorrelation between N/O and O/H (see below) in PNe I, but not in PNe II–III. This anticorrelation confirms this explanation.

As one can see from Table 3 and Figure 1, our results show, in contradiction to P91, an increase of the steepness in the O/H–N/H dependence under the transition from L- to M-PNe. The abundance of nitrogen in L-PNe changes slower than that of oxygen (and faster in M-PNe). This dependence is also present in the correlations between N/O and N/H. In the M-PNe sample, N/O increases slightly slower than in L-PNe under equal changes in N/H (the correlation coefficients are sufficiently high). This contradicts the assumption that in massive stars ($\sim$3–8 $M_\odot$) the NO-cycle is more active than in low-mass stars (masses $<3\,M_\odot$).

Any anticorrelation between N/O and O/H has not been found. Note that H90 and P91 found in PNe I the anticorrelation (weak in the P91 sample) between N/O and O/H.

Using the correlation data on O/H–N/H, O/H–N/O and N/H–N/O, H90 concluded that i) nitrogen in PNe is of primary origin, without essential enrichment, ii) the ON cycle works mainly in massive stars while the CN-cycle is more active in low-mass stars.

Any dependence of N/H on Ne/H is not present in our samples in contradiction with the results of P91 (note, however, that these correlations also are very weak in the P91 samples).

The dependence of N/O on He/H is pronounced in our samples. It is the strongest and steepest in In-PNe (Table 3 and Figure 1) and slightly weaker in M-PNe, in contrast to H90 and P91 results where a weak positive correlation was found for PNe II–III.

Using the correlations obtained here, we can conclude that the ON cycle can play an important role also in low and intermediate mass progenitor stars and the main fraction of nitrogen has a primary origin.

3.2. *Carbon*

If the CN cycle really plays the main role in low-mass progenitor stars (H90, P91), it would affect the correlations of carbon with nitrogen and oxygen. In particular, one can expect an anticorrelation between N/C and C/H, similarly to a weak anticorrelation between N/O and O/H obtained by H90 and P91 for the PNe I sample (we recall that the anticorrelation has not been found here—see above). Unfortunately, P91 did not investigate the correlations between N/C and C/H, N/C and N/H.

As can be seen from Table 3 and Figure 1, reliable anticorrelations have been revealed for all the PNe classes, with high correlation coefficient. The slope of the C/H–N/C dependence is ~ -1. Reliable correlations between N/C and N/H are present in our samples with the slope ~ 1 (possibly, the slope increases to ~ 1.8 for M-PNe).

Note also a very interesting behaviour of the correlations between He/H–C/H and He/H–C/O. For L–PNe, strong positive correlations are observed with large slope and relatively high correlation coefficient. For In-PNe, correlations are weak, and for M-PNe the correlations become negative with high correlation coefficient. Note that P91 have not found any correlation neither between C/H and He/H nor between C/O and He/H.

Correlations between C/N and O/N are also reliable for all the PNe classes having the slope ~0.5 and high correlation coefficients (P91 also obtained a pronounced correlation). Any correlation between C/H and N/H and between N/O and C/O has not been found in P91.

Basing on all the correlations, we conclude that the role of the CN cycle in all progenitor stars is more important than believed earlier. In L-PNe, the abundance of carbon increases with helium enrichment (that is, approximately with the increase of the progenitor star mass), but in M-PNe the abundance of carbon decreases while the abundance of helium continues to increase. This justifies the assumption that the CN cycle can play an essential role in stars with masses ~3–8 $M_{\odot}$. The possibile underestimate of C/H in M-PNe due to the presence of dust grains cannot explain neither the low average local value of carbon abundance, nor the strong anticorrelation between C/H and He/H. The strong anticorrelation between C/O and He/H for M-PNe is readily understandable because oxygen abundance shows reliable anticorrelation in this PNe class (18 PNe, $\rho = -0.70$). The slope of the dependence He/H −O/H is ~−1, much less than that of He/H–C/H. Note that P91 have not found any correlation between O/H and He/H.

The anticorrelation between C/O and He/H can be explained in terms of the third dredge-up process if a progenitor star mass exceeds 4.8–5 $M_{\odot}$ (Renzini and Voli, 1981). However, the typical progenitor star mass for M-PNe is ~4.6 $M_{\odot}$, and more than a half of all progenitor stars have masses less than 4.8–5 $M_{\odot}$. Any anticorrelation between C/O and He/H in this sample should be weak or absent.

Possible activity of the CN-cycle in 3–8 $M_{\odot}$ stars (this process leads to enrichment by nitrogen at the expense of carbon) can explain also the anomalously small value of $\langle C/O \rangle$ in M-PNe which contradicts the expected theoretical values.

3.3. *Other Elements*

Any correlation between Ne/H and He/H is absent in our sample. H90 and P91 did not find any correlation for type I PNe, but obtained a weak positive correlation for PNe II–III.

Correlation between Ne/H and C/H is weak (as in P91 sample too) and do not allow to obtain reliable conclusions. This is true also for the correlation between N/O and Ne/H.

Correlation between Ne/H and N/H is more reliable. H90 and P91 found positive correlations but do not quote the slope values. As one can see from Table 3, the slopes are not high, ~0.3, and do not depend on the PNe class.

Correlations between Ne/H and O/H are most reliable. According to Henry (1989a, b), the slope of the dependence of Ne/H on O/H is 1.13 ± 0.04 for PNe and 0.98 ± 0.06 for HII regions. Our samples give practically the same values for L-, In- and M-PNe, which are close to HII data. For A-PNe, the slope increases to ~2.2 which is possibly connected with enhancing of neon in the second PN envelope. The close agreement of our results with those of Henry (1989a, b) and P91 is connected with the independence of the slope of the PNe mass class. Thus, mixing of different PNe classes, as in Henry's (1989a, b) and P91's samples, cannot affect the result. The primary origin of neon in PNe discussed by Henry (1989a, b) and P91 is now confirmed (excluding A-PNe).

Interesting correlations between Ar/H and He/H, S/H and He/H have been obtained for our samples for the first time (Table 3 and Figure 1). A very steep dependence exists for L-PNe. The steepness is smaller for In-PNe and falls to zero (for Ar/H–He/H) or a negative value (for S/H–He/H) for M-PNe. ⟨Ar/H⟩ and ⟨S/H⟩ exhibit the same behavior. We can assume that argon and sulphur take part in the first dredge-up process while their role is not essential in the second and the third ones. An alternative to this assumption is a much stronger one that argon and sulphur can arise in low-mass progenitor stars (with the mass less than 2 $M_\odot$).

We also considered the possibility of correlations between Ar/H and O/H, S/H and O/H. If argon and sulphur in PNe are of primary origin, then the correlations are expected to be similar to the O/H–Ne/H one. However, any correlation has not been found for L- and A-PNe, but for In- and M-PNe both argon and sulphur show relatively strong positive correlation with the oxygen abundance (with the slope of ~1–1.5). If argon and sulphur actually do not arise in PN progenitor star then the assumption can be confirmed that these elements take part in dredge-up processes.

4. CONCLUSIONS

Our primary conclusion is that the classification of PNe according to their mass and the mass of the progenitor star (Amnuel *et al.*, 1989) reflects correctly the physical nature and origin of these objects.

Comparing our results with theoretical predictions leads to some conclusions which can be important for theory of stellar evolution and for investigations of dredge-up processes in AGB stars.

Note that among the correlations discussed above many ones (considered one by one) seem unreliable, in several cases the correlation coefficients are small (or the number of objects in a sample is small). It would be incorrect to base any radical conclusions on only one or two correlations. However, we discussed not only correlations themselves but, in the main, their dependences on PNe classes. In many cases just such analysis allows to reach interesting conclusions.

The correlations between different elements studied above allow to conclude that:

—The CN cycle obviously can play a role in progenitor stars of all the PNe classes. This leads, in particular, to low ⟨C/O⟩ in M-PNe (in comparison with earlier predictions). On the other hand, the ON-cycle exists not only in massive (~3–8 $M_\odot$) progenitors but also in stars with mass below ~3 $M_\odot$.

—As shown earlier, neon has primary origin. However, some enrichment by Ne can occur in the second PN envelope, if it arises (A-PN), while the abundances of other elements do not change essentially.

—Argon seems to play a more essential role than anticipated earlier in nucleosynthesis in the stars with mass below ~8 $M_\odot$ and/or in the dredge-up processes (in the first dredge-up process, especially).

—The most essential cooling agent in PNe is oxygen with nitrogen and carbon being less important.

Although the total number of PNe used here reaches 208, the subdivision of PNe into the mass classes reduces the number of PNe in each sample. This fact is of importance for the reliability of our conclusions. Of course, before one could put any constraint on theoretical calculations, the correlations discussed above should be verified using more spacious samples for all the PNe classes. It would be very interesting also to obtain analogous correlations and dependences for HII regions and to compare the results with PNe data.

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