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ELEMENT ABUNDANCES IN PLANETARY NEBULAE FROM RECOMBINATION LINE SPECTRA

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Abstract. The results of calculation of the effective recombination coefficients (ERC), supplemented by data from the literature, are presented for the ions CII–CIV, NIII, NIV and OIII–OV. The contributions from both the radiative and dielectronic recombination to ERC are taken into account. Functions $X(T_e)$, connecting the recombination line intensities, with the abundances of the recombinated ions are obtained. Using the observed recombination line intensities, the abundances of C, N and O in 61 planetary nebulae have been determined. Ionization correction factors are obtained from the ionization models of Aller and Czyzak (1983).

Key words: atomic data – molecular data – planetary nebulae: element abundances

1. Introduction

The presence of weak recombination lines of ions of C, N and O is a prominent feature in the spectra of planetary nebulae. These lines are very useful for the determination of element abundances. In low density plasmas of gaseous nebulae, recombination mainly proceeds to the ground states of ions. Some of the exceptions from this rule have been considered by Nikitin and Kholtygin (1980) and Kholtygin (1981).

Recombination followed by cascade transitions is an important mechanism of populating the high atomic levels. Total recombination rates include both the radiative and dielectronic recombination.

Here three-body recombination is unimportant. The contribution of the radiative and dielectronic recombination will be considered separately.

Extensive tables of the effective recombination coefficients for the lines excited by dielectronic recombination have been presented by Nussbaumer and Storey (1984, 1986, 1987). Unfortunately, there are no such tables for most of the lines excited by the radiative recombination except for those of H and He ions.

As related to the problem treated in the present paper, we should mention the results of calculations by Burgess and Seaton (1960) for OIII, OIV and OV, by Leibowitz (1972) for CIV and by Escalante and Victor (1990) for CI and NII and the results of extensive calculations of our group (Feklistova 1980, Kholtygin 1981, 1984, Nikitin et al. 1984, 1987, Bogdanovich et al. 1985, as well as summaries by Nikitin et al. 1988 and Golovatyj et al. 1991) for CII, CIII, NIII, NIV, OIII, OIV and OV.

In a recent paper by Pequignot et al. (1991), the results of calculations of the effective recombination coefficients in hydrogenic approximation corrected for some multi-electron effects for the CI–CVI, NI–NVII, OI–OVIII ions are presented. Unfortunately, in this work some of important lines observed in the spectra of planetary nebulae have been omitted. We have selected most reliable data for the dominant recombination lines in the spectra of planetary nebulae. Corresponding approximation formulae of the effective recombination coefficients are presented in Section 2. These coefficients are used for the C, N, O abundance determination for 61 planetary nebulae, the results being given in Section 3.

2. Effective recombination coefficients

The effective recombination coefficient $\alpha_k^{\rm eff}({\rm A})$ (in cm^{3}s^{-1}) on level k of ion A is related to the rate r_k (in cm^{-3}s^{-1}) at which level k is populated by recombination and all subsequent radiative cascades by

$$r_k = n_{\rm e}\, n^+\, \alpha_k^{\rm eff}({\rm A}), \tag{1}$$

where $n_{\rm e}$ and n^+ are the number densities of free electrons and ions $\rm A^+$, respectively.

The effective recombination coefficient $\alpha_{ki}^{\rm eff}$ of the line λ_{ki} arising from the upper level k is

$$\alpha_{ki}^{\rm eff} = \alpha_k^{\rm eff}\, B_{ki}, \tag{2}$$

where the branching ratio B_{ki} is the probability of decay via transition with the wavelength λ_{ki} with respect to the total probability of the radiative decay of level k.

The emissivity (in erg $\mathrm{cm}^{-3}\mathrm{s}^{-1}$) of the line λ_{ki} is

$$E_{ki} = n_\mathrm{e}\, n^+\, \alpha_{ki}^{\mathrm{eff}}\, h\nu_{ki}, \tag{3}$$

where $h\nu_{ki}$ is the energy of the line $k \rightarrow i$.

Following the papers by Nikitin et al. (1988) and Golovatyj et al. (1991), we use an approximation formula

$$\alpha_{ki}^{\mathrm{eff}} = \alpha_{ki}^{0} \left(\frac{T_\mathrm{e}}{10^4} \right)^{\eta_{ki}}, \tag{4}$$

where η_{ki} is a fit constant for the corresponding transition.

A slight modification of expression (4) has been carried out by Pequignot et al. (1991) who proposed the expression

$$\alpha_{ki}^{\mathrm{eff}} = 10^{-13} Z\, \frac{a u^b}{1 + c u^d}, \tag{5}$$

where $u = 10^{-4}\, T_\mathrm{e}/Z^2$, with Z being the charge number of ion A^+. The explicit presence of Z in the expression guarantees a slow variation of the parameters a, b, c and d along isoelectronic sequences. Here we will use the Pequignot et al. (1991) notations for all recombination lines, so we convert our approximation formula (4) into their form. The results of computation of $\alpha_{ki}^{\mathrm{eff}} \equiv \mathrm{Y}$ are given in Table 1.

The values Y in units $10^{-14}\mathrm{cm}^3\mathrm{s}^{-1}$ for $T_\mathrm{e} = 10^4$ K for ions of C, N and O have been taken from the papers referred to in the table, using a pure photorecombination approximation.

Planetary nebulae are transparent for photons of recombination lines and thus the luminosity corresponding to transitions between states k and i of ion A is given by the expression

$$E_{ki} = h\nu_{ki} \int_V n_\mathrm{e}\, n^+\, \alpha_{ki}^{\mathrm{eff}}\, dV. \tag{6}$$

Using the averaged values of n_e and $\alpha_{ki}^{\mathrm{eff}}$ and denoting the total number of ions A^+ by $N(\mathrm{A}^+)$, we can write Eq. (6) as

$$E_{ki} = h\nu_{ki}\, \alpha_{ki}^{\mathrm{eff}}(\bar{T}_\mathrm{e})\, \bar{n}_\mathrm{e}\, N(\mathrm{A}^+). \tag{7}$$

Table 1. Fit parameters and the effective recombination coefficients Y

Ion	Transition	λ(Å)	Case	a	b	Y	Ref
CII	$3p\ ^2P^0 - 4s\ ^2S$	3921	B	0.402	-0.700	21.2	2
CII	$3d\ ^2D - 4f\ ^2F^0$	4267	A,B	0.433	-0.720	23.6	1
CII	$3p\ ^2P^0 - 3d\ ^2D$	7231	B	0.616	-0.600	28.3	2
CIII	$4f\ ^3F^0 - 5g\ ^3G$	4070	A,B	0.087	-0.950	20.8	1
CIII	$3p'\ ^3D - 5f\ ^3F^0$	4156	A,B	0.022	-0.860	4.4	2
CIII	$4f\ ^1F^0 - 5g\ ^1G$	4187	A,B	0.033	-0.960	8.1	1
CIII	$3s\ ^3S - 3p\ ^3P^0$	4650	A,B	0.250	-0.600	28.0	1
CIV	$5fg - 6gh$	4658	A,B	0.144	-0.970	85.0	1
NII	$3s\ ^3P^0 - 3p\ ^3P$	4624	B	0.150	-0.742	8.4	3
NII	$3p\ ^3D - 3d\ ^3D^0$	4795	B	0.069	-0.904	4.8	3
NII	$3p\ ^3D - 3d\ ^3F^0$	5005	B	0.387	-0.807	23.7	3
NII	$3s\ ^3P^0 - 3p\ ^3D$	5679	B	0.397	-0.554	17.1	3
NIII	$4d\ ^2D - 5f\ ^2F^0$	4003	B	0.020	-0.613	2.3	2
NIII	$3s\ ^2S - 3p\ ^2P^0$	4097	A,B	0.496	-0.480	42.7	2
NIII	$4f\ ^2F^0 - 5g\ ^2G$	4379	A,B	0.032	-0.780	5.4	2
NIII	$3p\ ^2P^0 - 3d\ ^2D$	4640	B	0.930	-0.612	107	1
NIV	$4f\ ^1F^0 - 5g\ ^1G$	3078	A	0.023	-0.940	12.4	2
NIV	$3s\ ^3S - 3p\ ^3P^0$	3478	A	0.330	-0.606	70.8	1
OIII	$3p\ ^3S - 3d\ ^3P^0$	3133	B	0.063	-0.909	13.9	4
OIII	$3s\ ^3P^0 - 3p\ ^3S$	3340	B	0.024	-0.904	4.4	4
OIII	$3p\ ^3P - 3d\ ^3P^0$	3430	B	0.038	-0.919	8.7	4
OIII	$3p\ ^3P - 3d\ ^3D^0$	3715	B	0.119	-0.896	25.5	4
OIV	$3p\ ^2P^0 - 3d\ ^2D$	3412	B	0.046	-0.880	21.3	2
OV	$3s\ ^1S - 3p\ ^1P^0$	5113	B	0.125	-0.570	39.3	1

References

1. Golovatyj et al. (1991).
2. Kholtygin, unpublished.
3. Escalante and Victor (1990).
4. Kholtygin, obtained by extrapolation of the data [3] along the CI isoelectronic sequence.

From (7) it follows that the line intensity ratio (decrement) for recombination lines can be written in the following form:

$$\frac{I_{ki}}{I_{mn}} = \frac{\lambda_{mn}}{\lambda_{ki}} \cdot \frac{\alpha_{ki}^{\text{eff}}}{\alpha_{mn}^{\text{eff}}}. \tag{8}$$

The contribution of dielectronic recombinations we have taken as treated by Nussbaumer and Storey (1983, 1984, 1986, 1987). The values of total recombination coefficients,

$$\alpha_{ki}^{\text{R}} = \alpha_{ki}^{\text{eff}} + \alpha_{ki}^{di}, \tag{9}$$

are given in Table 2.

Table 2. The values of total and partial effective recombination coefficients ($\alpha_{ki}^{\text{R}} = \alpha_{ki}^{\text{eff}} + \alpha_{ki}^{di}$) in units $10^{-14}\text{cm}^3\text{s}^{-1}$

Ion	λ(Å)	Case	$T_e = 10^4$ K			$T_e = 2 \cdot 10^4$ K		
			α_{ki}^{eff}	α_{ki}^{di}	α_{ki}^{R}	α_{ki}^{eff}	α_{ki}^{di}	α_{ki}^{R}
CII	3921	B	21.2		21.2	13.1		13.1
	4267	A,B	23.6	0.02	23.6	14.3	1.51	15.8
	7231	B	28.3		28.3	18.7		18.7
CIII	4070	A,B	20.8	6.1	26.9	10.8	18.2	29.0
	4156	A,B	4.4	1.6	6.0	2.4	1.5	3.9
	4187	A,B	8.2	2.2	10.4	4.2	6.6	10.8
	4650	A,B	28.0	63.3	91.3	18.5	36.0	54.5
CIV	4658	A,B	85.0		85.0	43.7		43.7
	7726	A,B	98.9		98.9	43.6		43.6
NII	4624	B	8.4		8.4	5.0		5.0
	4795	B	4.8		4.8	2.6		2.6
	5005	A,B	23.7	0.1	23.8	13.6	0.8	14.4
	5679	A,B	17.1	0.2	17.3	11.2	1.0	12.2
NIII	4003	A,B	2.3	1.3	3.6	1.5	0.7	2.2
	4097	A,B	42.7	2.0	44.7	30.6	1.7	32.3
NIII	4379	A,B	5.4		5.4	3.1		3.1
	4640	B	107.0	100.2	207.2	70.0	109.3	179.3
NIV	3078	A	12.5	3.6	16.1	6.5	3.8	10.3

Table 2 (continued)

Ion	λ(Å)	Case	$T_e = 10^4$ K			$T_e = 2 \cdot 10^4$ K		
			α_{ki}^{eff}	α_{ki}^{di}	α_{ki}^{R}	α_{ki}^{eff}	α_{ki}^{di}	α_{ki}^{R}
NIV	3478	A	70.8	47.1	117.9	46.5	33.7	80.2
	4606	A	101.5	3.3	104.8	44.6	13.4	58.0
	7703	A	66.8	0.7	67.5	27.8	5.7	33.5
OII	4075	A	18.9	0.01	18.9	9.4	0.3	9.7
	4089	A	8.4		8.4	3.8		3.8
	4119	A	9.4		9.4	4.7		4.7
	4349	A,B	20.0	0.1	20.1	10.6	0.6	11.2
	4649	A,B	36.3	0.2	36.5	19.1	1.4	20.5
OIII	3133	B	13.9		13.9	7.4		7.4
	3266	A,B	63.4	35.6	99.0	33.9	30.1	64.0
OIII	3340	B	4.4	1.9	6.3	2.5	1.4	3.9
	3430	B	8.7		8.7	4.6		4.6
	3715	B	25.5		25.5	13.7		13.7
	3760	A,B	43.2	21.6	64.8	24.1	23.0	47.1
OIV	3412	B	21.3	65.1	86.4	11.6	49.4	61.0
	4632	A,B	101.5		101.5	44.6		44.6
OV	4930	A,B	142.2	1.2	143.4	61.5	8.4	69.9
	5113	B	39.3		39.3	26.4		26.4

As usual, two simple limiting cases can be distinguished: case A – all transitions of the ion are assumed optically thin, case B – all transitions involving directly the ground state are assumed optically thick. Notation A,B is used for the average between A and B values, when their differences do not exceed 20%. Thus we use the values labeled as A,B for the cases when we get the same result in the lines of the ion under consideration for both the transparent and thick planetary nebulae. A comparison of our results presented in Tables 1 and 2 with those by Pequignot et al. (1991) shows that the error in the values of effective recombination coefficients in any case does not exceed 50%.

3. Abundances of C, N and O in planetary nebulae

The present state of determination of element abundances from recombination spectra of planetary nebulae and the corresponding formulae have been presented in the papers by Kholtygin (1981, 1984), Nikitin et al. (1988) and Golovatyj et al. (1991).

The abundance ratio of a given ion A^+ relative to H^+ can be estimated from

$$\frac{N(A^+)}{N(H^+)} \equiv \{A^+/H^+\} = \frac{\lambda_{ki}}{\lambda(H_\beta)} \cdot \frac{\alpha^{\rm eff}(H_\beta)}{\alpha^{\rm eff}_{ki}} = X(T_e)\,\frac{I_{ki}}{I(H_\beta)}. \quad (10)$$

The coefficient $X(T_e)$ can be expressed by

$$X(T_e) = \chi_0\,(T_e/10^4)^\eta.$$

The numerical values of approximation parameters χ_0 and η, obtained with the effective recombination coefficients for lines of the C, N and O ions from Table 2 are given in Table 3.

Table 3. Fit parameter values for the function $X(T_e) = \chi_0 \left(T_e/10^4\right)^\eta$

Ion	λ,Å	Case	Photorecom.		Ph. and Di.-recom.	
			χ_0	η	χ_0	η
CII	3921	B	0.116	-0.23	0.116	-0.23
	4267	A,B	0.113	-0.19	0.113	-0.34
	7231	B	0.160	-0.32	0.160	-0.32
CIII	4070	A,B	0.122	0.03	0.095	-1.03
	4156	A,B	0.591	-0.04	0.433	-0.29
	4187	A,B	0.319	0.05	0.252	-0.97
	4650	A,B	0.104	-0.32	0.032	-0.17
CIV	4658	A,B	0.034	0.04	0.034	0.04
	7726	A,B	0.049	0.26	0.049	0.26
NII	4624	B	0.344	-0.17	0.344	-0.17
	4795	B	0.624	-0.03	0.624	-0.03
	5005	A,B	0.132	-0.12	0.132	-0.19
	5679	A,B	0.208	-0.31	0.205	-0.41
NIII	4003	A	1.090	-0.30	0.695	-0.21
	4097	A	0.060	-0.44	0.057	-0.45

Table 3 (continued)

Ion	λ, Å	Case	Photorecom.		Ph. and Di.-recom.	
			χ_0	η	χ_0	η
NIII	4379	A	0.507	-0.12	0.507	-0.12
	4640	B	0.027	-0.30	0.014	-0.71
NIV	3078	A	0.154	0.03	0.120	-0.27
	3478	A	0.031	-0.31	0.018	-0.36
	4606	A	0.028	0.27	0.028	-0.06
	7703	A	0.072	0.35	0.071	0.09
OII	4075	A	0.135	0.09	0.135	0.05
	4089	A	0.304	0.23	0.304	0.29
	4119	A	0.274	0.08	0.274	0.08
	4349	A,B	0.136	0.00	0.135	-0.07
	4649	A,B	0.080	0.01	0.080	-0.08
OIII	3133	B	0.141	-0.01	0.141	-0.01
	3265	A,B	0.032	-0.01	0.021	-0.29
	3340	B	0.475	-0.10	0.332	-0.23
OIII	3430	B	0.247	0.00	0.247	0.00
	3715	B	0.091	-0.02	0.091	-0.02
	3760	A,B	0.054	-0.08	0.036	-0.46
OIV	3412	B	0.100	-0.04	0.025	-0.41
	4632	A,B	0.028	0.27	0.029	0.27
OV	4930	A,B	0.022	0.29	0.022	0.12
	5113	B	0.081	-0.34	0.081	-0.34

Using the above formulae, we estimated the abundances of the C, N and O ions and atoms in 61 planetary nebulae by using the data on line intensities from the papers by Kaler (1976), Aller and Czyzak (1979, 1983) and Aller and Keyes (1987) and the correction factors due to observationally lacking ions according to the papers by Aller and Czyzak (1983) and Nikitin et al. (1987). The results are given in Table 4. In some cases, only the lower limits of the abundances could be obtained. These limits are marked by $\geq$.

Table 4. Abundances (in $10^4 cm^{-3}$ units) of C, N and O in planetary nebulae found from the intensities of the recombination lines

Nebula	E_w	$T_e/10^4$K	Type	{C/H}	{N/H}	{O/H}
NGC 40	2	0.85	II	$\geq$ 2.8		
650-I	8p	1.0	II	19.0		
1535	7	1.09	II	14.5	9.2	$\geq$ 7.8
2022	10	1.37	II	18.3	6.3	$\geq$ 14.6
2371-2	9p	1.08	II	10.2	7.7	$\geq$ 11.7
2392	8p	1.3	II	$\geq$ 4.4	2.1	
2440	9	1.4	I	9.6	30.5	14.0
3242	7	1.09	II	8.4	12.1	11.1
4361	10	2.3	II	24:		
6210	5	1.0	II	10.2	11.0	$\geq$ 4.5
6439	7	1.05	III	15.2	$\geq$ 9.2	
6543	5	0.80	II	9.1	$\geq$ 5.7	23.5
6567	5.5	1.06	III	12.9	3.6:	
6572	6	1.0	II	5.0	1.0:	8.3
6578	5	0.85	II	19.4	$\geq$ 5.5	
NGC 6620	6.5	0.99	I	12.6	21.8:	
6629	4	0.89	II	$\geq$ 10	$\geq$ 2.8	
6720	6p	1.0	II	19.3	10.0:	23.0
6741	8	1.16	I	17.0	10.3:	
6778	5	1.0		$\geq$ 17.8	$\geq$ 6.5	10.9
6790	6	1.2	I	5.4	6.1	
6803	6	0.93	I	8.9	12.4	
6807	5	1.12	III	$\geq$ 16.8	6.4	
6818	9	1.2	II	10.0	13.9	
6826	5	1.07	II	9.7	5.6:	14.8
6833	5	1.42	I	2.5	4.1:	
6879	5.5	1.2	II	$\geq$ 3.1	14.5:	
6881	8	1.27	I	18.8	10.4	
6884	6	1.05	II	8.5	7.4:	
6886	8	1.26	I	8.5	13.1	8.2
6891	5	0.93	II	8.2	11.0	
7009	6	0.9	II	9.4	$\geq$ 5.8	26.5
7027	10p	1.4	II	9.4	6.5	10.2
7662	8	1.3	II	7.7	11.0	13.8

Table 4 (continued)

Nebula	E_w	$T_e/10^4$K	Type	{C/H}	{N/H}	{O/H}
IC 351	8	1.2	II	12.1	7.8	
418	3	0.85	II	6.9	0.8	$\geq$ 19.5
1747	6	0.98	II	15.1	6.4:	
2003	8	1.1	I	9.4	5.1	10.8
IC 2165	8.5	1.3	I	8.5	8.5	7.7
4732	5	1.3	III	13.2		
4776	6p	0.84	II	2.9	1.0	
4846	5	1.0	II	4.2:	11.0	
4997	5	1.8	II	2.4	2.1	7.4
5117	6	1.2	II	7.3	8.2	
5217	6	1.09	II	5.6	5.3:	
J 320	5	1.2	II	3.4	3.5	
J 900	7	1.15	II	13.9	4.8	
Hb 12	4	1.3	II	4.3	8.0:	
Hu 1-1	6	1.15			8.5	
Hu 1-2	10	1.6	I	5.7	5.0	11.8:
Hu 2-1	4	1.0	II	5.4	$\geq$ 0.8	$\geq$ 8.6
Me 1-1	5	1.0	II	11.6	12.0:	
Me 2-2	4.5	1.1	I	6.7	2.7:	
CN 2-1	5.6	0.79	II		19.5	
CN 3-1	2	1.1	I	5.0	$\geq$ 2.0	
M1 4	6	1.16	II	9.2	9.4	
M1 74	2	0.93	II	8.5		
M1 80	7	1.23	I		$\geq$ 6.8	
M2 21	6.5	1.26	II		$\geq$ 6.9	
M3 20	5	1.04	II		$\geq$ 3.6	
Vy2 3	5	1.1			$\geq$ 4.9	

In Table 5 we give the element abundances found from both the recombinational (our calculations) and the collisional (results by Perinotto 1991, Aller and Czyzak 1979, 1983, Aller and Keyes 1987 and Torres-Peimbert et al. 1980) spectral lines. From these data it appears that the "recombinational" abundances essentially exceed the "collisional" abundances. As it has been shown, for example, by Kholtygin and Feklistova (1992), this circumstance is probably caused by temperature and density inhomogeneities in planetary nebulae.

Table 5. Comparison of the element abundances (in $10^4 cm^{-3}$ units) found from "recombinational" and "collisional" lines

Nebula	{C/H}		{N/H}		{O/H}	
	rec	coll	rec	coll	rec	coll
NGC 2371-2	10.2	18	7.7	2.6	$\geq$ 11.7	7.2
2440	9.6	3.5	30.5	6.3	14.0	4.8
6439	15.2		$\geq$ 9.2	2.9		4.5
6567	12.9		3.6:	0.6		2.6
6578	19.4		$\geq$ 5.5	1.1		6.3
6620	12.6		21.8:	4.5		6.9
6807	$\geq$ 16.8		6.4:	0.8		3.0
6818	10.0	4.5	13.9	1.4		5.5
6879	$\geq$ 3.1		14.5:	0.8		4.1
6891	8.2	4.8	11.0	0.5		3.7
7027	9.4	13	6.5	3.3	10.2	4.2
7662	7.7	4.0	11.0	0.7	13.8	3.2
IC 418	6.9	7.0	0.8	0.7	$\geq$ 19.5	4.4
CN 2-1			19.5	4.6		11.5
Hu 1-2	5.7	1.2	5.0	3.2	11.8:	1.1
M 1-4	9.2		9.4	0.5		2.7
M 1-80		7.4	18.0:	2.0		3.9
M 2-21			19.8	0.9		3.1
M 3-20			15.9	0.7		5.0
Me 1-1	11.6		12.0:	3.4		4.7
Me 2-2	6.7		2.7:	6.9		1.9

4. Conclusion

The effective radiative recombination coefficients have been calculated and presented as simple fit formulae for the lines of ions C, N and O. The contributions from both the photorecombination and the dielectronic recombination are included. The total element abundances of C, N and O in 61 planetary nebulae have been determined using the intensity of recombination lines. Analysis of these data indicates systematic overabundances of the recombinational abundances. The reason of this may probably be thermal and density inhomogeneities in nebulae.

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