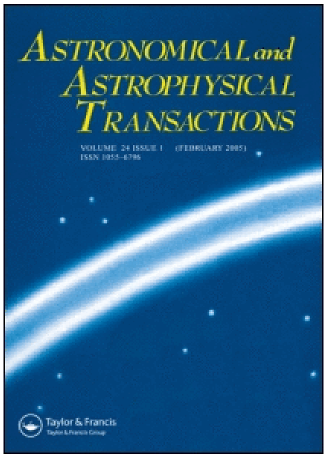

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Spectrophotometry of giant extragalactic regions of ionized hydrogen in dwarf galaxies of M81 galaxy group

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SPECTROPHOTOMETRY OF GIANT EXTRAGALACTIC REGIONS OF IONIZED HYDROGEN IN DWARF GALAXIES OF M81 GALAXY GROUP

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(13 February 1991)

The results of spectrophotometric study of 9 giant extragalactic HII regions in M81 group are presented. The physical conditions and chemical composition of gas in studied HII regions are determined. The observed differences between heavy element abundances determined from data in optical and far infrared + radio ranges are shown to be due to the radiation in radio and far infrared ranges, generated in different galaxy regions.

KEY WORDS Giant HII regions, dwarf galaxies.

1. INTRODUCTION

Some giant regions of ionized hydrogen, observed in irregular galaxies of M81 group are characterized by properties of blue compact dwarf galaxies (BCDGs) with intensive star formation processes. If anything, galaxies VII Zw 403 and NGC 2366 are classified as blue compact dwarf galaxies (Tully *et al.* (1981), Kennicutt *et al.* (1980), Andreasian *et al.* (1986)). The common properties of BCDGs are low luminosities ($M_B \simeq -13^m \div -17^m$), high ultraviolet excesses ($U-B \simeq -0^m.6$), which are caused by powerful bursts of star formation, high gas content ($10 \div 50\%$), low masses ($10^8 \div 10^9 M_\odot$), and low heavy element abundances ($Z/Z_\odot = 1/40 \div 1/2$) (Kunth (1987, 1988)). Recently, the most heavy element deficient blue compact dwarf galaxy SBS 0335–052 from the Second Byurakan Survey was observed by Izotov *et al.* (1989). The oxygen abundance in SBS 0335–052 is equal to only 1/77 of solar value.

The simplicity of BCDGs structure permits us to do the model calculations of their origin and evolution (Izotov (1989), Silk *et al.* (1987), and chemical evolution of matter (Dufour (1986), Kunth (1987), Lequeux *et al.* (1979)).

Nearly 5% of the blue compact dwarf galaxies probably lack of late population stars (Kunth *et al.* (1988), Loose and Thuan (1986)). This result is explained by BCDG's evolutionary youth.

The observations of BCDG's in the far infrared range show that the mass ratio of dust to gas in blue compact dwarf galaxies is 10–100 times lower than the heavy element abundance that is determined from the spectrophotometric observations in the optical range (Gondhalekar *et al.* (1986), Kunth and Sevre (1985)).

The radiocontinua of BCDG's are characterized by a small slope (Klein *et al.* (1984)) and are caused mainly by thermal radiation of ionized gas. Note, that BCDG's are visible as compact star-like objects without a distinct surrounding shell. A special interest is to investigate the characteristics of star-forming HII-regions embedded in the body of low surface brightness (LSB) irregular dwarf galaxies (see for example, the paper of Hunter and Hallagher (1985)). For large sample of LSB "magellanic" irregular dwarfs, the global mean characteristics are: $\langle M_B \rangle \sim -15^m$, $\langle A_{25} \rangle \sim 6$ kpc, $\langle B-V \rangle \sim +0.4$, $\langle U-B \rangle \sim -0.15$, $\langle M_H/M_T \rangle \sim 0.25$, so, these galaxies are redder than typical BCDG's. In comparison of BCDG's objects, LSB dwarf galaxies are practically undetected in IR (Karachentseva (1990)).

In this paper, we presented the results of spectrophotometric study of 9 giant extragalactic HII regions in 7 dwarf galaxies of M81 group. A comparison is made with data, which are determined by other authors in optical, far infrared and radio ranges.

2. OBSERVATIONS AND DATA REDUCTION

The spectrophotometric observations were conducted in the periods of 8–11 December, 1986, and 27–31 October, 1987, on the 6-meter telescope with use of the 1024-channel IPCS, of the Special Astrophysical Observatory of the USSR Academy of Sciences. The spectral resolutions for these two periods were 5 and 10 Å respectively. All reductions were carried out by the standard method, which is used in the observation processing on IPCS.

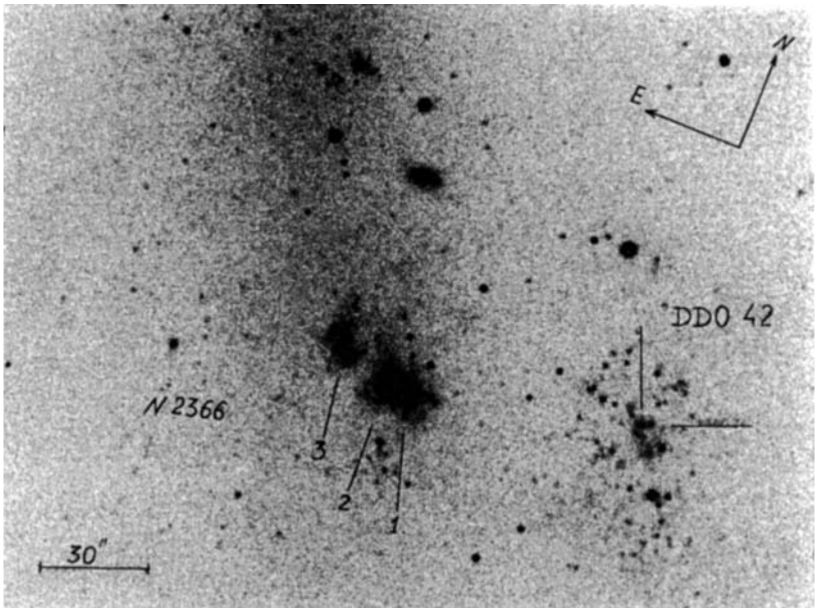
The images of the observed HII regions, obtained in prime focus of the 6-meter telescope, are shown on Figures 1–6.

The correction of emission line intensities for the extinction was made using normal reddening law (Whitford (1958)). The line intensities were corrected for the underlying stellar absorption according to McCall *et al.* (1985).

The corrected line intensities, as well as the extinction coefficients and equivalent widths of H_β line, are presented in Table 1.

3. PHYSICAL CONDITIONS AND CHEMICAL COMPOSITIONS IN HII REGIONS

In those HII regions where the line [OIII] $\lambda 4363$ Å was observed, the electron temperatures T_e were determined by using the line intensity ratio [OIII]



Figures 1–6 Images of the observed HII regions. 1) NGC 2366 and DDO 42, 2) VII Zw 403, 3) UGC 4483, 4) UGC 5423, 5) Holmberg II, 6) IC 2574. The reproductions are made from the plates obtained with the 6-meter telescope in B-system.

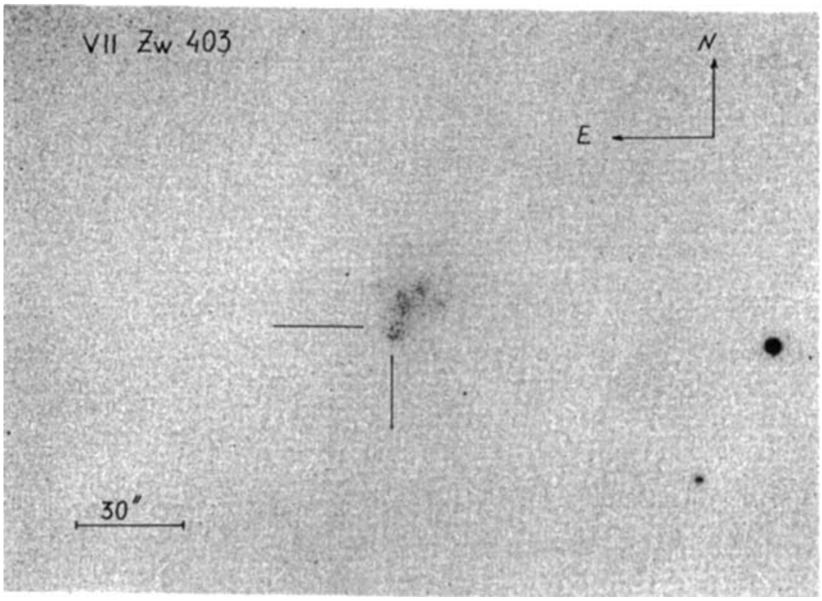
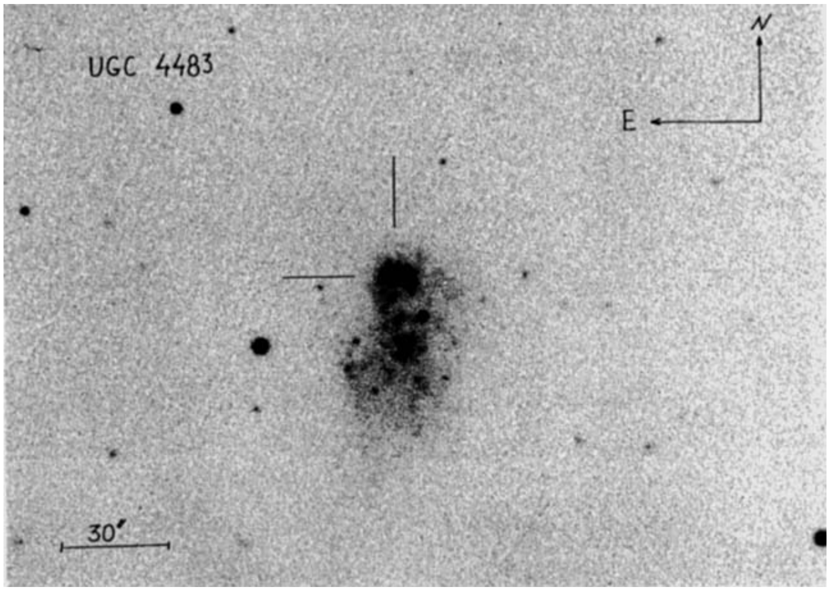


Figure 2 See legend (Fig. 1)



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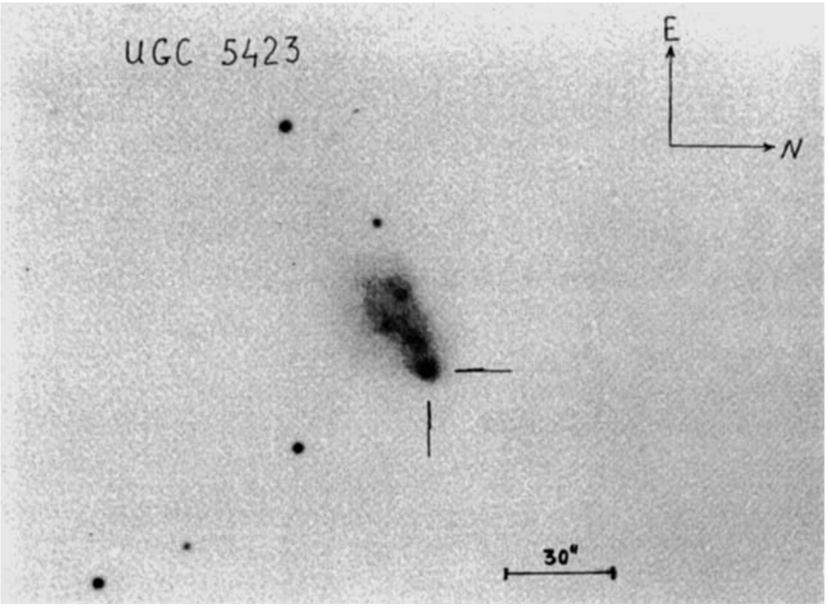

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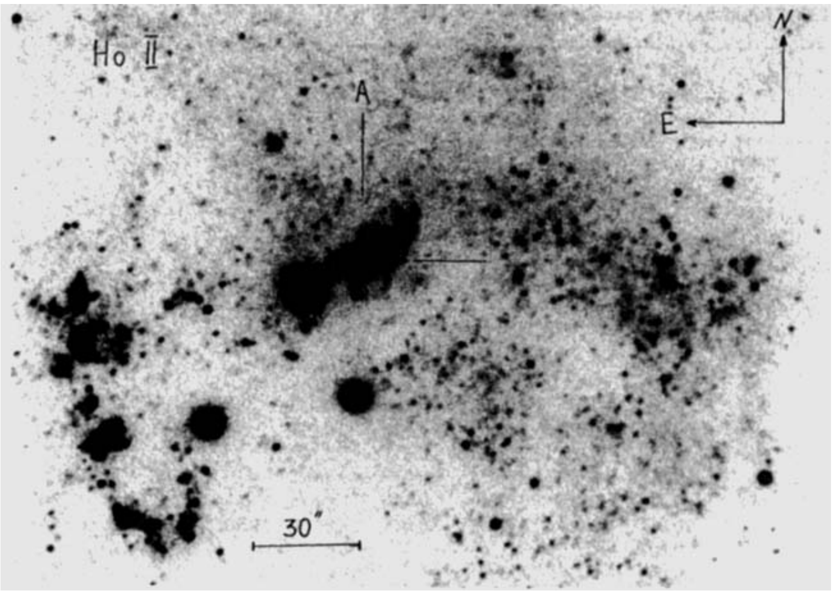

Figure 5 See legend (Fig. 1)

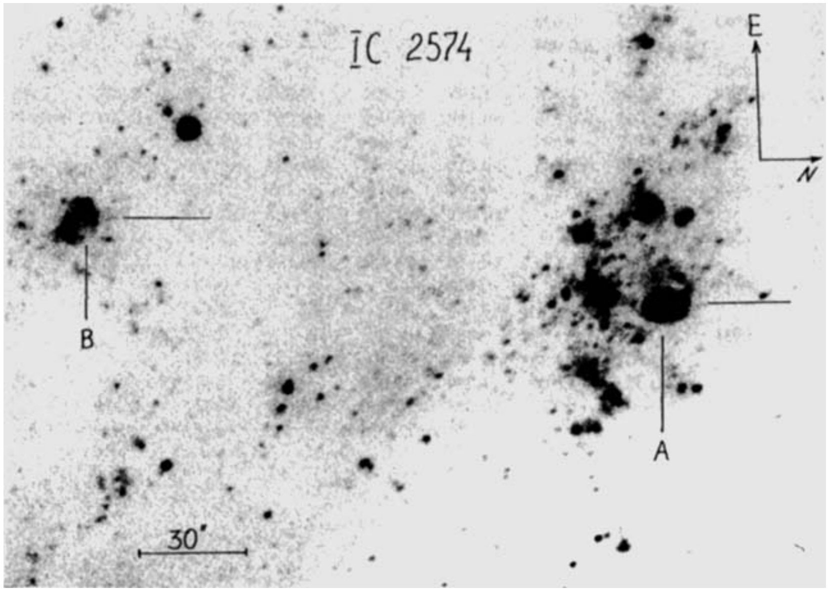

Figure 6 See legend (Fig. 1)

Table 1 The intensities of spectral lines

Lines	λ_0	*NGC 2366 reg. 1*	*NGC 2366 reg. 2*	*NGC 2366 reg. 3*	*VIIZw 403*	*UGC 4483*	*DDO 42*	*UGC 5423*	*Ho II reg. A*	*IC 2574 reg. A*
[OII]	3727	0.425	0.653	1.912	0.918	1.017	4.042	2.337	2.865	1.540
		±0.030	±0.202	±0.263	±0.112	±0.170	±1.028	±0.975	±0.707	±0.477
H12	3754	0.045	—	—	—	—	—	—	—	—
		±0.005	—	—	—	—	—	—	—	—
H11	3777	0.060	—	—	—	—	—	—	—	—
		±0.008	—	—	—	—	—	—	—	—
H10	3798	0.060	—	—	—	—	—	—	—	—
		±0.009	—	—	—	—	—	—	—	—
H9	3835	0.055	—	—	—	—	—	—	—	—
		±0.008	—	—	—	—	—	—	—	—
[NeIII]	3869	0.501	0.316	0.320	0.181	0.080	0.390	—	0.378	0.768
		±0.036	±0.082	±0.050	±0.039	±0.012	±0.108	—	±0.024	±0.131
HeI + H8	3889	0.130	0.097	0.184	0.253	0.207	—	—	0.226	—
		±0.018	±0.022	±0.036	±0.054	±0.028	—	—	±0.040	—
[NeIII] + H7	3968	0.274	0.228	0.146	0.136	0.119	0.144	0.137	0.248	—
		±0.014	±0.059	±0.033	±0.026	±0.014	±0.011	±0.019	±0.078	—
HeI	4026	0.027	—	—	—	—	—		—	—
		±0.003	—	—	—	—	—		—	—
H_δ	4102	0.275	0.228	0.266	0.196	0.230	0.203	—	0.336	—
		±0.011	±0.043	±0.028	±0.026	±0.019	±0.025	—	±0.067	—
H_γ	4340	0.428	0.494	0.469	0.468	0.487	0.426	0.468	0.373	0.578
		±0.036	±0.035	±0.029	±0.024	±0.037	±0.032	±0.028	±0.029	±0.127
[OIII]	4363	0.223	0.152	0.081	0.085	0.085	—	—	—	—
		±0.027	±0.018	±0.012	±0.007	±0.015	—	—	—	—
HeI	4472	0.054	0.047	—	—	—	—	—	—	—
		±0.001	±0.009	—	—	—	—	—	—	—
[ArIV] +HeI	4711	0.030	0.055	—	—	—	—	—	—	—
		±0.007	±0.016	—	—	—	—	—	—	—
[ArIV]	4740	0.027	0.029	—	—	—	—	—	—	—
		±0.002	±0.009	—	—	—	—	—	—	—
H_β	4861	1	1	1	1	1	1	1	1	1
[OIII]	4959	2.196	1.965	1.745	1.201	0.996	1.848	0.989	1.261	2.069
		±0.062	±0.216	±0.119	±0.015	±0.010	±0.216	±0.034	±0.049	±0.051
[OIII]	5007	8.172	4.692	4.783	5.268	3.414	5.481	3.647	3.122	5.914
		±0.065	±0.845	±0.615	±0.541	±0.585	±0.663	±0.399	±0.190	±0.314
HeI	5876	0.141	—	0.031	0.039	0.195	0.089	—	0.271	—
		±0.023	—	±0.011	±0.006	±0.085	±0.011	—	±0.068	—
H_α	6563	2.760	—	2.670	2.873	2.653	2.440	2.859	2.859	2.859
		±0.085	—	±0.560	±0.450	±0.595	±0.457	±0.490	±0.002	±0.001
[SII]	6717	0.049	—	0.016	—	—	0.067	—	—	—
		±0.008	—	±0.004	—	—	±0.012	—	—	—
[SII]	6731	0.031	—	0.008	—	—	0.042	—	—	—
		±0.006	—	±0.001	—	—	±0.007	—	—	—
C_{H_β}		0.332	1.012	1.274	1.604	0.676	1.867	0.846	0.878	1.255
		±0.056	±0.192	±0.293	±0.250	±0.097	±0.271	±0.130	±0.123	±0.103

(λ4959 + 5007 Å)/[OIII]λ4363 Å (Aller (1984)). In HII regions of DDO 42, UGC 5423, Ho II, IC 2574 the line [OIII]λ4363 Å was not detected. The electron temperatures T_e in these objects were determined from the empirical relation between T_e and total oxygen line intensities {[OII]λ3727 Å + [OIII](λ4959 + 5007 Å)}/H_β (Pagel *et al.* (1979)).

To derive the electron concentrations N_e, the line intensity ratios [SII]λ6717/6731 Å were drawn (Aller (1984)).

The ionic concentrations in HII regions were obtained from the relations cited in (Aller (1984)), and are shown in the Table 2 jointly with T_e and N_e.

Finally, the heavy element abundances are calculated using the correction factors (Zamorano and Rego (1985, 1986), Lequeux *et al.* (1982)):

$$\frac{\mathrm{O}}{\mathrm{H}}=\frac{\mathrm{O}^{+}+\mathrm{O}^{2+}}{\mathrm{H}^{+}}, \tag{1}$$

$$\frac{\mathrm{Ne}}{\mathrm{H}}=\frac{\mathrm{Ne}^{2+}}{\mathrm{H}^{+}}\frac{1}{1.2\,\mathrm{O}^{2+}/\mathrm{O}-0.2}, \tag{2}$$

$$\frac{\mathrm{S}}{\mathrm{H}}=\frac{\mathrm{S}^{+}}{\mathrm{H}^{+}}\frac{\mathrm{O}}{\mathrm{O}^{+}}, \tag{3}$$

$$\frac{\mathrm{Ar}}{\mathrm{H}}=\frac{\mathrm{Ar}^{2+}+\mathrm{Ar}^{3+}}{\mathrm{H}^{+}}\frac{\mathrm{He}}{\mathrm{He}^{+}}, \tag{4}$$

The heavy element abundances are presented in Table 2, along with the effective temperatures of ionizing radiation T_*, derived from the relation (Campbell (1988)):

$$\log T_* = -0.177\log\frac{\mathrm{O}}{\mathrm{H}} + 4.019. \tag{5}$$

One can see from the Table 2 that the oxygen abundances in studied HII regions are 3–10 times lower than that in Galaxy, and are typical for the blue compact dwarf galaxies. The upper limits of the temperatures of ionizing radiation are equal to $T_* = (4.5\text{–}5.9)\cdot 10^4$ K, and correspond to the temperatures of 03–05 type stars.

4. THE COMPARISON OF HII REGION PROPERTIES, DERIVED FROM OBSERVATIONS IN OPTICAL, FAR INFRARED, AND RADIO RANGES

Using the flux densities in HI line 21 cm for the observed galaxies presented in the paper (Huchtmeier and Richter (1986)), one can obtain the mass of neutral hydrogen $M_H/M_\odot$ (Davis and Seaquist (1983)):

$$\frac{M_H}{M_\odot} = 2.356\cdot 10^5 F_{HI} d^2, \tag{6}$$

where F_{HI} is the flux density in units Jy · km · s^{-1}, d is the distance to the galaxy in Mpc. For the galaxies of M81 group, we adopted the value $d = 3.6$ Mpc (Sandage and Tammann (1976)).

Table 2 The heavy element abundances in the HII regions

	NGC2366 *reg. 1*	*NGC2366* *reg. 2*	*NGC2366* *reg. 3*	*VII* *Zw 403*	*UGC4483*	*DDO 42*	*UGC5423*	*Ho II* *reg. A*	*IC2574*
T_e, K	18,407	19,027	14,053	14,430	17,389	11,643	10,000	10,400	11,342
n_e, cm^{-3}	100	100	100	100	100	100	100	100	100
O^+/H^+	2.10E−6	2.95E-6	2.05E-5	9.08E-6	5.84E-6	8.49E-5	8.98E-5	9.35E-5	3.57E-5
O^{2+}/H^+	5.23E-5	3.92E-4	6.29E-5	6.24E-5	3.01E-5	1.25E-4	1.26E-4	1.05E-4	1.46E-4
$\frac{Ne^{2+}}{H^+}$	7.14E-6	4.15E-6	9.45E-6	4.94E-6	1.31E-6	2.14E-5	—	3.15E-5	4.62E-5
$\frac{Ar^{3+}}{H^+}$	4.76E-8	—	2.27E-8	—	—	—	—	—	
$12+\log\frac{O}{H}$	7.74	8.60	7.92	7.85	7.56	8.32	8.33	8.30	8.26
$12+\log\frac{Ne}{H}$	6.87	6.62	7.13	6.76	6.52	7.62	—	7.86	7.78
$12+\log\frac{S}{H}$	6.09	—	4.96	—	—	5.59	—	—	—
$12+\log\frac{Ar}{H}$	5.43	—	—	—	—	—	—	—	—
T_*	59,300	—	55,100	56,700	—	46,800	46,600	—	—

Table 3 The flux densities of galaxies in radio and far infrared ranges

Objects	F_{HI}	S_{12}	S_{25}	S_{60}	S_{100}
UGC 4483	3.1	—	—	—	—
UGC 5423	2.8	<0.273	<0.248	0.538	<1.03
NGC 2366	297	<0.248	0.728	3.28	4.38
VII Zw 403	14.6	—	—	—	—
IC 2574	359.7	<0.302	<0.248	1.09	2.55
Ho II	—	<0.248	<0.248	1.14	2.73

Four galaxies, which were observed in the optical range, were detected by IRAS satellite. The flux densities for these galaxies in radio and far infrared ranges are presented in Table 3. Here S_{12}, S_{25}, S_{60} and S_{100} are flux densities in Jy at wavelengthes 12, 25, 60, 100 μm respectively.

If the FIR radiation of HII region is caused by "dirty ice" silicates with efficiency coefficient $Q_\lambda = 2.4 \cdot 10^4 \lambda^{-1}$ (Kunth and Sevre (1985)), where λ is wavelength in μm, then one can obtain the dust temperature (Izotov and Izotova (1988)):

$$T_d = \frac{41.7}{\log(S_{100}/S_{60}) + 0.89}. \tag{7}$$

The FIR luminosity of galaxy is equal to (Fitt *et al.* (1988)):

$$\frac{L_{\rm FIR}}{L_\odot} = 3.89 \cdot 10^5 (2.58 S_{60} + S_{100}) d^2 \tag{8}$$

and the mass of dust is:

$$\frac{M_d}{M_\odot} = 0.258 d^2 S_{60} \exp\left(\frac{240}{T_d}\right). \tag{9}$$

The integrated characteristics of the observed galaxies in optical, far infrared and radio ranges are shown in Table 4, where $Z_{\rm IR} = {\rm M}_d/{\rm M}_{\rm H}$ is the relative content of the heavy elements, contained in dust, $Z_{\rm opt}$ is the heavy element abundance determined from the oxygen line intensities. The oxygen mass fraction is supposed to be equal to 45% of the total amount of heavy elements (Lequeux *et al.* (1979)).

As it follows from the Table 4, the dust-to-gas ratio in studied galaxies is 10–100 times smaller than the heavy element abundance, which is determined

Table 4 The integrated characteristics of the galaxies

Object	B_T	$L_B/L_\odot$	$L_{FIR}/L_\odot$	$M_H/M_\odot$	$M_d/M_\odot$	T_d	Z_{opt}	Z_{IR}
UGC 4483	14.94	1.57E + 7	<1.2E + 7	7.71E + 6	—	—	—	—
UGC 5423	14.94	1.57E + 7	2.70E + 7	6.97E + 6	<1.23E + 3	>35.7	5.85E-3	<1.76E-4
NGC 2366	11.46	3.87E + 8	6.47E + 7	7.39E + 8	3.04E + 3	41.2	1.50E-3	4.11E-6
VIIZw 403	14.30	2.87E + 7	<1.2E + 7	3.63E + 7	—	—	1.94E-3	—
Ho II	—	—	1.18E + 7	≃1E + 7	4.51E + 3	33.0	1.80E-2	≃4.5E-4
IC 2574	11.12	5.28E + 8	2.22E + 7	8.95E + 8	4.12E + 3	33.2	7.04E-3	4.60E-6

from the spectrophotometric observations. This result is in accordance with data obtained by Kunth and Sevre (1985). In paper Kunth and Sevre (1985), the low content of dust in blue compact dwarf galaxies has been accounted for by the dust properties different from those in Galaxy. Gondhalekar *et al.* (1986) put forward two alternative explanations. The first one takes into account the intense ultraviolet radiation in the star-forming region, which inhibits the dust formation. The second one is connected with the fact, that the blue compact dwarf galaxies are young systems, in which not enough amount of dust is produced. The graphite dust grains are formed mainly in atmospheres of red giants of low and intermediate masses, the ice mantles are determined by abundances of CNO elements, which are low in studied galaxies. Only the silicate grains are formed in cooled shells of supernovae remnants and are connected with young star population.

Another possibility exists to account for the high gas-to-dust ratio in blue compact dwarf galaxies. The mass of neutral hydrogen, which is determined from the observations in radio range, corresponds to the galaxy region with size $\simeq 1$ kpc, while the star-forming region occupies the volume with radius $\simeq 10^2$ pc. If the dust grains in BCDG's are heated by a central cluster of massive stars, then their temperatures decrease with increasing of distance from the galaxy centre. The "warm" dust with temperatures $T_d \simeq 30$–40 K is the main contributor to the FIR radiation of blue compact dwarf galaxies. If one uses the relation between the dust temperature T_d, luminosity L of central energy source, and radius r of that galaxy region where the dust is heated to the temperature T_d (Graham (1983)):

$$r = 47 T_d^{-5/2} (L/L_{\odot})^{1/2}, \tag{10}$$

then for the region containing the "warm" dust grains we obtain $r \simeq 10^2$ pc. Hence, the high value of gas-to-dust ratio can be explained by the fact that the observations in far infrared and radio ranges are attributed to different parts of the galaxy. In addition to the foregoing, as it has been shown by Izotov *et al.* (1989), the far infrared point sources, which are located outside the HII region, may give the significant contribution to FIR radiation of the star-forming region. These point sources are probably the young stars of high and moderate luminosity surrounded by thick shells of gas and dust. In this case, the radiation in radio and far-infrared ranges is generated in different volumes too. As an example, we remember the results of the detailed surface UBV-photometry of UGC 5423 (Schmidt *et al.* (1985)). They obtained the break in the luminosity profile and in the colour distribution, and interpreted this fact as a phenomenon of starburst in the central body of a larger spheroidal component.

Both "blue" and "red" components are distinguished by their spatial extent as well as by their colours. The integral colours of UGC 5423 are $(U-B)_T = +0.1$ and $(B-V)_T = +0.25$.

5. CONCLUSION

In this paper the results of spectrophotometric study of giant HII regions in M81 group galaxies are presented, and the comparison of global characteristics of star-forming regions in optical, far infrared, and radio ranges are conducted. The main results of the paper are as follows:

(1) The chemical composition of 9 giant HII regions is determined. The heavy element abundances in studied galaxies are 3–10 times lower than solar value and are typical for blue compact dwarf galaxies abundances.

(2) The difference between the heavy element abundances, which are determined from the observations in optical and FIR ranges, is shown to be explained not only by the special properties of dust or special conditions of dust formation in BCDG's, but rather by the fact, that radiation in far infrared and radio ranges is generated in different parts of galaxy.

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