DETERMINATION OF Lc-SPECTRA, PHYSICAL PARAMETERS AND CHEMICAL COMPOSITION OF PLANETARY NEBULAE AND HII REGIONS IN BLUE COMPACT DWARF GALAXIES.

B.Ya.Melekh,
V.V.Holovatyy, and N.V.Havrylova

Chair of astrophysics, Ivan Franko National University of Lviv, Ukraine
E-Mail: melekh@physics.wups.lviv.ua

Main goals:

- Developing of the new method for calculation of Lyman continuum (Lc) spectrum of ionizing nuclei in HII regions of Blue Compact Dwarf Galaxies (BCDG).
- Correction of Clegg & Middlemass (1987) stellar athmosphere models of planetary nebulae nuclei for stellar wind presence.
- Developing of the method for the determination of physical characteristics and chemical composition of HII regions and planetary nebulae (PNe) which is based on optimized photoionization modelling and independent on ionization-correction factors.

Lc-spectrum calculation

Ionizing spectrum of starburst knots into HII regions

Main features of method:

- Main absorption agents are H^0, He^0, and He^+
- Representation of spectrum beyond λ≤912A by power law into three wavelength intervals which correspond to the ionization potentials of H^0, He^0, and He^+. Thus, Lc-spectrum is defined by 6 parameters: 3 fluxes at the beginning of every wavelength interval (F_{912},F_{504},F_{228}) and 3 parameters which characterize spectrum shape (for power-law it is spectral index α) into these intervals (α ', α '', α ''').
- Assumption about thermal and ionization-recombination equilibriums in nebular gas. Therefore, we have three equations of ionization-recombination equilibrium for H^0, He^0, and He^+ correspondingly and one equation for thermal equilibrium that are depending on observed fluxes in H_β, HeI and HeII lines and; on the other hand, on electron temperature in HeI and HeII zones, relative abundance H^+/H^0, optical thickness in λ3889HeI line and forbidden lines sum which can be obtained from photoionization modelling (below these parameters are named *iteration parameters*).
- We have obtained from analysis of results of Shaerer & de Koter (1996) (SdK) stellar athmosphere models for O-B stars dependence of SdK model effective temperature on spectral index in 912A≥λ≥504A. Using this dependence we can obtain from corresponding SdK model the shape of Lc-spectrum beyond λ≤228A and jump on λ 504A.
- We have developed code NLEHII (Nebula Light Exciter for HII regions) for fast calculation of Lc-spectrum.

PNe nucleus ionizing spectrum

We used for the determination of the PNe nucleous Lc-spectrum Clegg & Middlemass (1987) stellar athmosphere models (CMM) corrected for stellar wind presence using minimization between Zanstra relationship obtained at corresponding correction factor for quanta number beyond λ≤228A for CMM and corresponding value from Gabler et al. (1991).

Technique of optimized photoionization modelling

We use technique of optimization modelling for the finding of optimal photoionization model (PhM) of HII regions and PNe. This technique is based on the minimization of χ^2-function which represents non-coincidence degree between model and observed spectra of HII region or PN. The minimization procedure is based on finding of optimal values of input model parameters (so-called *free parameters*). For PhM calculation we used G.Ferland's (2002) code *Cloudy 96* and for optimization we used P.M. van Hoof code *Phymir* which is included to *Cloudy 96* as function.

HII regions modelling

The *free parameters* in our OPhMs:

1) the inner radius of HII region R_{in};
2) the full number of the ionizing quanta Q_{tot};
3) the hydrogen density at inner radius of HII region $n_H(R_{in})$;
4) the slope of the assumed power-law for radial hydrogen density distribution;
5) the filling factor ε;
6) the chemical abundances of He/H, 7) O/H, 8) N/H, 9) Ne/H, 10) S/H, 11) Ar/H, 12) Fe/H.

Output parameters used for calculation of χ^2-function are luminosity in H_β line, the relative intensities of 21 lines and outer radius of HII region.

We have modified code *Cloudy 96* for the taking into account stellar absorption in HeI lines during OPhMs calculation.

Calculation algorithm for HII regions modelling:

1) the initialization of the *iteration* parameters values (see above) and stellar absorption equivalent widths (EW) of HeI lines;
2) the calculation of Lc-spectrum using our method (NLEHII);
3) the calculation of the covering factor using minimization between predicted by PhM and observed values of EW(H_β);
4) the optimization of ionizing quanta number beyond λ≤228A by the difference minimization between relative intensities values I(4686HeII)/I(H_β) predicted by PhM and obtained from observations;
5) the calculation of HII region OPhM on the base of obtained above (points 2, 4) Lc-spectrum;
6) the extracting from OPhM result of new values of most iteration parameters;
7) the points from 2 to 6 must be repeated using new values of iteration parameters and optimal values of free parameters from OPhM;
8) the point 7 must be repeated to coincidence (in choosed error bars) of Lc-spectra obtained in the last and previous iterations correspondingly;
9) in result, correct Lc-spectrum and optimal values of OPhM free parameters will be obtained.

PNe modelling

We assumed:

- All OPhMs of PNe are spherically-symmetrical.
- The radial hydrogen density distribution was defined by law obtained in Golovaty et al. (1993) from real PNe isophotes analysis.

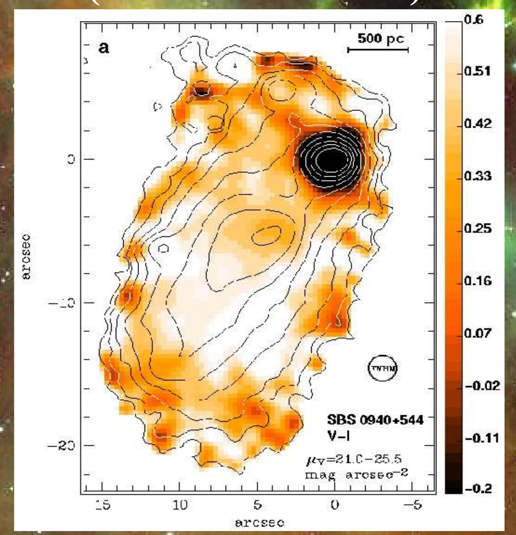
The *free parameters* in our OPhMs are following:

1) the total number of the ionizating quanta Q_{tot};
2) the maximum of the hydrogen density in the density distribution of the nebular gas n_{max}(H);
3) the filling factor ε;
4) the chemical composition of He/H, 5) C/H, 6) N/H, 7) O/H, 8) Ne/H, 9) S/H, 10) Si/H, and 11) Ar/H.

Output parameters used for calculation of χ^2-function are luminosity in H_β line and relative intensities in 14 spectral emission lines.

Images of objects:

HII region in SBS0940+544 (Guseva et al. 2001):



Planetary Nebula NGC6720:

Results

The results of calculations are shown in figures and tables

HII region in SBS0940+544

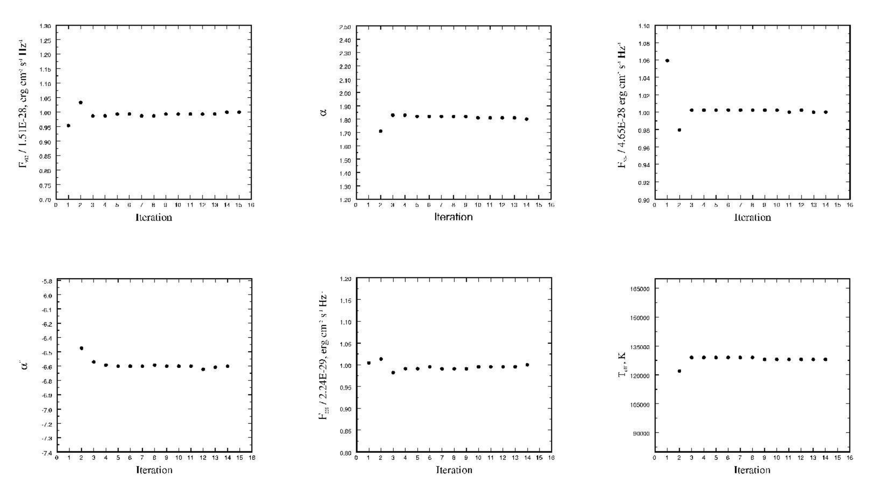


Fig. 1. The convergence of L_c spectra during iteration process.

Table 1. Comparison of observed spectrum of HII region in BCDG (Guseva *et al.* (2001)) with previous ones obtained from corresponding OPhMs presented in Table 2. In FDNT was used one line per one ion for χ^2 function calculation. In NSA we don't used correction for stellar absoption. In Max.Err. were used maximized error bars from atomic physics data.

Parameters	Observation	χ^2_{min}	χ^2_1	χ^2_2	χ^2_3	FDNT	NSA	Max.Err.
3727 [O II]	0.471 ± 0.008(0.071*)	0.504	0.505	0.506	0.500	0.494	0.507	0.569
3869 [Ne III]	0.356 ± 0.006(0.053)	0.356	0.356	0.357	0.356	0.356	0.356	0.381
4363 [O III]	0.128 ± 0.002(0.019)	0.120	0.120	0.121	0.120	-	0.120	0.120
3889 He I	0.095 ± 0.004(0.004)	0.087	0.089	0.086	0.087	-	0.090	0.104
3889 He I(SA)	→	0.095	0.096	0.095	0.095	-	-	0.114
4026 He I	0.014 ± 0.001(0.001)	0.016	0.016	0.016	0.016	-	0.017	0.020
4026 He I(SA)	→	0.018	0.018	0.019	0.018	-	-	0.022
4471 He I	0.037 ± 0.001(0.001)	0.035	0.035	0.036	0.035	-	0.036	0.042
4471 He I(SA)	→	0.039	0.038	0.039	0.038	-	-	0.046
4686 He II	0.006 ± 0.001(0.001)	0.006	0.006	0.006	0.006	0.006	0.006	0.006
4959 [O III]	1.402 ± 0.021(0.021)	1.399	1.400	1.395	1.406	-	1.396	1.404
5007 [O III]	4.204 ± 0.061(0.061)	4.211	4.212	4.200	4.231	4.102	4.202	4.226
5876 He I	0.097 ± 0.002(0.002)	0.088	0.087	0.090	0.087	-	0.092	0.088
5876 He I(SA)	→	0.101	0.100	0.103	0.100	-	-	0.106
6678 He I	0.027 ± 0.001(0.001)	0.025	0.024	0.025	0.024	-	0.026	0.030
6678 He I(SA)	→	0.028	0.028	0.029	0.028	-	-	0.034
7065 He I	0.024 ± 0.001(0.001)	0.026	0.024	0.027	0.024	0.024	0.027	0.031
7065 He I(SA)	→	0.025	0.024	0.026	0.024	0.024	-	0.030
6300 [O I]	0.010 ± 0.001(0.001)	0.003	0.003	0.003	0.003	0.003	0.003	0.003
6363 [O I]	0.004 ± 0.001(0.001)	0.001	0.001	0.010	0.001	-	0.001	0.001
6312 [S III]	0.011 ± 0.001(0.002)	0.026	0.026	0.026	0.026	0.023	0.026	0.020
6584 [NII]	0.012 ± 0.001(0.002)	0.012	0.012	0.012	0.012	0.012	0.012	0.013
4070 [S II]	0.009 ± 0.001(0.001)	0.004	0.004	0.004	0.004	-	0.004	0.003
6716 [S II]	0.035 ± 0.001(0.005)	0.028	0.028	0.028	0.028	0.025	0.028	0.023
6731 [S II]	0.028 ± 0.001(0.004)	0.020	0.020	0.020	0.020	-	0.020	0.016
7135 [Ar III]	0.026 ± 0.001(0.004)	0.026	0.026	0.026	0.026	0.026	0.026	0.026
4658 [Fe III]	0.005 ± 0.001(0.001)	0.005	0.005	0.002	0.006	0.005	0.005	0.005
5270 [Fe III]	0.004 ± 0.001(0.001)	0.003	0.003	0.001	0.003	-	0.003	0.003
$lg[L(H_\beta)]$	38.40	38.40	38.40	38.40	38.40	38.40	38.40	38.40
R_{out},pc	312.5	313.3	312.7	314.3	314.6	314.9	314.0	313.7
χ^2	-	22.05	22.64	22.77	22.82	27.34	22.02	7.36

All line intensities are given relative to $I(H_\beta)$=100. * - σ for calculation of Max.Err. OPhM. ** - Intensities in rows with pointer "→" are corrected for stellar absorption (SA) observed intensities using corresponding OPhM results.

Table 2. Optimal values of the OPhMs free parameters (hydrogen density distribution power-law slope (γ) included to the free parameters) for HII region in SBS0940+544. The best fit model is χ^2_{min}, and most closed to it (see figures 2) are χ^2_1, χ^2_2 and χ^2_3. Also Internal Testing (Int.Test) result and result of the OPhM with observational parameters errors maximalization (Max.Err.) are presented.

Parameters	χ^2_{min}	χ^2_1	χ^2_2	χ^2_3
R_{in}, pc	$4.93^{+0.09}_{-0.17}$	$6.42^{+0.13}_{-0.16}$	4.64	6.88
$n_H(R_{in}), cm^{-3}$	288^{+14}_{-13}	152^{+4}_{-4}	394	201
γ	$-1.27^{+0.02}_{-0.01}$	$-1.20^{+0.01}_{-0.01}$	-1.32	-1.29
$\log(Q_{tot})$	$52.16^{+0.01}_{-0.01}$	$52.16^{+0.01}_{-0.01}$	52.16	52.16
ε	$0.35^{+0.04}_{-0.10}$	$0.47^{+0.02}_{-0.04}$	0.28	0.36
He/H×10^2	$7.99^{+1.00}_{-0.01}$	$7.97^{+1.05}_{-0.01}$	8.08	7.90
O/H×10^5	$3.44^{+0.16}_{-0.15}$	$3.45^{+0.16}_{-0.18}$	3.41	3.46
N/H×10^6	$1.14^{+0.28}_{-0.29}$	$1.15^{+0.28}_{-0.22}$	1.12	1.17
Ne/H×10^6	$5.80^{+0.36}_{-0.33}$	$5.82^{+0.46}_{-0.43}$	5.76	5.81
S/H×10^6	$1.23^{+0.11}_{-0.08}$	$1.24^{+0.12}_{-0.14}$	1.22	1.23
Ar/H×10^7	$1.04^{+0.12}_{-0.12}$	$1.03^{+0.17}_{-0.16}$	1.02	1.02
Fe/H×10^6	$1.21^{+0.26}_{-0.23}$	$1.21^{+0.26}_{-0.26}$	0.44	1.25

Parameters	FDNT	NSA	Int. Test	Max. Err.
R_{in}, pc	$4.98^{+0.21}_{-0.05}$	$4.93^{+0.12}_{-0.13}$	$4.93^{+0.12}_{-0.60}$	$4.93^{+0.14}_{-0.10}$
$n_H(R_{in}), cm^{-3}$	292^{+6}_{-8}	287^{+21}_{-20}	288^{+25}_{-23}	273^{+8}_{-52}
γ	$-1.27^{+0.01}_{-0.01}$	$-1.27^{+0.02}_{-0.02}$	$-1.27^{+0.05}_{-0.02}$	$-1.24^{+0.06}_{-0.01}$
$\log(Q_{tot})$	$52.16^{+0.01}_{-0.01}$	$52.16^{+0.01}_{-0.01}$	$52.16^{+0.00}_{-0.00}$	$52.16^{+0.01}_{-0.01}$
ε	$0.34^{+0.01}_{-0.03}$	$0.35^{+0.02}_{-0.02}$	$0.35^{+0.02}_{-0.02}$	$0.32^{+0.02}_{-0.01}$
He/H×10^2	$7.64^{+0.73}_{-0.03}$	$8.31^{+0.32}_{-0.32}$	$7.99^{+0.55}_{-0.51}$	$9.65^{+1.78}_{-1.50}$
O/H×10^5	$3.33^{+0.14}_{-0.12}$	$3.43^{+0.13}_{-0.13}$	$3.44^{+0.14}_{-0.14}$	$3.53^{+0.15}_{-0.12}$
N/H×10^6	$1.13^{+0.16}_{-0.12}$	$1.12^{+0.43}_{-0.41}$	$1.13^{+0.44}_{-0.42}$	$1.08^{+0.64}_{-0.40}$
Ne/H×10^6	$5.76^{+0.28}_{-0.22}$	$5.80^{+0.37}_{-0.45}$	$5.80^{+0.40}_{-0.37}$	$6.35^{+3.72}_{-2.34}$
S/H×10^6	$1.07^{+0.09}_{-0.07}$	$1.23^{+0.10}_{-0.13}$	$1.23^{+0.12}_{-0.13}$	$9.59^{+2.48}_{-3.54}$
Ar/H×10^7	$1.02^{+0.12}_{-0.07}$	$1.03^{+0.15}_{-0.16}$	$1.03^{+0.15}_{-0.16}$	$1.01^{+0.59}_{-0.16}$
Fe/H×10^6	$1.19^{+0.46}_{-0.24}$	$1.19^{+0.70}_{-0.44}$	$1.20^{+0.70}_{-0.44}$	$1.10^{+0.64}_{-0.41}$

Table 3. Resulting spectrum of internal testing: for optimization we used resulting model spectrum (Synt. spectrum) from OPhM χ^2_{min}. All line intensities are given relative to $I(H_\beta)$.

Parameters	Synt. spectrum	Internal Test
3727 [O II]	0.504 ± 0.008	0.504
3869 [Ne III]	0.356 ± 0.006	0.356
4363 [O III]	0.120 ± 0.002	0.120
3889 He I	0.087 ± 0.006	0.087
4026 He I	0.016 ± 0.002	0.016
4471 He I	0.035 ± 0.002	0.035
4686 He II	0.006 ± 0.001	0.006
4959 [O III]	1.399 ± 0.021	1.399
5007 [O III]	4.211 ± 0.061	4.211
5876 He I	0.088 ± 0.003	0.088
6678 He I	0.025 ± 0.002	0.025
7065 He I	0.026 ± 0.002	0.026
6300 [O I]	0.003 ± 0.001	0.003
6363 [O I]	0.001 ± 0.001	0.001
6312 [S III]	0.026 ± 0.001	0.026
6584 [NII]	0.012 ± 0.001	0.012
4070 [S II]	0.004 ± 0.001	0.004
6716 [S II]	0.028 ± 0.001	0.028
6731 [S II]	0.020 ± 0.001	0.020
7135 [Ar III]	0.026 ± 0.001	0.026
4658 [Fe III]	0.005 ± 0.001	0.005
5270 [Fe III]	0.003 ± 0.001	0.003
$lg[L(H_\beta)]$	38.40	38.40
R_{out},pc	312.5	312.5
χ^2	-	10^{-6}

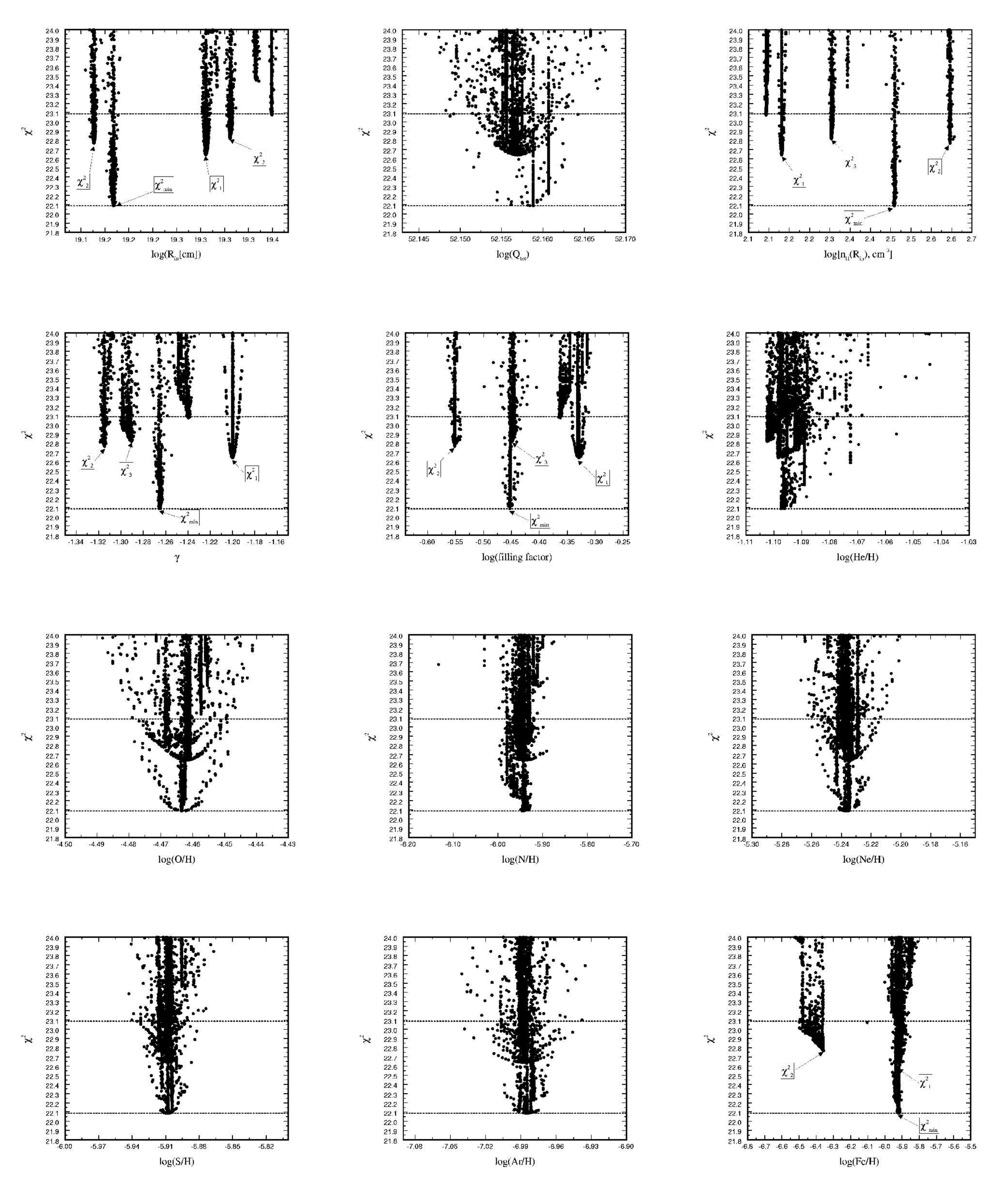


Fig. 2. The distributions of χ^2 function over free parameters of HII region OPhMs. The levels of χ^2_{min} and $\chi^2_{min}+1$ (because of one freedom degree) are shown by dashed lines. Best fit model is pointed by χ^2_{min}. Also, three most closed to the best fit models are pointed by χ^2_1, χ^2_2 and χ^2_3 correspondly. As it can see, we obtained many minimums of χ^2-function for some free parameters, but for most chemical elements abundance we have one minimum of χ^2-function.

Acknowledgements. The authors are grateful to Yu.I.Izotov (Main Astronomical Observatory, National Academy of Sciences, Ukraine) for useful discussions.

Planetary Nebula NGC6720

Table 4. Optimal values of the OPhMs free parameters for the planetary nebula NGC6720. Models *MJPS*,*AVR*,*MAX* and *MIN* are initialized by different sets of free parameters. In model FDNT used one line per one ion in χ^2-function calculation.

Parameters	*MJPS*	*AVR*	*MAX*	*MIN*	FDNT
$n_H^{max} 10^4, cm^{-3}$	$1.76^{+0.72}_{-0.63}$	$1.66^{+0.71}_{-0.52}$	$2.11^{+0.99}_{-0.73}$	$1.32^{+0.50}_{-0.33}$	$1.75^{+0.55}_{-0.40}$
$logQ_{tot}$	$45.7^{+0.02}_{-0.02}$	$45.7^{+0.02}_{-0.02}$	$45.7^{+0.02}_{-0.01}$	$45.7^{+0.02}_{-0.02}$	$45.7^{+0.02}_{-0.02}$
ε	$0.23^{+0.04}_{-0.04}$	$0.25^{+0.07}_{-0.05}$	$0.22^{+0.05}_{-0.04}$	$0.30^{+0.08}_{-0.07}$	$0.22^{+0.06}_{-0.04}$
He/H×10^2	$9.27^{+0.69}_{-1.30}$	$9.33^{+1.22}_{-1.21}$	$8.81^{+1.53}_{-0.79}$	$9.36^{+1.05}_{-1.22}$	$9.79^{+0.85}_{-1.55}$
O/H×10^4	$6.60^{+0.49}_{-0.50}$	$6.26^{+0.77}_{-0.63}$	$7.16^{+0.61}_{-0.82}$	$5.81^{+0.67}_{-0.59}$	$6.45^{+0.61}_{-0.62}$
N/H×10^4	$0.99^{+0.16}_{-0.17}$	$0.99^{+0.16}_{-0.13}$	$1.03^{+0.14}_{-0.20}$	$0.98^{+0.17}_{-0.15}$	$0.98^{+0.15}_{-0.07}$
Ne/H×10^5	$7.34^{+2.81}_{-2.74}$	$7.22^{+2.09}_{-2.05}$	$7.58^{+2.05}_{-2.45}$	$6.85^{+2.87}_{-2.40}$	$7.13^{+1.14}_{-1.81}$
S/H×10^6	$2.02^{+0.78}_{-0.75}$	$2.00^{+0.46}_{-0.44}$	$2.06^{+0.86}_{-0.50}$	$1.92^{+0.65}_{-0.57}$	$1.72^{+0.61}_{-0.18}$
Ar/H×10^6	$1.64^{+0.64}_{-0.61}$	$1.66^{+0.42}_{-0.48}$	$1.71^{+0.55}_{-0.55}$	$1.77^{+0.48}_{-0.74}$	$1.63^{+0.59}_{-0.50}$
C/H×10^4	$5.28^{+3.09}_{-1.99}$	$4.25^{+2.24}_{-0.97}$	$7.7^{+1.33}_{-3.19}$	$3.10^{+1.66}_{-1.05}$	$4.72^{+1.92}_{-0.67}$
Si/H×10^6	$1.96^{+0.41}_{-0.48}$	$1.71^{+0.65}_{-0.23}$	$2.28^{+0.57}_{-0.76}$	$1.55^{+0.41}_{-0.07}$	$1.81^{+0.23}_{-0.16}$

Table 5. Comparison of observed spectrum of planetary nebula NGC6720 (Barker (1987)) with previous ones from corresponding OPhMs presented in Table 4. All line intensities are given relative to $I(H_\beta)=100$.

Parameters	Observation	*MJPS*	*AVR*	*MAX*	*MIN*	FDNT
3727 [O II]	537.00 ± 26.9	543.53	537.47	534.13	548.31	538.87
3869 [Ne III]	138.00 ± 20.7	139.35	141.61	136.40	140.04	137.76
4363 [O III]	11.40 ± 1.71	13.24	13.84	12.49	14.83	–
4471 He I	4.31 ± 0.43	4.01	4.00	3.81	3.93	4.09
4686 He II	30.30 ± 3.03	34.34	34.58	33.53	35.01	35.01
5007 [O III]	1161.0 ± 34.8	1148.3	1152.9	1157.6	1175.4	1154.3
5876 He I	11.10 ± 1.11	12.37	12.37	11.74	12.15	–
6678 He I	3.70 ± 0.37	3.16	3.15	3.01	3.10	–
6584 [NII]	383.0 ± 19.2	383.76	385.86	388.89	383.65	382.69
6716 [S II]	11.40 ± 3.06	14.49	14.70	13.53	15.09	–
6731 [S II]	20.40 ± 3.04	23.75	23.82	22.82	23.53	20.36
7135 [Ar III]	20.30 ± 3.58	23.82	24.41	24.11	26.46	23.91
1891 [Si III]	1.70 ± 0.25	1.70	1.64	1.67	1.71	1.68
1549 [C IV]	54.00 ± 8.10	53.99	53.70	53.74	58.16	52.91
$lg[L(H_\beta)]$	33.43	33.43	33.43	33.42	33.43	33.43
χ^2	–	0.863	0.930	1.099	1.147	0.274

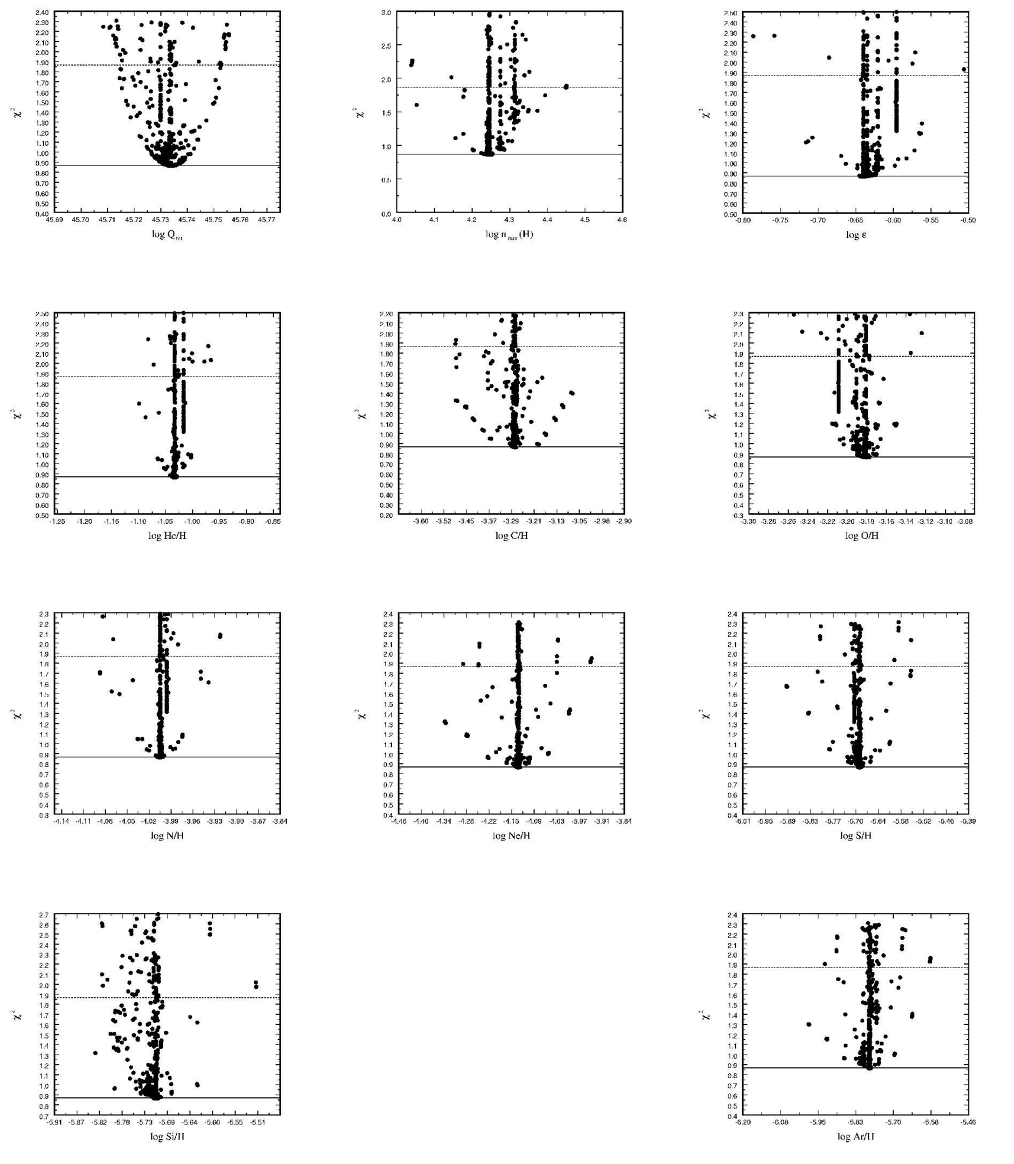


Fig. 3. The distributions of χ^2 function over free parameters of PN OPhMs. The levels of χ^2_{min} and $\chi^2_{min}+1$ (because of one freedom degree) are shown by horizontal lines. As it can see, we obtained one minimum of χ^2-function.

CONCLUSION

1. In the case of HII region modelling for some free parameters we obtained many minimums of χ^2-function, but for most elements abundances we obtained one χ^2-function minimum. Therefore, we concluded that OPhM is good method for the chemical composition determination in HII regions.
2. In the case of PN we obtained one minimum of χ^2-function for all free parameters.
3. In the future modelling of giant HII regions we will use rather many spectra obtained from their different parts. In this case every part of HII region will be modelled separately.

If You are interested by this work: You can take a full version of this Poster attached below. References are presented in full version of Poster.