A New Ionization Correction Factors for Chemical Composition Determination of the Galactical Planetary Nebulae and the HII Regions in the Blue Compact Dwarf Galaxies

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New analytical expressions for Ionization Correction Factors (ICFs) are obtained from the photoionization models (PhMs) grid separately for the planetary nebulae (PNe) and the HII regions in the Blue Compact Dwarf Galaxies (BCDG). The PhMs grid was calculated using the CLOUDY94 code of Ferland [1]. All the PhMs were spherically symmetric.

The free parameters for PNe grid were the spectral energy distribution (SED) of the PNe nuclei at λ912A, chemical composition of the nebular gas taken as averaged values from [2], the nebular gas filling factor (0.1, 0.5 and 1).

The SEDs of the nuclei at λ912A correspond to the stellar atmosphere models of Clegg & Middlemass [3] corrected for the stellar wind presence by using Zanstra relationships Z(HeII) from Gabler, Kudritzki & Mendez [4]. Our correction based on "increasing" or "decreasing" Clegg & Middlemas SEDs at the range λ≤228A for coincidence of new Zanstra rations with ones from [4]. The stellar atmosphere models from Clegg & Middlemas were approximated at $\lambda \le 228$A by a power-law spectra and the number of ionizing quanta was changed in this range without the color temperature changing of the corresponding model.

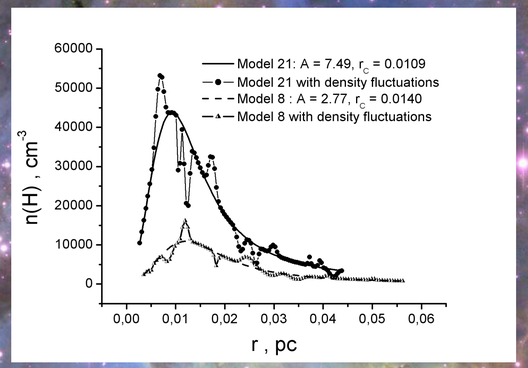
To allow for various types of gas density inhomogeneity in the PNe enveloples, we considered two types inhomogeneities of nebular gas density. (Fig.1). Type I inhomogeneity (or macrofluctuation) corresponds to the radial distribution of gas density that was derived in [5] and was specified by the following empirical relationship:

$$n(r)=\frac{x^2(1+3e^{-1.2x})}{(x^2-1)^2+0.36r_c^{-0.43}x^2}\cdot\frac{A}{r_c^2}, \qquad (1)$$

where $x=r/r_c$ and $r_c=v_{exp}t$. Here r is the distance from the central star to a given point in the nebula, $n(r)$ is the gas density at this point, v_{exp} is the average expansion velocity of the envelope, and t is the envelope age (the values of r and r_c in (1) are given in parsecs). The parameter A describes the outflow of stellar material during the detachment of the nebular envelope [6]. The parameter A for every model was selected in order to value $n(r)$ from (1) and n_e obtained from ionization balance were equivalent. For most PNe the values of A are into the interval from 0.8 to 8.0, which corresponds to mass-lost rates of (0.5 - 1.8)10^{-5} $M_\odot$/year at a velocity v_{exp} of about 15 km/s.

To take into account microfluctuations of the gas density (type II inhomogeneity) we developed code that superimposed inhomogeneities on the distribution (1) using a standard random-number generator. The input parameters were: (1) the parameters of the PN envelope: r_c and A [see (1)], and the inner and outer radii of the envelope r_{in} and r_{out} ($r_{in}= r_c/3$, $r_{out}=3r_c$); (2) the parameters of the inhomogeneities: n_{min} and n_{max} are the minimum and maximum numbers of fluctuations (5 – 15), d_{min} and d_{max} are the minimum and maximum sizes of the fluctuations in percent relative to the envelope radius $r = r_{out} - r_{in}$ (0,5 – 5%), ρ_{min} and ρ_{max} are the minimum and maximum deviations of the density of an inhomogeneity from the main distribution (5 – 30%), and the maghitudes of the fluctuations themselves (to 20%).

Fig.1. Radial distribution of the gas density in the envelopes of two PNe models.



For HII regions the free parameters were: the SED obtained for HII regions in BCDG by our method [7] from high-quality observations [8-10] of these objects (the method uses stellar atmosphere models of O-B stars [11-12]); the nebular gas filling factor (from 0.0001 to 1); the relative abundance of heavy elements; the concentration of hydrogen atoms n_H.

In result we calculated 540 PNe PhMs and 270 HII regions PhMs. Integral spectra of these models were considered as "observed", and then they were analyzed by the standard method of nebular gas diagnostics using code DIAGN [13] with atomic data that correspond to the CLOUDY94 code data. We considered different dependences which allowed to determine the chemical composition as $log(A/H)=log(A^{+i}/H^+)-f(x)$ (see method [5]). Here X^{+k+1}/X^{+k} corresponds to He^{++}/He^+, O^{++}/O^+, S^{++}/S^+ or Ar^{3+}/Ar^{2+} and $x=log(X^{+k+1}/X^{+k})$. All these correlations were approximated by polynomial function

$$f(x)=\sum_{n=0}^{5} C_n\times x^n \qquad , \qquad (2)$$

where C_n are the polynomial coefficients. These expressions were tested for the purpose of reproduction of chemical composition given in corresponding PhMs and the accuracy was higher than 10% for best ICF expressions of PNe and HII regions in BCDG.

Obtained new analytical expressions for ICFs (see Tab.1 and Tab.2) were used for chemical composition determination of nebular gas in galactical PNe and in HII regions in BCDG. We have used PN spectra from different papers published previously (1976 - 1996 yr., see data on the ftp://astro.franko.lviv.ua/PN/Chem_CompPN2004) and HII regions spectra [8-10]. For PNe abundances of He, N, O, Ne, S and Ar for 193 objects are determined and for HII regions in BCDG the corresponding data for 41 objects are determined.

The He/H abundance is determined using new emissivities from Benjamin et al. [14] and method of Olive & Skillman [15] for two types of the nebular objects. Analysis of the formulas for helium abundance indicated that they are not entirely exact, so we adopted ICF(He) = 1 when determining the helium abundance; i.e., $He/H = He^+/H^+ + He^{++}/H^+$.

We also analyzed possible gradients of the elements abundances with distance from the Galactic center for type II of PNe. The abundance gradients for each element studied, $d[\log(A/H)]/dR$, in kpc, are:

(He/H) = -0.0124 ± 8.97*10⁻⁶ (n = 16);*
*(He/H)** = -0.0082 ± 2.86*10⁻⁶ (n = 60);*
O/H(I) = -0.0252 ± 0.0118 (n = 65);
O/H(II) = -0.0180 ± 0.0183 (n = 61);
N/H(I) = -0.0287 ± 0.0179 (n = 66);
N/H(II) = -0.0215 ± 0.0201 (n = 61);
Ne/H(I) = -0.0330 ± 0.0131 (n = 59);
Ne/H(II) = -0.0322 ± 0.0312 (n = 16);
S/H(I) = -0.0255 ± 0.0139 (n = 62);
S/H(II) = -0.0234 ± 0.0150 (n = 59);
Ar/H(I) = -0.0247 ± 0.0156 (n = 55);
Ar/H(II) = -0.0280 ± 0.0169 (n = 48).

While deriving the helium-abundance gradients, we used the data for PNe with 4 HeI lines ((He/H)*) and the average values <He/H> ((He/H)**) taking into account the corresponding errors. Data for the two types of inhomogeneity are presented (*A/H(I)* and *A/H(II)*). The number of objects (*n*) used to find each gradient is given in parentheses. We adopted the PNe distances *R* from [15]. Our calculations cover Galactocentric distances *R* = 2–15 kpc.

Although the distance scale adopted strongly affects the values of the gradients, our helium-abundance gradients coincide with the data of [17], and the gradients of other elements coincide with the data of [18] within the errors.

Table 1. New ICFs for PNe.

ICFs for type I (F) and type II (FF) inhomogeneity in the gas density distribution.

N	A^{+i}/H^+	X^{+k+1}/X^{+k}	Polinomial coefficients				τ	$(A/H)_{mod}/(A/H)_{mod}$
			C_0	C_1	C_2	C_3		
			He/H : 1.2(x ∈ [−3.012.. − 0.178))					
F1	He^+	He^{2+}/He^+	-0.23870	-0.60140	-0.33475	-0.05832	0.91	1.011
F2	He^{2+}	He^{3+}/He^+	-0.23870	0.39860	-0.33475	-0.05832	0.99	1.011
			O/H : 3(x ∈ [−0.848..1.445)); 4(x ∈ [−0.601..1.111)); 5(x ∈ [−1.538.. − 0.278))					
F3	O^+	O^{2+}/O^+	-0.27601	-0.61017	-0.45654	0.04707	0.91	1.033
F4	O^{2+}	S^{2+}/S^+	-0.37506	0.76762	-0.80102		0.65	1.008
F5	O^+	Ar^{3+}/Ar^{2+}	-1.36939	-2.26755	-1.44714	-0.32455	0.84	1.041
			N/H : 6(x ∈ [−0.842..1.445)); 7(x ∈ [−0.589..1.093)); 8(x ∈ [−2.069..0.121))					
F6	N^+	O^{2+}/O^+	-0.27782	-0.62239	-0.34683		0.96	1.149
F7	N^+	S^{2+}/S^+	-0.16105	-0.71193	-1.04641	0.30716	0.88	1.189
F8	N^+	Ar^{3+}/Ar^{2+}	-1.36959	-2.17432	-1.43771	-0.34048	0.84	0.870
			Ne/H : 9(x ∈ [−0.708..1.502)); 10(x ∈ [−2.042..0.101))					
F9	Ne^{2+}	O^{2+}/O^+	-0.06150	-0.08428	-0.21927	0.06389	0.43	1.024
F10	Ne^{2+}	Ar^{3+}/Ar^{2+}	-0.32702	-0.51322	-0.22932	-0.00919	0.49	1.016
			S/H : 11(x ∈ [−0.821..1.467)); 12(x ∈ [−0.842..1.424)); 13(x ∈ [−0.598..1.093)); 14(x ∈ [−2.077..0.121))					
F11	S^+	O^{2+}/O^+	-0.33302	-0.62060	-0.26100	-0.07336	0.94	1.021
F12	S^{2+}	O^{2+}/O^+	-0.17925	-0.03041	-0.36595	0.03666	0.78	1.007
F13	S^+	S^{2+}/S^+	-0.20142	-0.86441	-0.72479	0.11284	0.94	1.015
F14	S^+	Ar^{3+}/Ar^{2+}	-1.37852	-2.40162	-1.76205	-0.45096	0.79	1.093
			Ar/H : 15(x ∈ [−0.821.. − 1.424)); 16(x ∈ [−0.864..1.445)); 17..18(x ∈ [−2.060..0.122))					
F15	Ar^{2+}	O^{2+}/O^+	-0.07643	-0.22497	-0.23215	0.03283	0.76	1.017
F16	Ar^{3+}	O^{2+}/O^+	-0.98922	1.05332	-0.59124	-0.03053	0.88	1.050
F17	Ar^{2+}	Ar^{3+}/Ar^{2+}	-0.55070	-1.00470	-0.63547	-0.13461	0.78	1.015
F18	Ar^{3+}	Ar^{3+}/Ar^{2+}	-0.55070	-0.00471	-0.63547	-0.13461	0.95	1.015
			He/H : 1(x ∈ [−3.696..0.1778)); 2(x ∈ [−3.523.. − 0.050))					
FF1	He^+	He^{2+}/He^+	-0.22559	-0.53991	-0.26862	-0.04109	0.74	1.011
FF2	He^{2+}	He^{3+}/He^+	-0.13271	0.77099	-0.04971		0.99	1.016
			O/H : 3(x ∈ [−0.236..1.098)); 6(x ∈ [−2.081.. − 0.177)); 4(x ∈ [−0.843...1.315)); 5(x ∈ [−0.351...0.7263))					
FF3	O^+	O^{2+}/O^+	-0.28347	-0.60137	-0.41236		0.89	1.033
FF4	O^{2+}	O^{2+}/O^+	-0.29168	0.46012	-0.39720	-0.07055	0.94	1.046
FF5	O^{2+}	S^{2+}/S^+	-0.38583	0.78229	-0.68946	-0.13053	0.67	1.027
FF6	O^+	Ar^{3+}/Ar^{2+}	-1.35031	-2.19380	-1.37347	-0.30467	0.84	1.051
			N/H : 7(x ∈ [−0.794..1.414)); 8(x ∈ [−0.360..0.668)); 9(x ∈ [−2.081.. − 0.052))					
FF7	N^+	O^{2+}/O^+	-0.27858	-0.62683	-0.34379		0.96	1.314
FF8	N^+	S^{2+}/S^+	-0.18648	-0.68632	-0.76086		0.87	1.326
FF9	N^+	Ar^{3+}/Ar^{2+}	-1.28947	-2.09108	-1.34620	-0.31297	0.84	1.325
			Ne/H : 10(x ∈ [−2.0819.. − 0.187))					
FF10	Ne^{2+}	Ar^{3+}/Ar^{2+}	-0.32575	-0.49150	-0.19030		0.84	1.025
			S/H : 11(x ∈ [−0.769...1.340)); 12(x ∈ [−0.601..1.340)); 13(x ∈ [−0.351..1.098)); 14(x ∈ [−2.050.. − 0.021)); 15(x ∈ [−1.155.. − 0.082))					
FF11	S^+	O^{2+}/O^+	-0.32238	-0.65139	-0.32790		0.93	1.031
FF12	S^{2+}	O^{2+}/O^+	-0.18345	-0.03747	-0.31307	-0.00846	0.76	1.014
FF13	S^+	S^{2+}/S^+	-0.19761	-0.85607	-0.76149	0.12733	0.95	1.012
FF14	S^+	Ar^{3+}/Ar^{2+}	-1.36016	-2.31242	-1.65119	-0.41463	0.79	1.095
FF15	S^{2+}	Ar^{3+}/Ar^{2+}	-0.58767	-1.06149	-0.83329	-0.19345	0.79	1.003
			Ar/H : 16(x ∈ [−0.794..1.196]); 18(x ∈ [−2.081..0.062]); 17(x ∈ [−0.754..0.6211]); 19(x ∈ [−2.092.. − 0.167))					
FF16	Ar^{2+}	O^{2+}/O^+	-0.08066	-0.22004	-0.20358		0.74	1.020
FF17	Ar^{3+}	O^{2+}/O^+	-0.98865	1.05557	-0.57037	-0.06337	0.88	1.049
FF18	Ar^{2+}	Ar^{3+}/Ar^{2+}	-0.55086	-1.00056	-0.62990	-0.13395	0.78	1.012
FF19	Ar^{3+}	Ar^{3+}/Ar^{2+}	-0.55086	-0.58722	-0.62990	-0.13395	0.96	1.018

Table 2. New ICFs for HII regions.

N	A/H	A^{++}/H^+	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	SD
			$x = lg(He^{++}/He^+)$: $x \in [-2.1.. -1.5)$:									
G1*	He/H	He^{++}/H^+	1043.9	2950.1	3318.2	1858.5	518.06	57.489	0	0	0	0.02
			$x = lg(O^{++}/O^+)$: $G2(x \in [-1..2.36])$; $G3, G4(x \in [-2..2.36])$:									
G2	O/H	O^0/H^+	-1.232	-0.710	-0.068	0.023	0	0	0	0	0	0.14
G3*	O/H	O^+/H^+	-0.279	-0.432	-0.258	0.014	0.008	0	0	0	0	0.08
G4*	O/H	O^{++}/H^+	-0.279	0.568	-0.258	0.014	0.008	0	0	0	0	0.08
			$G5(x \in [-1.8..1.8])$; $G6(x \in [-2..1])$; $G7(x \in [-1.72..2.36])$; $G7(x \in [-1.65..2.36])$:									
G5	N/H	N^0/H^+	-1.673	-1.008	-0.292	0.068	0.081	0	0	0	0	0.18
G6*	N/H	N^+/H^+	-0.367	-0.489	-0.242	0.018	0.008	0	0	0	0	0.09
G7*	Ne/H	Ne^{++}/H^+	-0.210	0.459	-0.286	0.007	0.022	0	0	0	0	0.14
G8	S/H	S^+/H^+	-0.547	-0.563	-0.131	0.015	0	0	0	0	0	0.13
			$x = lg(O^{++}/O^+)$: $G9(x \in [-1.76..2.33])$; $G10(x \in [-1.65..2.33])$; $G11(x \in [-1.06..2.37])$:									
G9*	S/H	S^{++}/H^+	-0.167	0.062	0.014	0.158	-0.231	-0.05	0.07	0.006	-0.007	0.12
G10	Ar/H	Ar^{++}/H^+	-0.008	0.092	-0.117	0.001	0.003	-0.008	0	0	0	0.07
G11	Ar/H	Ar^{3+}/H^+	-1.413	1.056	-0.258	-0.077	0.09	-0.009	-0.005	0	0	0.07
			$x = lg(S^{++}/S^+)$: $G12(x \in [-0.91..1.54])$; $G13(x \in [-0.37..1.54])$; $G14, G15(x \in [-1.4..1.54])$:									
G12	He/H	He^+/H^+	0.043	0.017	0.013	0.015	0	0	0	0	0	0.03
G13	O/H	O^0/H^+	-0.904	-0.893	-1.087	3.226	5.31	-22.53	20.58	-5.796	0	0.29
G14*	O/H	O^+/H^+	-0.207	0.091	0.779	-0.817	-2.844	0.376	2.083	-0.047	-0.467	0.29
G15*	O/H	O^{++}/H^+	-0.743	0.885	-0.055	-0.031	-0.058	0	0	0	0	0.18
			$G16(x \in [-0.9..1.5])$; $G17, G18(x \in [-1.55..1.56])$; $G19(x \in [-1.41..1.54])$; $G20(x \in [-1.56..0.61])$; $G21(x \in [-0.89..1.5])$; $G22(x \in [-0.61..1.54])$:									
G16	N/H	N^0/H^+	-1.273	-0.971	-0.456	-0.148	0.179	0	0	0	0	0.17
G17*	N/H	N^+/H^+	-0.234	-0.028	0.641	-0.663	-2.585	0.266	1.904	-0.027	-0.426	0.26
G18*	Ne/H	Ne^{++}/H^+	-0.589	0.643	-0.117	0.03	0.045	0	0	0	0	0.23
G19*	S/H	S^+/H^+	-0.339	-0.402	0.362	-0.292	-1.799	0.099	1.34	0.001	-0.301	0.18
G20*	S/H	S^{++}/H^+	-0.296	0.602	-0.359	-0.301	-0.051	0.102	0.024	0	0	0.18
G21	Ar/H	Ar^{++}/H^+	-0.177	0.164	-0.196	1.259	0.603	-4.37	0.382	3.666	-1.601	0.16
G22*	Ar/H	Ar^{3+}/H^+	-1.998	1.224	0.565	-0.416	0	0	0	0	0	0.26
			$x = lg(Ar^{3+}/Ar^{2+})$: $G23(x \in [-2.4.. - 0.88])$; $G24 - G26(x \in [-2.48..1.02])$: $G27(x \in [-2.41..0.2])$; $G28, G29(x \in [-2.4..0.9])$:									
G23	He/H	He^+/H^+	0.126	0.05	-0.052	-0.05	-0.011	0	0	0	0	0.03
G24*	O/H	O^0/H^+	-2.436	0.725	0.201	0.074	0	0	0	0	0	0.20
G25	O/H	O^+/H^+	-1.497	-0.953	0.394	0.114	-0.365	-0.199	-0.028	0	0	0.10
G26	O/H	O^{++}/H^+	0.075	0.067	0.014	0.006	-0.156	-0.051	0	0	0	0.09
G27*	N/H	N^0/H^+	-3.168	-0.132	1.618	0.852	0.132	0	0	0	0	0.24
G28*	N/H	N^+/H^+	-1.543	-1.416	0.53	0.827	-0.344	-0.489	-0.111	0	0	0.30
G29	Ne/H	Ne^{++}/H^+	-0.014	-0.036	-0.053	0.097	0.024	0	0	0	0	0.06
			$G30(x \in [-1.38..0.79])$; $G31 - G33(x \in [-2.4..0.88])$:									
G30	S/H	S^{++}/H^+	-0.369	-0.700	-0.431	0.310	0.161	-0.259	-0.212	-0.043	0	0.09
G31	Ar/H	Ar^{++}/H^+	-0.299	-0.485	-0.212	0.113	-0.018	-0.160	-0.101	-0.019	0	0.06
G32*	Ar/H	Ar^{3+}/H^+	-0.299	0.515	-0.212	0.113	-0.018	-0.160	-0.101	-0.019	0	0.06

* - Вирази отримані з врахуванням точок сітки ФМС по параметру E1 (для розподілів енергій з α >-4.9)

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