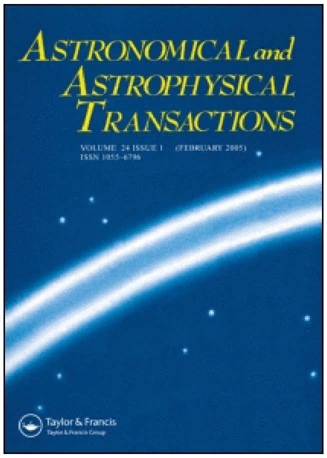

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Spectrophotometric studies of 40 star-forming regions

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SPECTROPHOTOMETRIC STUDIES OF 40 STAR-FORMING REGIONS

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We present and discuss observations of the spectra of diffuse nebulae performed in 1969–1989 at the 70 cm telescope of the Fesenkov Astrophysical Institute. Observations of the spectra of nebulae and stars at the 6 m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences are also discussed. Ten of the objects discussed are compact H II regions, the remaining objects are at later evolutionary stages and differ from classical H II regions in their smaller linear sizes and higher electron densities. All the nebulae are related to molecular clouds.

We discuss the relative intensities of emission lines, electron densities N_e[S II], emission measures in the Hα line and in the radio range, extinction values A_v for the nebulae and A_v^* to their exciting stars, and also the spectral class of these stars and the distances to the objects.

In all the objects, components with densities exceeding 10^3 cm^{-3} have been observed. Some of them are secondary star-forming regions.

By comparing optical and radio data, we show that the value of N_e[S II] does not always provide a measure of the real electron density. In some nebulae, there are regions with $N_e > 10^5$ cm^{-3} which do not emit in forbidden lines. There are also unionized regions whose emission spectra are due to reflection by dust of emission from bright emission-line regions. The largest values of N_e and A_v are observed at the interfaces between ionized gas and various molecular structures.

In "dusty" nebulae containing dense molecular gas, emission lines of the hydrogen Balmer series and sometimes also He I lines are suppressed by their blending with absorption lines of the stellar spectra reflected by dust particles. In particular, this results in errors in the estimations of the ratio of hydrogen to forbidden line intensities, especially in nebulae associated with early B stars.

By comparing A_v and A_v^*, we show that all of the compact H II regions have the exciting stars which posses circumstellar envelopes (disks) absorbing the stellar light, sometimes by 10 mag. One may conjecture that the amount of the absorption depends on the spatial orientation of the rotation axis of the disk. This also affects the apparent structure of the nebula whose appearance is largely determined by dense molecular filaments, cloudlets and their shadows.

From the analysis of the spectra of nebulae and stars, we derive empirical criteria for an approximate estimation of the spectral class of the exciting star from the observed nebular spectrum. These criteria can be made more accurate provided that a theoretical model for the nebular emission is available, which allows for a combined effect of stellar wind and stellar Lc emission on emission line intensities.

The comparison of the stellar spectra obtained at different times shows that all of the stars are spectrum variables and reliable identification of their spectral classes should be based on an observational series obtained at high spectral resolution.

KEY WORDS Diffuse nebulae, compact H II regions, physical parameters, exciting stars

1 INTRODUCTION

The most recent review of the observations of diffuse nebulae was published by Johnson (1968), who derived basic physical parameters of the nebulae from optical observations. During the last 25 years, an enormous amount of information has been collected on the nature of the nebulae: regions of recent and ongoing star formation have been detected (compact H II regions, giant molecular clouds, and sources of OH and H_2O maser emission, etc.), and point-like and extended infrared (IR) sources have been identified with protostars and young stars, which often exhibit bipolar molecular outflows and jets. Optical observations play a rather modest role in these studies. Nevertheless, optical observations are the main source of basic information independent of the distance and light extinction estimates about the ionization structure of nebulae, the spectral classes of the exciting stars and electron densities.

Studies of the spectra of diffuse nebulae at the Fesenkov Astrophysical Institute started in December 1968. The observational program covered those nebulae whose angular sizes are, as a rule, less than $5'$ (as restricted by the size of the spectrograph slit) in order to assess the brightness of the central and outer regions directly from a spectrogram. There was practically no information on the nature of these objects, except the Palomar plates (POSS). In the course of collecting and interpreting the observational material, in about 1970, it has become clear that some nebulae (NGC 6618, 7635, 7538 and 2024) contain small regions ($10''$–$40''$) with electron density N_e[S II] = 10^3–10^4 cm^{-3}. These regions sometimes do not coincide with optically bright features of the nebulae. This confirmed the conclusions of Schraml and Mezger (1969) on the existence of compact H II region at different evolutionary stages. After the nebulae S106 and IC1470 had been observed, whose densities are about 10^4cm^{-3} and extinctions are 5–10^m, the conclusion was made that these objects are optical analogues of compact H II regions detected in 1967 in the radio range (Glushkov and Karyagina, 1971). Radio observations of S106=M1-19 performed soon afterwards by Parijskij led to the detection of the radio flux of about 24 ± 4 Jy from an area of less than 1 sq. min at $\lambda = 4$ cm (Parijskij and Glushkov, 1973), and this has proved that compact H II regions can be observed in the optical range as well.

Our program of the search for compact H II regions commenced in 1972. One hundered and sixty diffuse nebulae had been observed by 1989 and most of the star-forming regions bright in optical range had been detected before that time.

In this paper we briefly outline the results of our observations together with observations of nebulae and their exciting stars at the 6 m telescope.

2 OBSERVATIONS AND DATA REDUCTION. DETERMINATION OF PHYSICAL PARAMETERS

All the observations have been performed with a diffraction spectrograph equipped with the image tube intensifier (ITI) UM92 installed at the Cassegrain focus of

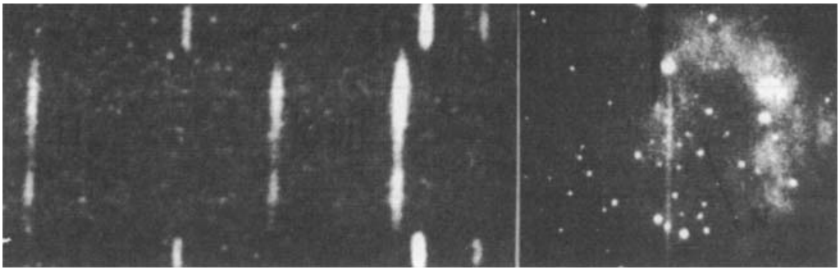

Figure 1 Photograph and spectrum (Hβ and [O III] lines) of M17 (region of the dark bay) with the position of the spectrograph slit shown as the light strip. Spectral line height corresponds to the slit length on the nebula photograph. North is marked by arrow.

the 70 cm telescope AZT8. The design of the spectrograph was developed by E. K. Denisyük. Because of a rotation device, the spectrograph slit can be adjusted to any required position angle. The slit length was 360″ and the width was variable between $3\overset{''}{.}6$ and $7\overset{''}{.}5$ (both in projection onto the sky). The ends of the slit were used for the comparison spectrum consisting of Ne, Ar and He lines. The total spectral range was 3700–8100 Å. Most of the spectrograms were obtained in the ranges $\lambda\lambda$4100–5500 Å and 5800–7400 Å. A set of diffraction gratings allowed spectra with dispersions ranging from 11 to 300 Å/mm to be obtained, at the spectral resolution from 1 to 20 Å. The basic dispersion values used were 40, 70, 100 and 160 Å/mm.

An important advantage of the spectrograph is a device which projects onto the input photocathode of the ITI an area on the sky of the size about $10' \times 10'$ with the slit being shifted away. It serves for pointing the telescope to a faint object (a problem which is very difficult with small telescopes). In this manner we could use stars down to 17 mag for field identification and pointing. The same system allows us to take photographs of sky areas at exposures 10^s–20^s; stars of 21^m can be then detected if the image quality is good. If desired, a sky-illuminated image of the slit can be projected onto such a photographic plate; this provides the possibility of determining exactly the area of a nebula at which the spectrograph slit is aimed. The whole procedure of producing a photographic plate with the slit projection imposed takes about 1 min after the spectrogram has been obtained (see Figure 1).

Calibration curves were obtained using a photometric wedge installed at a special support accessible when the spectrograph slit is shifted away. Its image illuminated by the sky light was also projected onto the photocathode of the ITI and its photographs were taken at several exposures.

All of the spectral photographs were obtained on the A600 film produced by GosNIITekhFotoProekt (Kazan, USSR). In total, more than 2000 spectrograms of about 160 diffuse nebulae were obtained with this equipment.

The spectrograms were reduced using an MF4 microdensitometer equipped with various devices to obtain records of spectra in intensities. When observing separate details of a nebula, the microdensitometer slit was adjusted to isolate strips of 10″–30″ width aligned with the spectral line. To obtain physical parameters of the neb-

Table 1. Relative line intensities of (6–1) band of OH molecule

$\lambda(A)$	6499	6506	6524	6534	6545	6554	6563	6570	6578	6598	6605
Design.	Q_1	Q	p_1	P_1	p_2	P_2	$H\alpha$	p_3	P_3	p_4	P_4
I(λ)	1.30	0.60	0.40	1.04	0.55	1.30	0.40	0.40	1.00	0.25	0.55

ulae, we used intensity ratios of emission lines, including $I(\lambda6717)/I(\lambda6731)$[S II], $I(\mathrm{H}\alpha)/I(\lambda6584)$[N II], $I(\lambda5007)$[O III] $/I(\mathrm{H}\beta)$. The accuracy of the estimation of these ratios is 5–10% depending on the number of spectrograms used and the brightness of the emission lines.

The noise level and sensitivity of the ITI were sufficiently stable during an observation night. The accelerating voltage and currents in the magnetic focussing coils were controlled within an accuracy of 0.5%. This admitted the absolute intensities of emission lines, in particular the Hα line, to be obtained in units erg cm^{-2} s^{-1} Sr^{-1} during nights with stable weather conditions and good transparency. For this purpose, two secondary standards were obtained, namely certain fixed sections in the nebulae NGC 2068 (for winter-time observations) and Simeiz 57 (for summer-time observations) (Glushkov and Karyagina, 1971), and the central part of NGC 1976 was used as a primary standard. The Hα brightness of NGC 1976 exceeds that of most of the nebulae by a factor of about 1000. The accuracy of the $I(\mathrm{H}\alpha)$ determinations, with allowance for systematic errors in the brightness of the standard, does not exceed 20%.

It is natural to use hydroxyl line intensities for approximate estimations of $I(\mathrm{H}\alpha)$, especially for objects with low surface brightness. A (6–1) OH line is observed in the Hα and [N II] region. The OH line wavelengths and their relative intensities are given in Table 1. The line intensities are normalized using that of the P_3 line, which varies between 1.0×10^{-6} and 4.0×10^{-6} erg cm^{-2} s^{-1} Sr^{-1} (Karyagina and Mozhaeva, 1969). We adopt its average value as about 2.0×10^{-6} erg cm^{-2} s^{-1} Sr^{-1}. A similar variation (by about a factor of 2 around the average value) characterizes the geocoronal Hα intensity, which is approximately equal to $I(p_3\mathrm{OH}\lambda6570)$.

A precise determination of $I(\mathrm{H}\alpha)$ in nebulae requires the sky spectra in their immediate vicinities to be obtained. This allows us to take into account the weak emission background of the Milky Way and the Hα emission of the geocorona.

Theory of gas emission in nebulae is one of the most advanced fields of astrophysics. We obtained a number of formulae and tables devised to facilitate interpretation of our spectrometric observations (Glushkov, 1973; Glushkov *et al.*, 1979b).

The measured values of absolute intensity in Hα can be used to determine the electron density and emission measure EM(Hα). When the electron temperature in the nebulae is T_e = 7500 K, we have $EM(\mathrm{H}\alpha) = 0.96 I(\mathrm{H}\alpha) 10^7$ pc cm^{-6}; for $T_e = 10^4$ K the first numeric factor becomes equal to 1.20.

Table 2. Calculated electron densities Ne[S II] as function of I (λ6717)/I (λ6731)

$\frac{I(\lambda 6717)}{I(\lambda 6731)}$	$Ne[S\,II]\ cm^{-3}$		$\frac{I(\lambda 6717)}{I(\lambda 6731)}$	$Ne[S\,II]\ cm^{-3}$	
	$Te = 7500\,K$	$Te = 10\,000\,K$		$Te = 7500\,K$	$Te = 10\,000\,K$
0.40	35500	36190	1.00	650	730
0.50	6740	7490	1.10	440	510
0.60	3370	3780	1.20	280	305
0.70	2070	2330	1.30	155	160
0.80	1380	1545	1.40	54	46
0.90	950	1060	1.45	10	~3

By comparing $EM(\mathrm{H}\alpha)$ and the emission measure in the radio range, EM(R), one can determine the light extinction for a given nebula, $A_v = 3.2\log[\mathrm{EM(R)}/\mathrm{EM(H}\alpha)]$.

Electron densities in the objects were obtained from intensity ratios of the λ6717 and λ6731 lines using data of Nosov (1980) obtained with improved atomic data for the S II ion. In Table 2 we give the electron density values together with the $I(\lambda 6717)/I(\lambda 6731)$ values. All the values of N_e[S II] given in our papers published before 1978 should be divided by about 4.5 to obtain the correct values.

In the nebulae which contain stars earlier than O7, where ionized helium regions are present, sulphur is in the state S^{++}. Electron density in these regions can be obtained from the intensity ratio of the lines λ5538 and λ5518 of [Cl III]. Ionization potentials of the ions S II, Cl II and He I are close to each other. However, lines of [Cl III] are weaker than those of Hα by a factor of 300–400. Therefore the former are observable only in bright nebulae.

We compared the quantities N_e[S II] and N_e[Cl III] for the central region in NGC 1976 (Glushkov *et al.*, 1983a). These agree well with each other in average. This is an important result indicating that N_e[S II] provides a good measure of densities in highly excited regions of diffuse nebulae, for which almost all of the optical data on the densities are based on intensity measurements for the red doublet [S II].

We also considered the possibility of determining the electron temperature in nebulae using the ratio $I(\mathrm{H}\alpha)/I(\lambda 6584)$[N II], and T_e for 12 nebulae have been determined (Glushkov, 1973; Glushkov *et al.*, 1979b). This method requires that chemical composition and degree of ionization of nitrogen are known, but this is practically the only method available to determine T_e in the optical range for nebulae with stars later than O7.

3 SPECTRA OF NEBULAE AND EXCITING STARS

The main goal of the section is to show how spectra of nebulae vary with the spectral class of the exciting star. Another question also arises as to whether the spectral class of the exciting star can be predicted on the basis of the observed nebular spectrum.

Similar problems were first formulated and, as far as possible, solved by Hubble (1922). In his two extensive papers he classified nebulae into reflection, diffuse and planetary ones on the basis of the whole wealth of data on spectra of nebulae and stars available at that time.

Spectra of about 250 diffuse nebulae are known now, with about 1000 of them visible on the northern sky. The stellar population of nebulae is much worse known. Even stellar magnitudes of the brightest stars are not available for the vast majority of the nebulae. Information on the spectra of the exciting stars is very contradictory; different catalogues and papers give different spectral classes for them. This is a result of the following: (i) a bright background produced by the nebulae, which hampers photometric and spectral measurements for stars of $12–20^m$; (ii) the spectral variability of the stars; (iii) the fact that many stars are spectroscopic binaries, so that high spectral resolution is required for their study.

The term "irregular Orion-type variables" seems to apply to the stellar populations of all diffuse nebulae irrespectively of stellar mass. The question of spectroscopic variability of the stars is very important and deserved a separate study. Here we discuss only general aspects of this problem required for our discussion that follows. Below we use data from an extensive library of variable stars of Sternberg Astronomical Institute in order to see what is the variation in the spectra of hot stars of Trapezium (θ^1 Ori). Their spectral classes are given together with references. The spectral class estimates seem to be reliable insofar as they belong to well-known experts in spectral classification of early-class stars.

θ' OriA=HD37020: B0.5V (Abt, 1979), O8V–B0.5n (Cardelli and Clayton, 1988), B3III–IV (Bossi *et al.*, 1988).

θ' OriB=HD37021: B1–3V+A7IV (Hoffleit, 1982), B0V (van Altena *et al.*, 1988), B3V (Abt *et al.*, 1991).

θ' OriC=HD37022: O6 (Walker, 1969), O6p (Cardelli *et al.*, 1989), O7(Conti and Alschuler, 1971), O7V–O7Vp (Howarth and Prinja, 1989), O6–O4p (Walborn, 1981).

θ' OriD=HD37023: B1 (Walker, 1969), B0.2 (Kopylov, 1958), O9.5V (Slettebak, 1963), B0.5Vp (Johnson *et al.*, 1966).

We cite examples of spectral variations of both isolated stars and spectroscopic binaries. In January 1979, Walborn (1981) detected variations in the spectral class of θ' OriC from O6 to O4 over a period of 7 days.

It is quite plausible that spectral classes of stars in all other nebulae can vary in a similar manner. Goy's (1980) catalogue and our data given in Table 4 provide evidence for this. Therefore, confident results for each star necessitate monitoring of the spectral variability of the exciting stars.

It is unclear how the above spectral variations affect the nebular spectra: there are no relevant observational data. We may mention only two cases of related data. In 1894, Campbell (1895) performed visual observations of the Trifid Nebula (M20) and noted that the line $\lambda 5007$ is slightly brighter than $H\beta$ at the center of the nebula, whereas $H\beta$ is significantly brighter than $\lambda 5007$ in the outer regions. Our observations of 1988 showed that $\lambda 5007/H\beta = 1.2–1.0$ at the center nebula,

Table 3. [O III] line in the Cygnus constellation

$\alpha(1950)$	$\delta(1950)$	$H\beta/\lambda5007$
$20^h\,19^m\!.0$	$47°\,32'$	*only* $H\beta$
20 14.6	43 20	~3.0–5.0
20 16.2	41 40	~2.0–3.0
20 12.0	39 45	~0.7–2.0
20 18.5	37 00	~0.5–2.0
20 11.0	35 50	~1.0–1.5

while this ratio is 0.2–0.4 in the outer regions; thus, this ration remains about the same for hundred years. However, in 1922 Hubble found for NGC 2024 that Hβ is about 3 times brighter than λ5007. According to our 1993 determination, Hβ is brighter than λ5007 by a factor of 10. We take into account that spectra of the stars can vary, on average, by one spectral subclass in both directions with respect to a certain median value.

The high sensitivity of our equipment allowed us to detect emission lines in the nebular spectra that are weaker than the majority of the OH lines of the night sky, i.e. those with emission measure of order 10–20 pc cm^{-6}. This is true, for example, for the [S II] lines in the nebulae S235C, NS14, S226 and MonR2. It might seem that in this situation one can easily clarify at which spectral class stars acquire a noticeable Stromgren sphere. However, this is hampered by the following:

1. In the whole Milky Way band and in regions like the Orion complex, a weak emission line background is present and the lines Hα, [N II] and sometimes [S II] are observed; this happens even at those places where red POSS plates ($\lambda\lambda$6300–6700 Å) do not reveal any traces of a nebula because intensities in the lines Hα, [N II] are smaller than the total OH line intensity.

   When observing several objects in Cygnus, we noticed that even the lines [O III] are present in a wide part of the Milky Way band, seen against a weak emission background. In Table 3 the coordinates of these regions are given together with the values of Hβ/λ5007. The apparent reason for the [O III] emission are O and WR stars (numerous in this part of the sky) that are not related to any nebula, or dim supernova remmants.

2. In some cases, outer layers of the nebulae may be ionized by neighboring hot OB stars. This is the case in Orion, in a group of nebulae to the west of NGC 6523, in NGC 6589–6590 and in some other cases.

3. Emissions in the nebula may be due to the light of a bright stellar envelope reflected by dust. This is the very nature of emissions in most nebulae connected with Ae–Be Herbig stars and T Tau stars, although in some cases emission arises owing to shocks associated with stellar winds. In NGC 7023 (B3III–IVe), the Hα emission is detectable up to a 4$'$ distance from the star, but a rapid decrease of the Hα intensity with distance to the star implies that

what is observed in this case is the stellar Hα light reflected by dust in the nebula. Some of these questions are discussed in more detail by Glushkov (1973) and Glushkov *et al.* (1979b, 1972).

An H II region more or less confidently detected by us is that in the nebula Ced66 excited by a B2.5V star.

All of the nebulae associated with B1–B2 stars have their own H II regions. In the nebulae that have a strong continuous spectrum, i.e. contain a large amount of dust, the size of the Stromgren sphere is smaller than the observed nebula size by a factor of 3–6. Impressive examples are provided by NGC 2068 and 2023 (see Section 4). The H$\alpha/\lambda 6584$ ratio always exceeds 3 in such nebulae. All nebulae containing B1 and later stars are bright in blue light (O POSS plates). All nebulae with B0.5 and hotter stars are brighter in red light (E POSS plates).

Transition from B1 to B0 stars is accompanied by a very variation in the nature of the nebular emission from an almost purely reflection spectrum to an almost purely emission one. For example, ionized hydrogen contributes only 1% to the continuum in NGC 2068 (B1), whereas the opposite situation is observed in S232 and S254 (B0).

Nebulae excited by B0 and O9.5 stars are notable for their large sizes (no less than 4 pc) and relatively uniform, low surface brightness. Various dark regions are hardly pronounced. Almost all such nebulae reside not far from compact, bright nebulae and apparently have a common origin. For instance, each nebula containing a B0 or O9.5 star (IC434, IC1284, IC4685, S232, S254 and S153) belongs to a group of nebulae containing a B2, B5, B1, B0.5, O9 or O9V star, respectively. These are evidently the oldest objects in each group. A large linear size and low surface brightness distinguish these objects from bright compact nebulae excited by B0.5 stars. The [O III] lines have been observed in neither of these nebulae; anyway, we have H$\beta/\lambda 5007 \simeq$ 10–20 and H$\alpha/\lambda 6548 \simeq$ 2.00–3.0. He I lines have not been observed at all.

A strong difference between emissions in the spectra of the nebulae and strong variation in effective stellar temperature $T_{\rm eff}$ indicate that the division of the interval B1–B0 into two subintervals is too crude. A new spectral classification distinguishes spectral subclasses like B0.7, B0.5 and B0.2. This classification still has not been applied to stars in nebulae. Meanwhile, inspection of spectral classes in Table 4 shows that some observers estimate them as B0 or O9.5 for the exciting stars in bright compact nebulae S148, S235, S237, S257 and S297, even though other estimates were also proposed. Allowing for the variations in the spectral class of the stars, we believe that in some nebulae the stars are closer to B0.5 for most of the time, while in others they are closer to O9. This is indicated also by intensity variations in the [O III] lines or their absence in the spectra.

The lines [O III] and He I are observed in all of the nebulae containing O9 and earlier stars; however, as follows from Table 4, it is difficult to distinguish nebulae with O9 stars from those with O8 and O7 stars because of uncertain spectral classes of the stars. It is known that the ratio $I(\lambda 5007)/I(\mathrm{H}\beta)$ must grow with $T_{\rm eff}$. This question was discussed in detail by Kaler (1978) and others; we note discussions

Table 4. **Relative emission line intensities and physical parameters of nebulae**

Nebula	$\frac{I(H\alpha)}{I(\lambda 6584)}$	$\frac{I(\lambda 5007)}{I(H\beta)}$	Sp^*	r kpc	A_v m	A_v^* m
			Compact H II regions			
N					10.4	
S106	1.7–4.5	1.0–1.2	O8–O9	0.6–2.0		21
S					9.2	
S235AB	1.8–4.0	Hβ	B0.5–B0	1.6	9.6	9
					10.6	
MonR2	2.3	?	B0.5	∼0.6	7.1	–
					14.7	
S146	3.8–5.8	∼3.0	O7–O6	4.7	9.9	16
					12.1	
NS11	7.0	1.2–1.5	O7	1.4	6.8	17
NS14	4.3–5.3	Hβ	B0.5	1.4–2.1	8.8	>8
S87	1.9	?	B0.5	1.3	9.7	–
S159A	2.0	?	B0.5	3.5	11.0	–
S270	5.0	Hβ	B0.5	2.1	6.6	13.5
Ap2–1	2.1	0.3–0.5	O9	∼3.0	5.9	–
			Dense H II regions			
S61	1.8–2.2	Hβ	B0.5–B1V	2.5	–	–
S83	9.0–15.0	4.5–5.0	O5–O6	>7.0	7.3	–
S93	1.7–2.6	1.1	O8–O9.5V	2.6	6.4	–
S128	5.7–10.4	4.2	O6–O7V	∼7.0	8.1	6.1
S138	3.0	Hβ	B0.5–B0	5.3	6.4	–
					11.4	
S148	1.8–2.3	0.3	O8V–O9V–	4.3–5.4	3.5	4.2
			B0V–O9.5V		5.0	
S152	1.9–4.0	0.7–1.5	O8–O9V	3.6–4.0	3.4	4.2
					4.5	
S156	2.2–4.4	1.0–2.1	O6.5V–O7V	5.3	2.6	4.0
					6.2	
S158A	3.0–9.2	>3.0	O7V–O6	3.5	7.1	5.6
			O8V+B2II			
S186	2.2–2.9	0.3	O9	3.5	6.4	–
S226	9.9–13.3	3.8	O6–O5	5.3	6.7	9.6
S228	1.9–4.1	1.2	O8Ve–B0V	2.4	4.8	4.4
			O8V+B2II			
S235	3.5	Hβ	O9.5V–B0.5	1.6	3.0	4.0
S235C	3.1	?	B0.5	1.6	6.5	–
S237	2.2–3.0	Hβ	B0.5V–B0V	1.9–3.5	4.4	2.4
S255	2.4–3.7	0.4–0.05	O9–B0V–B0III	2.4	4.7	4.0
					4.6	
S257	2.1–3.4	Hβ	B0V–B0.5V	2.4	3.4	3.0
					5.8	
S269	2.3–5.0	0.2–0.8	O9–B0.5V	3.8	8.1	4.5
S283	2.6–2.9	?	B0.5	–	–	–
S288	4.0–5.4	0.3–2.5	O7–B0V–B0III	∼5.0	4.5	3.1
S297	3.3	Hβ	B0V–B1–B2V	0.5–0.8	3.6	0.9
					6.4	
S307	2.2–4.2	0.5	O9V–B0V	2.2	5.0	–

Table 4. (Continued)

Nebula		$\frac{I(H\alpha)}{I(\lambda 6584)}$	$\frac{I(\lambda 5007)}{I(H\beta)}$	Sp^*	r kpc	A_v m	A_v^* m
NS7		3.0–4.3	?	B0.5	2.0	3.7	–
	A(1)	5.3				4.6	
NGC7635	A(2)		0.9–1.7	O6.5IIIf	2.4	4.0	2.2
	C_3	4.8				2.6	
The star-forming regions with IR stellar clusters							
NGC2024		1.7–4.2	0.08	B0.5Vp	0.47	8.7	9.3
NGC2023		4.6	$H\beta$	B1.5V	0.47	~4.0	1.5
NGC2068		4.4	$H\beta$	B1V–B2II–III	0.48	2.8	5.6
NGC1579		$H\alpha$	$H\beta$	B1IIe	0.9	2.1	–
						9.6	
S252A		4.65	2.0	O9	2.0	–	–
NGC6618		2.0–13.0	2.0–5.1	O4–O5	2.2	2–15	–

Table 4. (Continued)

Nebula		$EM(H\alpha)$ pc cm^{-6}	$EM(R)$ pc cm^{-6}	$Ne[S\,II]$ cm^{-3}	$Ne[S\,II]max$ cm^{-3}
Compact H II regions					
	N	1060	1.9×10^6	2570	
S106					5.7×10^4
	S	1700	1.3×10^6	3070	
S235AB		500	5×10^5	1280	1.4×10^4
		500	10^6		
MonR2		180	3.0×10^4	370	650
		220	9.0×10^6		
S146		470	5.8×10^5	820	3.5×10^4
		470	2.9×10^6		
NS11		1900	2.1×10^5	880	1100
NS14		150	5.5×10^4	440	1900
S87		170	1.8×10^5	–	–
S159A		680	1.8×10^6	820	–
S270		360	3.8×10^4	650	2100
Ap2-1		1210	8.4×10^4	2100	–
Dense H II regions					
S61		–	–	200	1380
S83		1350	2.5×10^5	<100	–
S93		1700	1.7×10^5	760	2600
S128		2000	7.0×10^5	600	2000
S138		670	6.9×10^4	500	1600
		670	2.4×10^6		
S148		2400	3.1×10^4	600	2100
		2400	9.1×10^4		
S152		6600	7.5×10^4	560	2400
		6600	1.7×10^5		

Table 4. (Continued)

Nebula	*EM(Hα)* pc cm^{-6}	*EM(R)* pc cm^{-6}	*Ne[SII]* cm^{-3}	*Ne[SII]max* cm^{-3}
S156	27000	1.8×10^5	3000	4900
	27000	2.4×10^6		
S158A	6100	10^6	370	4200
S186	1040	1.1×10^5	440	4600
S226	480	5.5×10^4	460	650
S228	1150	3.3×10^4	300	1600
S235	920	0.8×10^4	155	–
S235C	95	0.9×10^4	790	–
S237	1300	3.1×10^4	280	2100
S255	1500	4.3×10^4	200	650
	2400	6.5×10^4		
S257	1500	1.7×10^4	350	700
	2700	1.8×10^5		
S269	490	1.7×10^5	400	1200
S283	490	?	210	1380
S288	6000	3.7×10^5	390	880
S297	910	1.2×10^4	210	900
	1000	10^5		
S307	2900	1.1×10^5	820	6200
NS7	860	1.1×10^4	400	1100
A(1)	$\sim 3 \times 10^4$	8.2×10^5	6200	–
NGC7635 A(2)	$\sim 10^4$	1.3×10^5	3600	–
C_3	4700	0.3×10^5	1200	–
The star-forming regions with IR stellar clusters				
NGC2024	700	3.6×10^5	650	2000
NGC2023	230	?	100	–
NGC2068	130	900	150	460
NGC1579	670	3000	–	–
	670	7.3×10^5		
S252A	–	4.3×10^4	360	–
NGC6618	–	–	–	1.3×10^4

in Glushkov *et al.* (1972). Chopinet *et al.* (1976) and Hunter (1992). Indeed, we found the maximum values of $\lambda 5007/\mathrm{H}\beta$ in planetary nebulae that were earlier believed to be diffuse: S71, S89, NS15 and NS16 (Glushkov, 1972; Glushkov *et al.*, 1975b; Glushkov and Kondrat'eva, 1986; Balbekov *et al.*, 1988). The maximum vales of $\lambda 5007/\mathrm{H}\beta$ are observed in diffuse nebulae with O5–O4 stars, and these do not exceed 6.0. Using Table 4 and Kaler's (1976) catalogue, where basic data on emission line intensities prior to 1976 are compiled, we can provide the following limits of the variation of $\lambda 5007/\mathrm{H}\beta$ and $\mathrm{H}\alpha/\lambda 6584$ for different nebulae:

(i) For central regions in nebulae with O9–O8 stars: $\lambda 5007/\mathrm{H}\beta < 1.0$ and $\mathrm{H}\alpha/\lambda 6584 \simeq 2.0$–$5.0$.

(ii) for nebulae with O7 stars: $\lambda 5007/\mathrm{H}\beta \simeq 1.0$–$2.0$ and $\mathrm{H}\alpha/\lambda 6584 \simeq 2.0$–$5.0$.

(iii) For nebulae with O6 and earlier stars: $\lambda5007.H\beta > 3.0$ and $H\alpha/\lambda6584 \simeq 5.0$–10.0 and more.

In nebulae of this type, the He I line $\lambda6678$ has the maximum intensity with respect to average intensities of the [S II] lines, $\frac{1}{2}I(\lambda6717 + \lambda6731)$. This quantity reaches a value of 1.1 in NGC 1976, 1.8 in NGC 6618, 0.8 in S128 and 0.7 in S156, but this is as low as 1.0–0.5 in many diffuse nebulae and it correlates neither with [O III] line intensities nor with the stellar spectral class.

Of course, high-speed gas streams and shock waves produced by stellar winds play an important role in forbidden line emissions. However, theoretical models incorporating the joint action of these effects and the Lc emission still are unavailable.

The above empirical criteria for the spectral class of the exciting star are rather approximate, but they still allow to distinguish nebulae containing B1–B2, B0.5, B0–O9.5, O9–O7 and O6–O4 stars and to avoid crude errors in identifying the spectral class, especially when the exciting star is not visible in the optical range.

4 RELATIVE INTENSITIES OF EMISSION LINES AND PHYSICAL PARAMETERS OF STAR-FORMING REGIONS. INDIVIDUAL OBJECTS AND SPECTRA OF EXCITING STARS

First results of our optical studies of compact H II regions were presented by Glushkov (1973) and Glushkov *et al.* (1974b, 1975a). Since 1975, papers on our observations have been published mainly in *Astronomicheskij Tsirkuljar* where more than 30 papers were published in 1971–1990 as a series entitled *Spectrophotometric Studies of Galactic Nebulae.* Generalized results of these studies are presented in Table 4 where they are supplemented with new observations in the optical and radio ranges. At the time of publication, there were no radio data at all for many of the nebulae, and those available had low angular resolutions. For such objects, we performed additional optical observations when new radio data had appeared, for instance for NGC 1931, S158, S138, S226, S228, S269, S255 and S257. We also give results of our 1978 observations of the nebulae S106, S235AB and NGC 1931 at the prime focus of the 6 m telescope (UAGS spectrograph combined with the ITI UM92). We obtained 42 spectrograms at spectral resolution 2 Å and angular resolution of about 2″. We also present preliminary results of the observations of the exciting-star spectra obtained with the spectral scanner of the 6 m telescope.

Given in Table 4 are the intensity ratio of the Hα and [N II] λ6584 lines and also those of the Hβ and [O III]λ5007 lines (the maximum and minimum values are given, and also mean values are given for some objects). We further give the spectral classes of the exciting stars. These are based on our criteria for their determination, and on radio and IR data together with direct determinations (the luminosity class is indicated) taken mainly from Hunter and Massey (1990), Georgelin *et al.* (1973, 1975), Crampton *et al.* (1978), Moffat *et al.* (1979) and Chini and Wink (1984). The data on distance to the objects r and emission measures in radio EM(R) are mainly from Felli and Harten (1981), Kazès *et al.* (1975, 1977), Israel (1976) and Pyatunina (1980). The mean values of EM(Hα) and N_e[S II] (at $T_e = 7500$ K) are obtained by averaging over data for 4–12 regions of a size about 20″ × 6″ for each nebula. The maximum values of N_e[S II] are given, and for some nebulae we also give emission measures for the brightest spots. A_v is the visual extinction obtained by comparing EM(R) and EM(Hα). We also give A_v for the exciting stars obtained using IR photometry data and $B - V$ values from the papers mentioned above, where stellar spectral classes are given; the value of $R = A_v/E(B - V)$ is taken as 3.4.

Below we briefly characterize each object from this list except for S106 and S235AB. After a generally accepted name of the object we give references to our earlier papers where the reader can find further information.

4.1 Compact H II regions

S106=MI-19 (Glushkov and Karyagina, 1971; Parijskij and Glushkov, 1973; Glushkov, 1973; Glushkov *et al.*, 1975d). This undoubtedly one of the best studied compact H II regions. A bipolar nebula is projected onto the center of a dense molecular cloud. The exciting star is surrounded by a rotating, expanding molecular disk, and its extinction value is 21^m, including 6^m produced by a dense envelope of a radius of 1000 AU (Felli *et al.*, 1984a). A light spot (of a diameter about 10″) surrounded by a dark ring can be seen at this position on the E POSS plate. OH and H_2O maser sources are connected with this nebula, and recently a cluster of 160 stars was detected (Hoddap and Rayner, 1991).

In 1974, we concluded from spectra obtained with dispersions 11 and 18 Å/mm that the Hα and [N II] lines have blue wings in the southern part of the nebula, which implies gas motion at a velocity of about 200 km s^{-1} (Glushkov *et al.*, 1975d). This was later confirmed by Soft and Garsenty (1982), who used better angular and spectral resolutions.

Seventeen spectrograms ($\lambda\lambda$6200–7200 Å) were obtained at the 6 m telescope for 4 sections (or slit directions) across the nebula, with 3–5 spectrograms per section. The spectrograph slit width was 1.″3. Angular resolution, about 2″ on average, was determined by the quality of the image.

The analysis of the spectra obtained revealed that, for some regions of 2″–10″ in size located at the same sections across the nebula, [S II] lines have widely differing relative intensities for different spectrograms (including those obtained at similar exposures). These differences are greater than any possible photometric error, including that due to thermal noise of the ITI. The explanation for this fact was found only after the publication of the observations of the central region of the Orion nebula with the Hubble Space Telescope (Hester *et al.*, 1991). In these very lines, [S II], bright, narrow (0.″1–1.″0), dense (10^4 cm^{-3}) filaments are observed, which delineate ionization fronts and jets. Similar filaments are probably observed also in S106. Owing to unsteady atmospheric conditions and guiding errors, these filaments may be prominent in one spectrogram and absent in another.

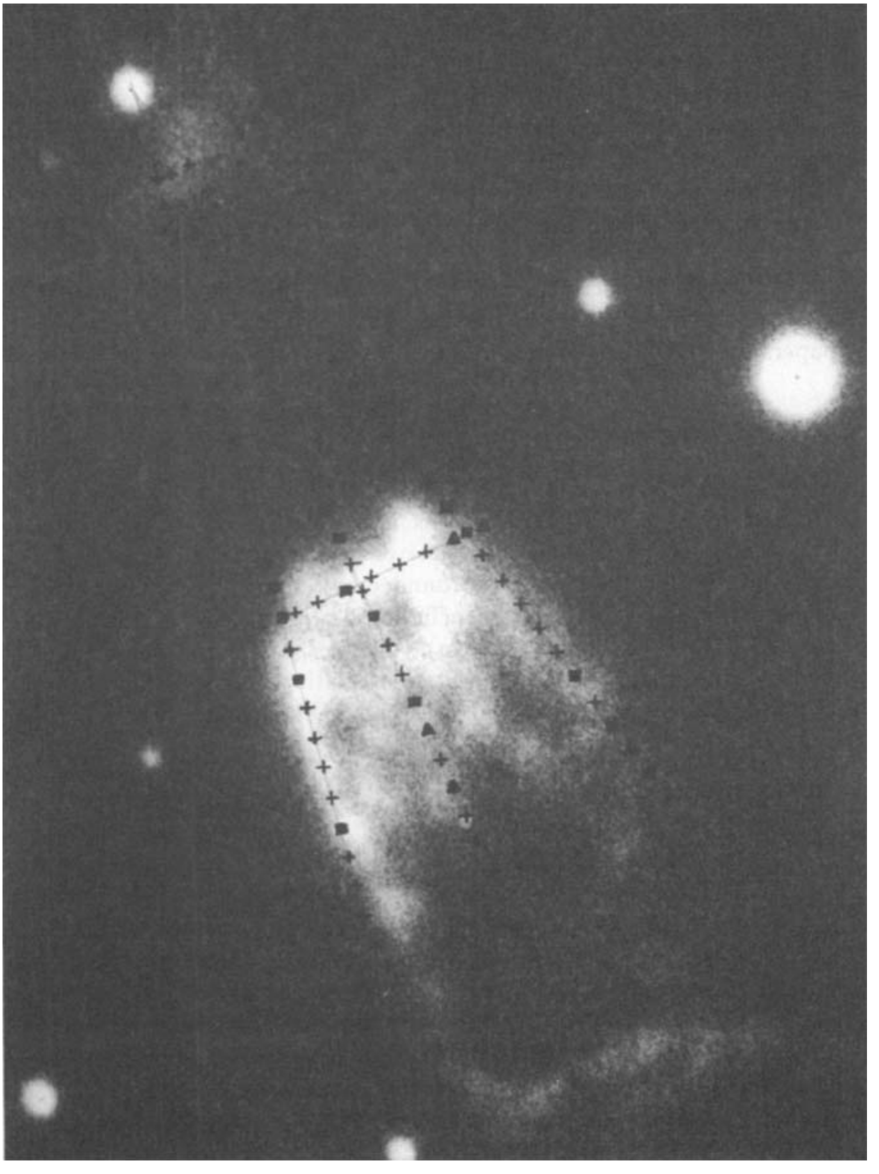

Figure 2 Photograph of S106 taken with the 2.6 m telescope of the Byurakan Obs. in red light. The scale of this reproduction is 0.9″/mm. Electron densities: ▲, Ne[S II]> 10^4 cm^{-3}; ■, $5 \times 10^3 < Ne$[S II]$< 10^4$; +, $10^3 < Ne$[S II]$< 5 \times 10^3$; •, Ne[S II]$< 10^3$.

Electron density maps for 76 regions of a size of $3.''6 \times 2.''0$ are shown in Figures 2, 2a. Figure 3 shows a radio map of the nebula obtained at $\lambda = 1.3$ cm with angular resolution $2.''3$ (Felli *et al.*, 1984a). We have N_e[S II] $> 10^4$ cm^{-3} in 21

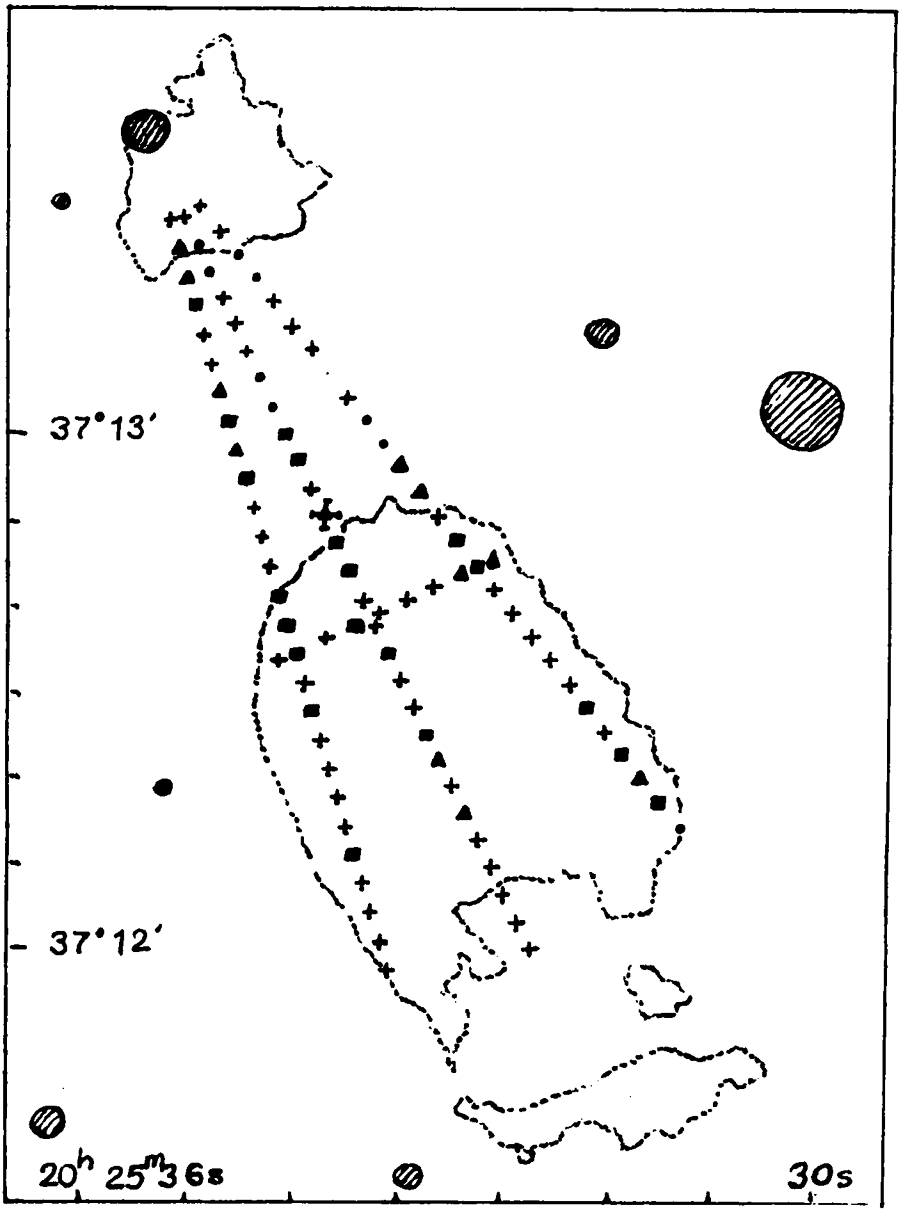

Figure 2a Scheme of S106. Electron densities. Same designations as Figure 2.

regions. The values of N_e[S II] agree fairly well with those obtained by Deharveng and Maucherat (1978), who used approximately the same sections in the nebula at angular resolution $4''.6 \times 8''.6$. Electron densities in an individual clump, as revealed in the radio range (Felli *et al.*, 1984a), are 3–5 times larger than N_e[S II]. This is

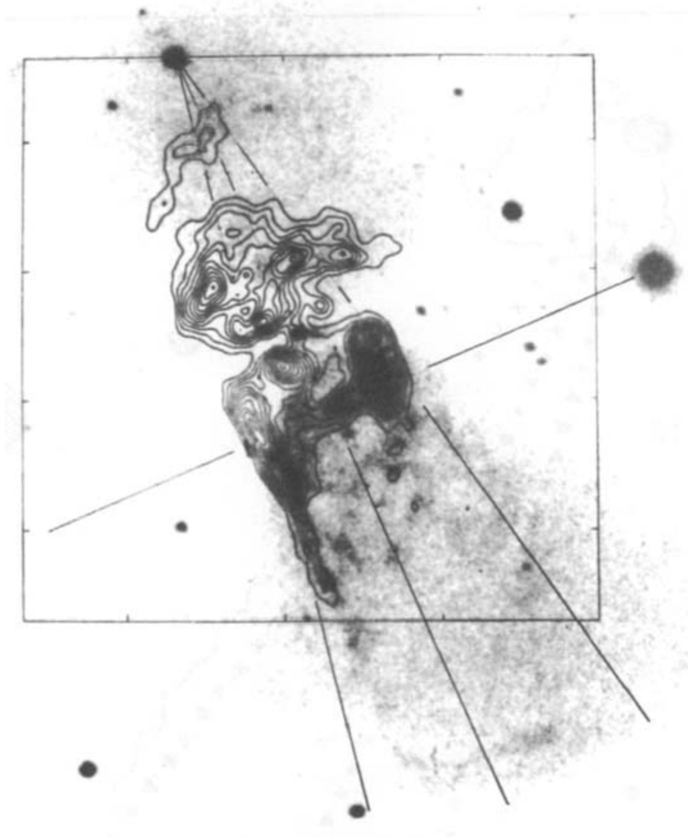

Figure 3 A map of S106 at λ1.3 cm (Felli *et al.*, 1984a). The slit direction is the same as Figures 2 and 2a.

understandable, because some radio-bright clumps are not visible in optics owing to extinction that is especially strong in the south-eastern part of the northern half of the nebula where A_v is as high as 15–30^m (Felli *et al.*, 1984a). Nevertheless, we believe that the widely accepted value of the distance to the nebula, 600 pc, is understimated by a factor of 2–3. Analysis of the stellar density in the IR cluster and its age leads to a similar conclusion (Hoddap and Rayner, 1991).

At the same time, there are some regions near the center and in the outer parts on the south which have $N_e[\mathrm{S\,II}] \simeq 10^4$ cm^{-3} and they are still invisible in the radio range. These are, probably, neutral condensations reflecting the light of bright, dense ionized clumps.

One of the investigated sections of the nebula passes through the central source (marked by a cross in Figure 2, 2a). In this region, $N_e[\mathrm{S\,II}] \simeq 1.2 \times 10^4$ cm^{-3} We believe that the emission of this region is the light of the central parts of the nebula reflected by an outer neutral envelope of the star. According to Felli *et al.* (1984a), N_e is at least $\simeq 1.8 \times 10^5$ cm^{-3}.

In connection with the radio data of Felli *et al.* (1984a), it would be very interesting to repeat optical observations having oriented the spectrograph slit as to cover the most interesting radio sources.

S235=MI-82, S235 ABC (Glushkov, 1973, 1980, 1990a; Glushkov *et al.*, 1972, 1974a, 1974b, 1975a; Glushkov and Karyagina, 1982). S235 is the brightest member of a group of four nebulae. Our spectra were obtained for S233 and S232 but physical parameters were never determined for these nebulae (Glushkov *et al.*, 1972). As indicated by radio isophotes (Israel, 1976) and POSS plates, S235 is half inside a dense molecular cloud. In Table 4 we give integral parameters for a central section of the nebula.

In 1974 we discovered a new compact H II region located at about 9′ to the south of S235, denoted S235A by Glushkov *et al.* (1974a, b; 1975a). This is a classical compact H II region located at the center of a molecular cloud, which is associated with an H_2O maser source (Israel, 1976) and IR stellar cluster (Zinnecker *et al.*, 1993). Winnberg (1981) observed this region at the 100 m Bonn radio telescope with the aim to detect an OH maser source. There was no OH emission detected in the range of LSR velocities from about −30 to −9 km s^{-1}.

An elliptic nebula of the size about 10″ is observed in red light at about 1′ to the south of S235A; in blue light, this appears as a star of about ~17.5 magnitude. Its spectrum has a strong $H\alpha$ emission with extended wings that imply velocities $V_r \sim -530$ and $+370$ km s^{-1}. This object, denote as S235B by us, is a source of IR emission and shows no sign of radio emission (Israel and Felli, 1978; Krassner *et al.*, 1979, 1982). It can be seen from a photograph obtained with the 6 m telescope, shown in Figure 4, that this object has the shape of a classical cometary nebula of the NGC 2261 type. A relative bright cometary tail is observed to the east of the central source and a dark cometary cone is seen to the west against the background of a weak emission. CO observations reveal a bipolar molecular outflow (Makota and Shigeomi, 1986). Only a weak emission line $H\beta$ can be seen in the blue region of the spectrum obtained by us with the 6 m telescope. Simultaneously, strong Paschen-series lines of hydrogen and a strong $\lambda 8446$ Å line are observed; the Paschen jump in emission is the same as that of a rapidly rotating Be star ϕ Per (McGregor *et al.*, 1984).

It is quite plausible that S235B is a Becklin-Neugebauer-type object at a later evolutionary stage which is surrounded by a dense, rapidly rotating, decaying disk having optically thin polar regions. At the same time, the envelope of the star must be expanding because the $H\alpha$ line profile has two maxima, with the blue component being 1.5 times brighter than the red one (Glushkov *et al.*, 1974a,b, 1975a).

The cometary tail is a reflection nebula. Therefore, the extinction estimate for S235B $A_v \simeq 19^m$ given by us (Glushkov *et al.*, 1974a) is incorrect, since we supposed that the elliptic envelope (as seen in a POSS E plate) is ionized. A value $A_v \simeq 7^m$ given by Krassner *et al.* (1982) is more plausible.

We obtained 14 spectrograms for 7 sections of S235A with the 6 m telescope. The sections were chosen to cross the most interesting structural regions of the nebula and the stars located there. Values of N_e[S II] were estimated for 85 regions in the nebula (of the size about $1.''5 \times 1.''5$). The results are shown in Figure 4;

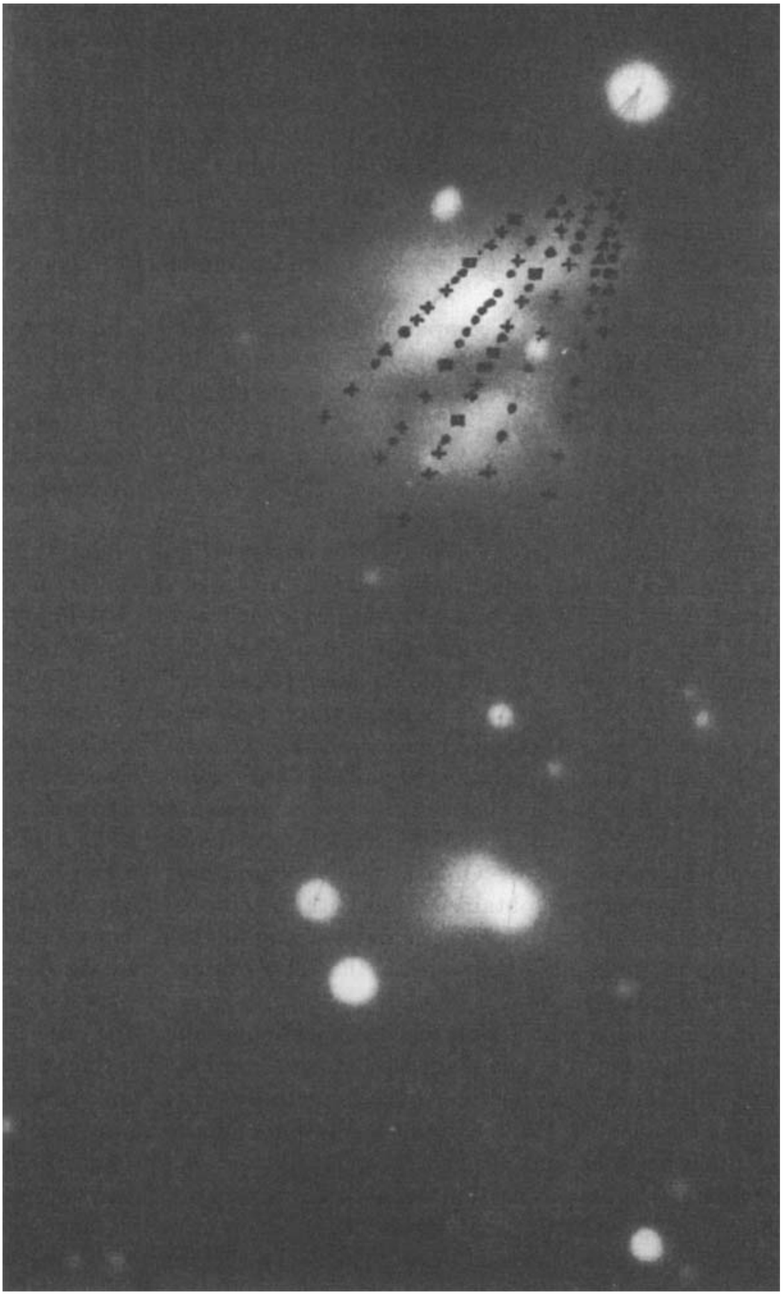

Figure 4 Photograph of S235AB taken with the 6 m telescope of the Special Astrophys. Obs. in red light. The scale of this reproduction is 0.7″/mm. Electron densities: ▲, Ne[S II]> 10^4 cm^{-3}; ■, 3 x 10^3 < Ne[S II]< 10^4; •, 10^3 < Ne[S II]< 3 x 10^3; +, Ne[S II]< 10^3.

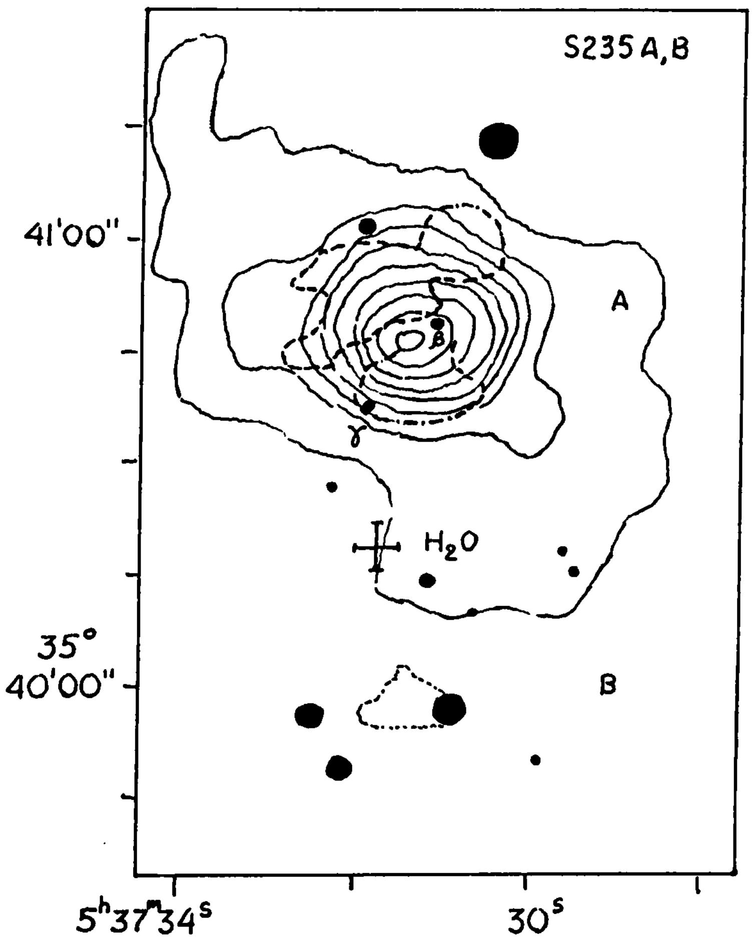

Figure 4a Scheme of S235AB. A map of S235AB at 11.1 cm (Krassner *et al.*, 1979).

some of them were also discussed by GLushkov and Karyagina (1982). In the brightest regions of the nebula we have $N_e \simeq 1.5 \times 10^3$ cm^{-3}. The maximum values $N_e > 5 \times 10^3$ cm^{-3} are observed at the interface of the H II region and a molecular cloud, including a dark lane diving the nebula into two approximately equal parts.

Figure 4a shows radio isophotes of the nebula obtained by Krassner *et al.* (1979) superimposed on optical contours. The β and γ stars are IR sources; the β star, which probably belongs to the BOe class, is the exciting star, whereas γ is a protostar (Krassner *et al.*, 1979). A weak trace of the continuum of the β star can be seen in one of our spectrograms but we have not detected any enhancement of the Hα emission brightness.

S235C is located about 4′ to the south of S235AB, apparently within the same molecular cloud. This is a low-brightness emission nebula and is a later stage of evolution than S235A (Glushkov, 1990a).

The group of nebulae S235 represents a good example of objects at different evolutionary stages located within a relatively small volume.

Mon R2=G213.7-1.26 This is a anonymous nebula of the size about $3' \times 4'$ excited by a star surrounded by a dense absorbing cloud, whose edges exhibit weak emission. A compact H II region revealed in the radio range has a very high emission measure and also contains OH and H_2O maser sources (Downes *et al.*, 1975); an IR stellar cluster was recently discovered here (Zinnecker *et al.*, 1993). Bright filaments and dark channels extend from this region to the nebulae Ced 65, 66, 63 and DG92. Even for the central part, the value of N_e[S II] does not exceed 10^3 cm^{-3}. The main flux of radio emission seems to originate in rather dense (of about 10^5 cm^{-3}) clumps that do not emit in forbidden lines.

S146 (Glushkov *et al.*, 1975c). This is a compact H II region associated with a dense molecular cloud and an H_2O maser source (Felli and Harten, 1981; Palagi *et al.*, 1993). A point-like IR source has been detected at the center of the nebula; it is assumed to be an O7 star with $A_v = 16^m$ (Eiroa *et al.*, 1981). The average values of N_e[S II] have been obtained with account for Hunter's (1992) data; the maximum value of N_e[S II] was also found by this author. We should note that the values of N_e[S II] given by Hunter should be divided by 3.3 since he used old values of the S II atomic parameters.

NS11 (Balbekov and Glushkov, 1988). This is an object from the list of Neckel and Staude (1984). The value of A_v obtained by us, $A_v = 6\overset{m}{.}8$ (see Table 4), is smaller than that obtained by Neckel and Staude by almost 10^m. It seems that the exciting star is surrounded by a pronounced circumstellar envelope similar to IRS4 in S106. This is also indicated by the presence of a point-like radio source detected in VLA observations (White and Gee, 1986). On the basis of the latter results, we have estimated EM(R). The nebula spectrum features very bright (relative to HeI) lines of [Ar III] λ7136 and especially [O II] λ7319 and λ7330 Å.

NS14 (Glushkov *et al.*, 1984). Fifteen small anonymous nebulae are observed near the dark cloud L1649. One of them, NS14, is a good example of a biconical nebula with a central star embedded in an optically thick disk with optically thin polar regions. Here an elliptic nebula of a size $12'' \times 26''$ is seen against the background of a dark strip; two dimmer nebulae are adjacent to this nebula on the western and eastern sides. Neckel and Staude (1984) found that the central star (invisible in optics) is of the B0.5 class and its extinction is $A_v = 13\overset{m}{.}7$. We found the extinction value $A_v = 8\overset{m}{.}8$ for the central region of the nebula assuming that only its small portion is ionized (Glushkov *et al.*, 1984). This was confirmed by VLA observations (White and Gee, 1986). Neckel *et al.* (1989) presented results of extensive optical, radio and IR observations and found a trapezium of four newborn B0.5-A5 stars with $A_v = 8$–17^m projected onto the center of the nebula.

This is unique object in which the main part of the nebula is a reflection one, even though an emission spectrum is also observed. When exploring this part of the sky, we have found a new group of Herbig-Haro objects (Glushkov *et al.*, 1986).

S87 (Glushkov, 1990a). Two compact objects are observed against the background of this weak emission nebula. We obtained the spectrum of one of them, which coincides with a bright radio source (Felli and Harten, 1981). [S II] lines are very weak and we were unable to estimate N_e[S II]. There are an H_2O maser (Palagi *et al.*, 1993) and a molecular bipolar outflow associated with this nebula.

S159 (Glushkov *et al.*, 1975c). In this nebula, only spectra of the bright condensation coinciding with the radio source S159A (Israel, 1976) were studied; this feature is probably a secondary star-forming center having its own exciting star.

S270 (Glushkov and Karyagina, 1986). A bright part of this nebula has the size of about $20'' \times 20''$. The exciting B0.5 star with $A_v = 11^m.3$ can be seen in a photograph in near IR (Neckel and Staude, 1984). The nebula is associated with a molecular cloud and is a rather strong IR emitter. Our estimate of A_v for the nebula is almost by 5^m smaller than A_v for the exciting star. It is quite plausible that this star has a strong dust envelope. It is also possible that only a small part of the nebula is ionized, like in the case of NS14.

Ap2-1 (Glushkov *et al.*, 1974a). This nebula has been detected by Apriamashvili (1962) and included into a catalogue of planetary nebulae. Our results imply that this is a compact H II region.

4.2 H II regions with dense clumps

S61 (Glushkov, 1990a). A dense clump with $N_e > 10^3$ cm^{-3} is observed to the south of the exciting star in this nebula. An interesting feature of this nebula is an emission filament with a chain of stars. The filament density is about 50 cm^{-3}.

S83 (Glushkov, 1990a). Outwardly, this nebula resembles much a compact H II region. However, this is a very distant object with $N_e \simeq 100$ cm^{-3} (Felli and Harten, 1981) and its degree of ionization is unusually high for diffuse nebulae. Denser regions of the nebula possibly emit in the [S III] lines.

The spectrum of the exciting star was obtained with the 6 m telescope. We failed to identify any spectral details except the absorption line He II λ4200 Å and emission line Fe III λ4658 Å (C IV λ4658?)

S93 (Glushkov *et al.*, 1979a). The shape of the radio isophotes (Israel, 1977) indicates that this nebula is half embedded into a molecular cloud. A star identified by Hunter and Massey (1990) with the exciting star is more likely a field star.

S128 (Glushkov *et al.*, 1979a). This nebula is projected onto the south-west edge of IC1396 but its distance is about 7 kpc. The spectrum of the exciting star was estimated as O7V (Chini and Wink, 1984), although the nebula spectrum and radio data of Ho *et al.* (1981) indicate that it is closer to O6.

An ultra-compact H II region with an H_2O maser source was detected at $60''$ to the north of S128 (Ho *et al.*, 1981).

S138 (Glushkov, 1990a). A compact detail with $N_e = 2500$ cm^{-3} is prominent in the radio range (Felli and Harten, 1981), and it is not observed in optics. We believe that, like in the case of MonR2, this feature consists of individual clumps with $N_e > 10^5$ cm^{-3} that do not emit in forbidden lines.

S148=MI-20 This nebula was erroneously identified with S149 by Glushkov *et al.* (1975c), although the separation of these nebulae is about $2'$. The values of N_e[S II] obtained by us are in good agreement with results of Hunter (1992).

S152=MI-21 (Glushkov *et al.*, 1975c). This nebula is located at 26′ from S148 and, possibly, is connected with the same molecular cloud as S148; however, it is usually assumed that these are two different clouds, although the available distance estimates are very uncertain.

Our spectral data are in a fair agreement with the results of Heydari–Malayere and Testor (1981). We noted that the observed degree of ionization in this nebula is maximum near a star with $V \simeq 15^{m}_{.}5$ located at 12″ to the south-east of the exciting star. This star (S152.2) is seen at the center of the brightest clump in S152. We assumed that a secondary star-forming region is observed in this region of the nebula, like that in NGC 7538A (Glushkov *et al.*, 1975a).

Four spectra of the star S152.2 were obtained in 1991–1992 over the range $\lambda\lambda$3700–5400 Å with the spectral scanner of the 6 m telescope. Spectral resolution was largely low (about 4 Å), and we did not estimate the equivalent widths of the lines. Here we provide a qualitative description of the spectra in order to illustrate how nonstationary are stars in nebulae. Qualitative estimates of the spectral class are based on comparisons of the observed spectra with those of OB stars from the atlas of Walborn and Fitzpatric (1990).

The star S152.2 is a spectrum variable, of class Oe–Be. In February 1991, its spectrum contained P Cyg profiles of Hϵ and Hδ lines, the He I λ4471 and He II λ4686 emission lines, weak absorption lines of O II and N II at nearly the noise level, and a strong interstellar line KCa I. In June 1991, a P Cyg profile was noticed also for the Hγ line, there appeared strong absorption lines of He II λ4541 and He I λ4471 with the same ratio as for an O6 star, and also the He II λ4686 emission line. In January 1992, the P Cyg profiles disappeared and the spectra featured only interstellar H and KCaI lines together with the He I λ4471 emission line; all the remaining lines were at the noise level. The spectrum was obtained again in January 1993 with a good signal to noise ratio (of about 50:1). The P Cyg profiles of hydrogen lines appeared again, and emission in Hϵ was absent. The absorption line He II λ4200 appeared and, at the place of the He I λ4471 line, the absorption line λ4463 was seen merged with a wide ($\pm$5 Å at half intensity) emission line having its maximum at λ4483. These data hardly can lead to a confident estimate of the stellar effective temperature but it seems plausible that the star makes an important contribution into ionization of the nebula. The star S152.2 and a dense part of the nebula surrounding it can be considered as a secondary star-forming region in S152.

NGC 7538=S158 (Glushkov *et al.*, 1972b; Glushkov, 1973; Glushkov *et al.*, 1975a). Even the first observations of this nebula showed that ionization is the strongest near the star = 2 (Glushkov *et al.*, 1975) or = *IRS*5 (Deharveng *et al.*, 1979) located at about 30″ to the west of the exciting star 1 = IRS6. Based on the intensity ratios Hα/[N II] > 8 and λ5007/Hβ > 3, we suggested that this is an O5–O6 star embedded in a region with strong absorption. UBV observations of IRS5 were performed in 1993, which yielded $V = 14^{m}_{.}28 \pm 0.03$, $B - V = +1.35 \pm 0.03$ and $U - B = +0.06 \pm 0.08$ (Lyutyj, 1993).

Analysis of photographs obtained with interference filters gave even greater values of the intensity ratios for the above lines, with the brightness of the [O III] line being distributed symmetrically with respect to IRS6 and $\lambda5007/H\beta$ reaching 6.0 (Deharveng *et al.*, 1979). These great values are not observed even in the nebula NGC 6618 excited by O4–O6 stars. Large velocities of the ionized gas, similar to those observed in S106, have not been detected (Deharveng *et al.*, 1979).

Four spectra of the star IRS5 were obtained in 1991–1993 with the spectral scanner of the 6 m telescope. The star turned out to be a spectrum variable and, simultaneously, a spectroscopic binary with the components of the spectral classes near O8V and B2II. Molecular bands of TiO were detected in the stellar spectrum at $\lambda4761$ and $\lambda4584$ in January 1992. The TiO bands were detected in neither blue nor red spectral ranges in June 1993, but instead P Cyg profiles of the $H\epsilon$, $H\delta$ and $H\gamma$ lines appeared. This star has many other peculiar features but we are confident that it cannot maintain the observed high excitation of the nebula.

All the data given in Table 4 refer to the bright region in NGC 7538 around the star IRS5.

S156=IC1470 (Glushkov and Karyagina, 1972b; Glushkov, 1973; Glushkov *et al.*, 1975c). This nebula is associated with a large molecular cloud (Heydari–Malayere *et al.*, 1980; Israel, 1976). Along the edge of the cloud, three other small nebulae are observed, which are equally bright in blue and red lights, and also a small stellar cluster embedded in a dark cloud with ionized edges.

This object is the brightest member of our list in the $H\alpha$ line. The nebular spectrum and the O6.5V stellar spectrum (Chini and Wink, 1984) meet our empirical criteria.

S186 (Glushkov *et al.*, 1979a). The outer parts of this small ($\simeq 40''$) nebula are dotted with small globules which seem to be responsible for the strong IR emission. Average values of N_e obtained from observations in optical and radio ranges (Felli and Harten, 1981) agree with each other fairly well.

S226 (Glushkov, 1990a). This nebula, whose bright part has the size of about $1'$, is embedded in a dense, dark cloud. Three dense clumps ($N_e \simeq 2000$ cm^{-3}) were detected in the radio range (Felli and Harten, 1981). The values of N_e[S II] do not exceed 650 cm^{-3} in the same regions. These condensations apparently have a very strong absorption or $N_e > 10^5$ cm^{-3} but the filling factor is low.

Three stars are observed at the center of the nebula, with the brightest one having $m(B) \simeq 17\overset{m}{.}5$. Their spectra were obtained in December 1989 with the spectral scanner of the 6 m telescope together with the spectrum of the exciting star in S228. The southern star of S226 exhibits very strong He II absorption lines, especially at $\lambda4541$, whereas the line He I $\lambda4471$ is very weak; other He I lines are rather strong. We believe that this star is a spectroscopic binary O5V+B1Ib. The northern star can be crudely estimated to be a binary consisting of a late and early B supergiants. The spectrum of the third star (the eastern one), which has $m(B) > 18^m$ allows us to say only that this is a spectroscopic binary whose one component is near O8V.

Assuming the distance to S226 to be about 5.3 kpc and the absolute magnitude of the hottest star to be $M_v = -5\overset{m}{.}2$, we obtain extinction for the central stars to be about $9\overset{m}{.}6$, which exceeds that for the nebula by about 3^m.

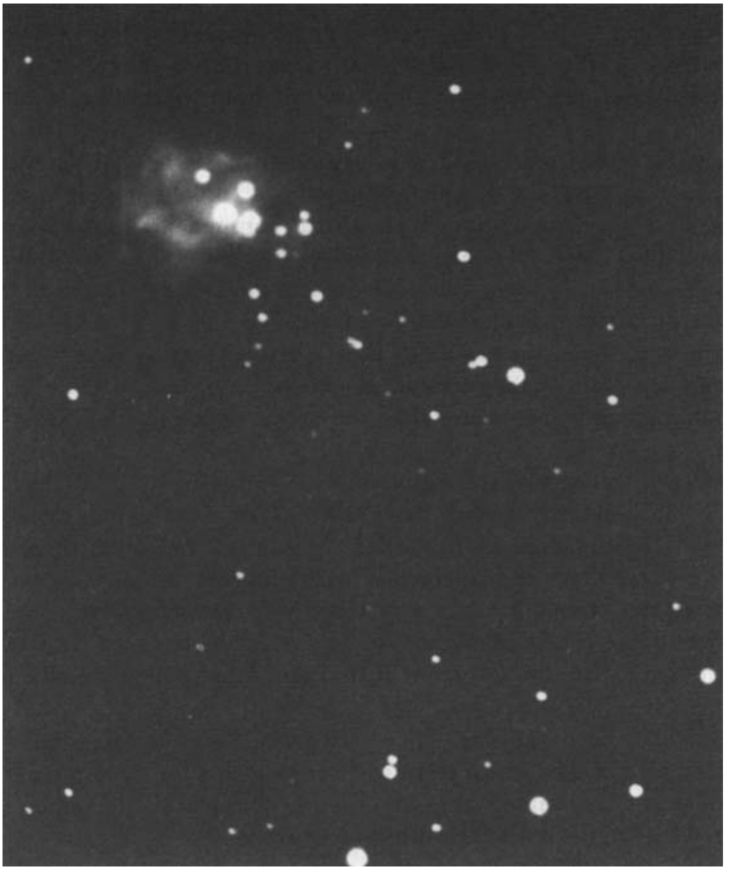

Figure 5 Photograph of NGC1931 taken with the 6 m telescope of the Special Astrophys. Obs. in red light. The scale of this reproduction is 2.9″/mm; north is at the top and east to the left.

S228 (Glushkov, 1990a). This nebula is located at about 40′ away from S226 but its distance is much smaller than 2.5 kpc. The maximum value of electron density N_e[S II]=1600 cm^{-3} is observed near the maximum of the radio intensity.

According to our estimates, the exciting star is a spectroscopic binary having the components close to O8V and B2II. Our spectrum appears to be obtained when both stars were visible because earlier estimates of the spectral classes are O8Ve (Chini and Wink, 1984) and B0V (Hunter and Massey, 1990).

An IR cluster containing 70 stars was recently detected in this nebula (Zinnecker *et al.*, 1993).

S237=NGC 1931 (Glushkov and Karyagina, 1972b; Glushkov, 1973). This is a nebula with a strong continuum. A bright part has the size of about 3′ × 3′, but a weak emission can be seen within the region of about 7′ × 7′. A spectacular

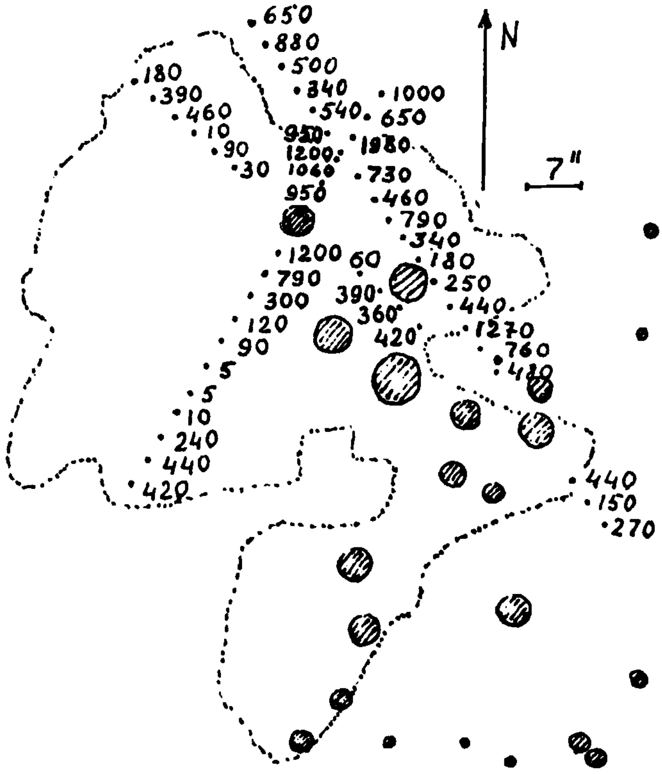

Figure 6 Scheme of central part of NGC1931. Electron densities (cm^{-3}).

but almost unexplored stellar cluster is seen against the center of the nebula. A trapezium of four stars ($m_v \simeq 11^m_{\cdot}5$–$14^m_{\cdot}0$) excites the emission of the nebula (see Figure 5). Spectra of these stars were obtained with the 6 m telescope. Preliminary results of their analysis are as follows. The star 4 (according to notation introduced by Hunter and Massey, 1990) has a very strong blue excess in continuum, which is not typical of stars in nebulae. Deep, strong B2V stellar absorption are observed. All lines in the spectrum of the star 2 are very weak and no definite conclusion about its spectral class can be made, even though this star is known as B0.5V (Hunter and Massey, 1990). The star 3 has signatures of B0.7Ib–B1.5Ia. The spectrum of the northern star of the trapezium resembles most that of an O9.7Iab star, the Hγ line exhibits a P Cyg profile and the $\lambda 4430 A$ bands is visible. The largest (over the nebula) electron density of $10^3 - 2 \times 10^3$ cm^{-3} is observed within about $10''$ of this star.

Nine spectrograms for 3 sections across the nebula were obtained with the 6 m telescope. A sketch of the nebula and N_e[S II] values are shown in Figure 6. It is interesting that some bright clumps in the central part of the nebula have very low values of $N_e[S\,II] \simeq 50$–100 cm^{-3}: these are rarefied filaments oriented along the line of sight. High electron densities $N_e > 500$ cm^{-3} are observed at the interface with a molecular cloud. The average values of N_e[S II] and EM(Hα) given in Table 4 were estimated from photometry of 10 spectrograms of the nebula obtained with the 70 cm telescope in 1974.

S255=IC2162 and S257 (Glushkov, 1973; Glushkov *et al.*, 1972; Glushkov and Karyagina, 1972b). The distance to these objects was obtained as 2300±150 pc assuming that the exciting stars of S254 and S257 are spatially close to each other and $R = 3.4$ (Glushkov, 1973). A dark, dense cloud is found between the nebulae, with an IR stellar cluster consisting of 170 stars detected against the center of the cloud (Zinnecker *et al.*, 1993) together with a bright radio source and OH and H_2O masers (Israel, 1976; Chopinet *et al.*, 1974). The electron density reaches a maximum of about 700 cm^{-3} along the edges of S255 and S257, i.e. on the interface with this molecular cloud. In S257, this interface represents a chain of three globules having ionized edges.

S269 (Glushkov, 1973; Glushkov *et al.*, 1972). This is a region of active star formation containing OH and H_2O masers and IR stellar cluster (Heydari–Malayere *et al.*, 1982; Zinnecker *et al.*, 1993). An especially interesting fact is the detection of a high-speed ($\simeq 200$ km s^{-1}) outflow from the region of the maser sources.

A B0.5V star was detected near the center of the nebula within a dark channel; this is believed to be the exciting star. However, the presence of [O III] and He I lines in the nebular spectrum implies that this star must belong to an earlier spectral class.

The spectrum of a star of about 18^m located about $10''$ to the north of B0.5V was obtained by us with the 6 m telescope in 1990. This turned out to belong to the class F0V with a very strong absorption band at $\lambda 4430$. Thus, the question of the identification of the exciting star sill remains open.

S283 (Glushkov, 1990a). This is a very poorly studied nebula possessing a stellar cluster, dense clumps and H_2O maser (Palagi *et al.*, 1993).

S288 (Glushkov *et al.*, 1983b) This a distant nebula, bright in Hα, having a distinct [O III] region. It is at an earlier evolutionary stage than M20 but at a later one than IC1470. The exciting star was classified as B1 (Moffat *et al.*, 1979) or O7+B1 (Glushkov *et al.*, 1983b). We obtained two spectrograms of this star with the 1m telescope and UAGS spectrograph and believe that this is a spectroscopic binary with P Cyg profiles of the lines Hβ, Hγ and Hδ.

S297=Ced90 (Glushkov, 1973; Glushkov *et al.*, 1972). Radio isophotes (Pyatunina, 1980) and POSS plates indicate that the western end of this nebula is obscured by a dense molecular cloud. The exciting star seems to be a spectroscopic binary, whose spectral class is most probably B0.5 as estimated from radio data.

S307 (Glushkov *et al.*, 1975c). The large electron density $N_e > 3 \times 10^3$ cm^{-3} found by us along the north–south section containing a central star probably refers to an ionization front at the molecular cloud interface. This can be also from the radio isophotes of Felli and Harten (1981). For most of the nebula, $N_e <$ 500 cm^{-3}.

NS7 (Glushkov and Karyagina, 1986). This nebula is located at the north–west outskirts of NGC 2175. In order to estimate the absorption towards this

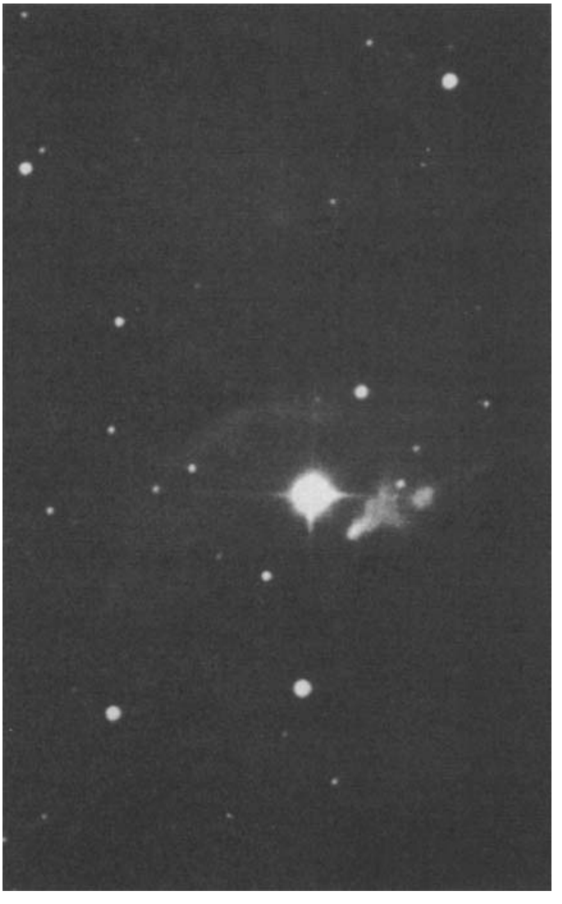

Figure 7 **Photograph of NGC7635 taken with the 1 m telescope of the Fesenkov** Astrophys. Inst. in red light.

object, we used the radio data of White and Gee (1986). The value $A_v = 9^m\!.9$ obtained for the exciting star by Neckel and Staude (1984) seems to be strongly overestimated.

NGC 7635 (Glushkov, 1973, 1990b; Glushkov and Karyagina, 1972; Glushkov *et al.*, 1975c). The most interesting details of this remarkable nebula are a cometary feature and a ring surrounding the exciting star. The cometary feature consists of two clumps (see Figure 7) and I believe that the ring is a result of the evolution of these two clumps, which decay as giant comets under the action of the radiation field and stellar wind of the star BD+60°2522. It is interesting to note that the clump A(2) is adjacent to globules whose edges are ionized on the north, so that they resemble a jet emanating from the clump A(2). The spectrum of the "comet" contains a prominent [O I] λ6300 line suggesting a shadow effect.

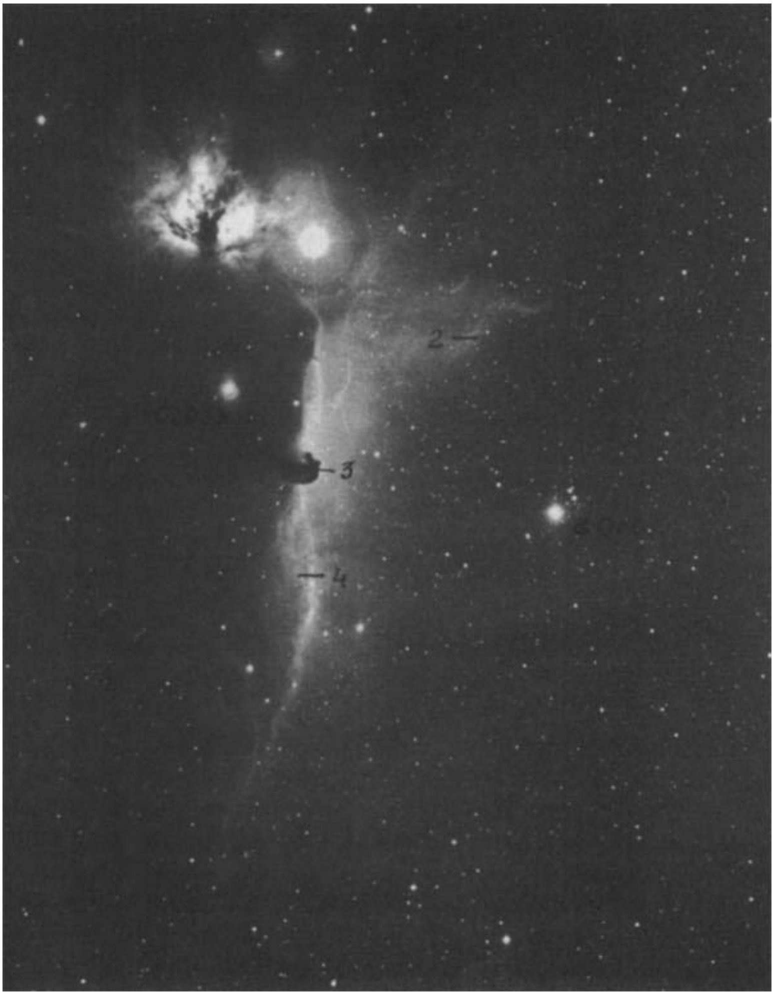

Figure 8 Photograph of region of IC434, NGC2024, NGC2023 taken with the 50 cm Maksutov telescope of the Fesenkov Astrophys Inst. in red light.

Another system comprising three bright spots is located to the north of the exciting star. The eastern spot probably is a filament oriented along the line of sight, since its electron density is as low as $N_e \simeq 50\ \mathrm{cm}^{-3}$.

We used the results of Israel (1976) in order to estimate absorption for individual details. The values of A_v thus derived are in good agreement with the results of Barlow *et al.* (1976).

No large molecular cloud was detected in NGC 7635, but we believe that small molecular clouds with ongoing star formation should be associated with the system of clumps C and the globules.

4.3 Star forming regions with infrared stellar clusters

NGC 2024=W12=OriB (Glushkov, 1973; Glushkov and Karyagina, 1972b). The dark cloud L1640 containing another major star-forming region in Orion is located near ζOri. Here 4 IR stellar clusters were detected within nebulae: NGC 2024 (209 stars), NGC 2068 (192 stars), NGC 2071 (105 stars) and NGC 2023 (21 stars) (Lada, 1992). All these nebulae are poorly studied in optics.

The nebula pairs IC432-431 and NGC 2023-IC435 are positioned symmetrically with respect to NGC 2024. IC432 and NGC 2023 are located to the north and south of a dark channel (along its direction) that divides NGC 2024 into halves, each at the distance of about 26′ to the geometric center of NGC 2024. These objects undoubtedly form a single complex containing also IC434 (see Figure 8). NGC 2024 is the brightest and most massive of these objects.

Prominent dark channels divide this nebula into several parts consisting of individual patches. A compact H II region is located almost at the vertex of the dark channels; an H_2O maser and numerous IR sources, both point-like and extended, are associated with this H II region.

One of the exciting stars, IRS1, is observed at the edge of a dark channel; its spectrum is B0.5Vp and it has $A_v = 9\overset{m}{.}3$ (Johnson and Mendoza, 1964). Absorption is very inhomogeneous in this nebula and, according to our estimates, it reaches $A_v = 5$–10^m even for very bright details. The star that excites the compact H II region is IRS2. It is interesting to note that the value of $\lambda 5007/H\beta \simeq 0.08$ on average over the nebula is about 4 times smaller than that found by Hubble (1922). Most probably, an envelope absorbing stellar Lc emission has been formed around the exciting star during the last 70 years or, otherwise, stellar Lc flux has become weaker.

It is quite plausible that some regions represent independent objects with their own exciting stars. It cannot be excluded that ζOri (O9.5Ia) contributes to the ionization of some regions in NGC 2024.

NGC 2068=M78 (Glushkov, 1973; Glushkov *et al.*, 1979). This is a nebula with a strong continuum located at 140′ to the north–east of NGC 2024. Separated by 13′, NGC 2071 is observed to the north of this nebula, and a group of Herbig–Haro objects can be seen at 20′ to the south–west. When inspecting the structure of the nebula, the impression is that it all consists of globules of a size 5″–10″ illuminated by stars, which have different shapes depending on position.

The Stromgren sphere is clearly distinguished in spectrograms by [N II] and [S II] lines; its radius is as low as 0.2 pc, while the total size of the nebula is 1.4 × 1.7 pc. The exciting star is surrounded by a dense disk which is prominent in photographs; the extinction value for the star is $A_v = 5\overset{m}{.}6$, which exceeds the average value for the ionized nebular gas by almost 3^m. We used the radio data for NGC 2068 obtained by Matsacis *et al.* (1976).

Our observations and calculations show that only 1% of the continuum emission is due to ionized hydrogen (Glushkov *et al.*, 1979).

The continuum emission is practically completely represented by stellar light scattered by dust. Apart from two B stars, the nebula contains an A0II star and 192 stars of an IR cluster.

Even these three early-class stars have strong absorption lines of the Balmer series. There is no emission in the nebular spectrum already in the Hβ line.

The cases of NGC 2068 and NGC 2023 (discussed below) illustrate especially well the necessity of allowance for the effects of hydrogen absorption lines in stellar spectra reflected by dust on the visibility of hydrogen emission lines in the nebular spectra.

This implies that estimates of the Balmer decrement as well as of the ratios Hα/[N II] and [O III]/Hβ are to some extent erroneous for all nebulae containing a sufficiently large amount of dust.

NGC 2023 (Glushkov, 1973; Glushkov *et al.*, 1979). This nebula is very similar to NGC 2068, but its IR cluster is poorer by an order of magnitude, even though the masses of dense molecular gas in these nebulae are equal to each other. In the central part of the nebula, a weak Hβ emission line can also be seen. Its brightness grows with distance from the center (other Balmer-series lines simultaneously become visible) and keeps growing beyond the nebula boundaries out to the edge of a molecular cloud, whose western part is ionized by the light of the star σOri. To the south of NGC 2023, the dark cloud does not exhibit even a weak emission typical of the whole region, i.e. the dark Horsehead Nebula completely protects this part of the cloud from the emission of σOri. Here, in the shadow region, a group of Herbig–Haro objects is also observed.

Intense [N II] and [S II] emissions are observed in the spectrum of NGC 2023 only within about $1\rlap{.}'5$ of the exciting star, whereas the nebula radius is about $4'$.

A large amount of dust in NGC 2023 and NGC 2068 facilitates the cooling of the nebulae and their electron temperature is about 7000 K as we found from the intensity ratio Hα/λ6854. This is lower by 1000 K than T_e in the nebulae IC432 and Ced44 that have similar exciting stars but weak continua (Glushkov, 1973; Glushkov *et al.*, 1979).

We failed in finding in the literature reliable radio data on NGC 2023; the amount of absorption in the nebula can be estimated by comparing average values of N_e^2[S II]$\cdot l$ and EM(Hα). Taking the line-of-sight size of the emitting region as $l = 0.4$ pc, we obtain $A_v = 4\rlap{.}^m0$, while $A_v = 1\rlap{.}^m5$ for the exciting star. A similar procedure yields $A_v \simeq 5\rlap{.}^m9$ for NGC 2068. The value $A_v \simeq 2\rlap{.}^m8$ given in Table 4 requires that the radius of the Stromgren sphere is about 10 times smaller than the observed one, i.e. only an insignificant part of the volume is occupied by ionized gas within the Stromgren sphere.

NGC1579=S222 (Glushkov, 1973; Glushkov *et al.*, 1972). A bright part of this nebula has the size about $4' \times 4'$. The spectrum of the exciting star LkHα101 has not been classified precisely enough and its spectral class B1IIe was determined indirectly from radio and IR data (Brown *et al.*, 1976). A compact H II region is associated with this star, having the diameter of about $1'$ and high emission measure (Brown *et al.*, 1976). A rich stellar cluster was detected in the IR range (Barsony *et al.*, 1991).

The nebular spectrum obtained with the slit passing through LkHα101 contains only an emission Hα line having approximately uniform brightness over the distance of about 4′ and also a weak Hβ line visible only close to the star. The absence of [N II] and [S II] lines might be explained by assuming that the density of the compact H II region exceeds 10^5 cm^{-3} (Harris, 1976) and that the main part of the nebula emits a reflected light; however, a rather uniform distribution of the Hα brightness makes this possibility dubious.

S252A (Glushkov, 1973; Glushkov and Karyagina, 1972a). This is a bright condensation ($0\overset{'}{.}8 \times 1\overset{'}{.}2$) with an O9 star at the center; the condensation is surrounded by a dark ring well visible against the background of NGC 2175, near whose center it is observed. All emission lines in its spectrum are strongly enhanced in comparison with the background. Most plausibly, the nebula is only projected onto the central part of NGC 2175 and it is actually located in its outer region, like NS7.

Photographs in the near IR range reveal a compact stellar cluster containing 21 stars around an O9 star (Chavarria *et al.*, 1987). In this case we possibly observe early stages of evolution of a tiny stellar cluster similar to that around σOri.

NGC 6618=M17=Omega Nebula (Glushkov, 1973; Glushkov and Karyagina, 1972a; Glushkov *et al.*, 1978; Glushkov *et al.*, 1980; Glushkov *et al.*, 1982). The Omega Nebula is among those brightest H II regions whose physical nature is most difficult to understand. The nebula contains one of the richest clusters prominent basically in the near IR range and having more than a hundred of OB star alone (Zinnecker *et al.*, 1993). Tens of molecular and radio emission centers were recently revealed in this nebula (Felli *et al.*, 1984b; Stutzki *et al.*, 1990).

We obtained an extensive observational data set (containing more than 200 spectrograms) in order to study the density and ionization of the nebula. Figure 9 shows the central part of the nebula, where circles mark the centers of strips of the average size about 25″ × 6″. These strips correspond to the positions of the microphotometer slit used when reducing the spectrograms. Pluses indicate the centers of regions where N_e [S II]$> 10^3$ cm^{-3}. Crosses show regions where $I(\lambda6678[\mathrm{He\,I}])/I(\lambda6717 + \lambda6731)/2 > 1.0$. We recall that this ratio does not exceed 1.1 near the Trapezium in the Orion Nebula. Asterisks denote regions where the observed density is greater than 10^3 cm^{-3} and ionization is high. The outer boundary of the radio isophotes (for the λ21 cm continuum) is also indicated as observed at VLA by Felli *et al.* (1984). Individual clumps are also indicated and the circle shows the position of an ultra-compact H II region. O stars are indicated by numbers (according to Chini *et al.*, 1980).

The highest ionization is observed at the boundaries of ionization fronts extended along the southern part of the northern bar in the region of bright filaments which are prominent in a dark region and especially near the ultra-compact H II region. It is unclear why an extended high-density region located to the east of the dark region is invisible in VLA data. No high ionization was observed in this region, although there are two nearby O5 stars (stars 2 and 3). These stars are probably only projected onto this region.

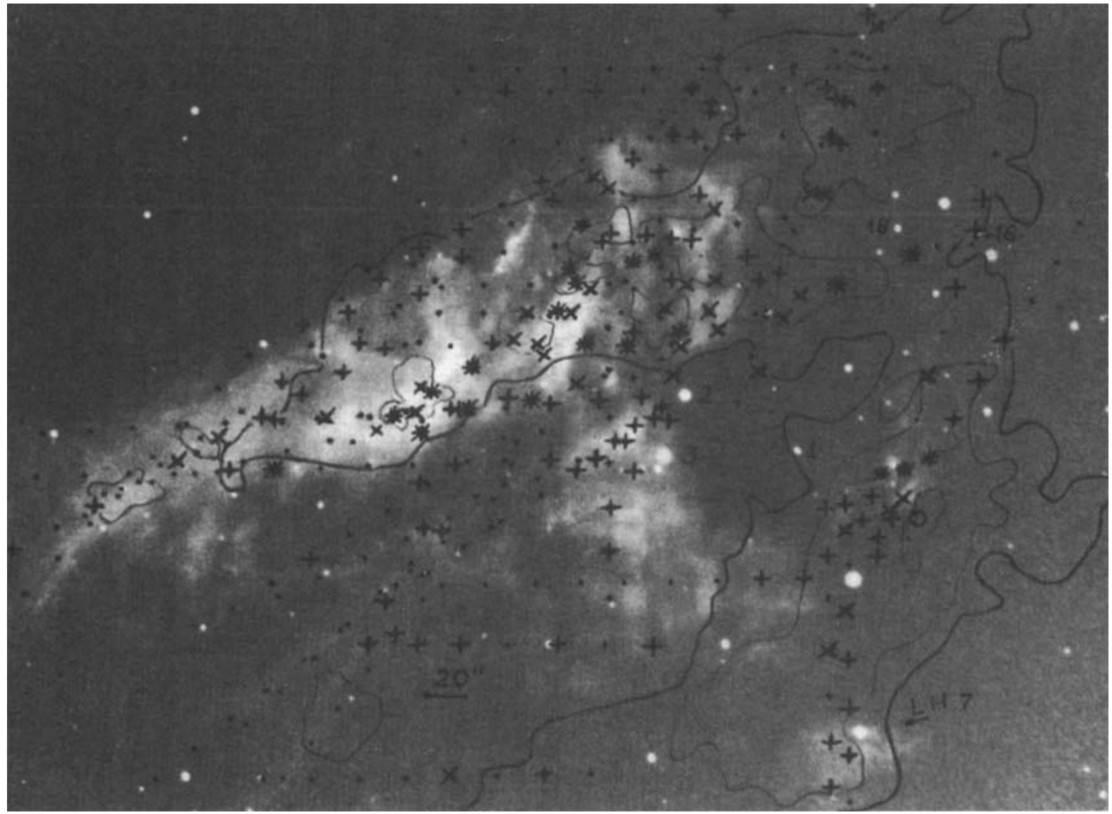

Figure 9 Photograph of NGC6618 taken with the 2.6 m telescope of the Byurakan Obs. in red light. The scale of this reproduction is 4″/mm; north is at the top and east to the left. +, electron densities Ne[S II]$> 10^3$ cm^{-3}; ×, I(λ6678HeI)/I(λ6717 + λ6731)[S II]/2 > 1. The contour is the lowest one of the 21 cm map (Felli *et al.*, 1984b).

Further discussion of these results will be published elsewhere. Here we only note that the spatial structure of the nebula remains obscure notwithstanding extensive observational data in all spectral ranges.

5 DISCUSSION

All of the above objects are star-forming regions associated with molecular clouds. In accordance with the classification of H II regions proposed by Israel (1976) and Habing and Israel (1979), we divided these objects into two basic groups.

The first group includes classical compact H II regions with diameters smaller than 1 pc and densities greater than 10^3 cm^{-3}, which contain H_2O masers and exciting stars possessing dense gas-dust disks. These are H II regions of type II (Habing and Israel, 1979).

The second, more numerous group of objects belongs to H II regions of type III (Habing and Israel, 1979) that contain dense clumps. This group is more diverse with respect to the physical parameters of its members. Some objects resemble compact H II regions (S148, 152, 156 and 269), others are close to classical H II regions (S83, 158, 226, 228, 235, 237, 255, 257, 288 and NGC 7635).

The third group of objects has only one feature in common, namely an IR stellar cluster. As one can see from Section 4.3, these are very diverse objects.

5.1 Stellar clusters and secondary star-forming regions

The following facts can be considered proven:

1. Every diffuse nebula is associated with a stellar cluster, that is any massive OB star has always a cluster of low-mass stars associated with it, which still have not reached the main sequence (pre-main-sequence, or PMS stars).

2. Some nebulae have a single massive OB star, the others have several such stars that form a cluster similar to the Trapezium in M42.

3. Formation of stars in a given molecular cloud can proceed in several stages. Stellar clusters being at different stages of evolution may be observed even within a single nebula.

Several types of relative positions of OB stars, PMS stars and diffuse matter can be found in classical H II regions:

IC5146 An O star is observed at the center of the nebula (apparently, a spectroscopic binary), surrounded by a cluster containing 100 PMS stars.

NGC 2244 (*Rosette Nebula*) A rich cluster of OB stars is observed against the center of the nebula.

NGC 6523 (*Lagoon Nebula*) A large stellar cluster is observed around a O6 star against the center of the nebula and a secondary star-forming region with an O7 star is located away from the center (Hourglass Nebula).

NGC 6611 A rich cluster of OB stars is observed away from the brightest part of the nebula. Our preliminary analysis of the ionization structure of the nebula (unpublished) suggests that the hottest O4–O6 stars of the cluster are several parsecs away from the bright part of the nebula that is a site of ongoing formation.

NGC 1931 A trapezium of stars is located in the brightest part of the nebula but away from the main cluster of PMS stars.

NGC 2264 The exciting star S Mon is surrounded by a cluster containing 9 stars and is located against the center of the nebula. Two clusters of PMS stars are in the brightest regions of the nebula and are rather distant from S Mon. A IR source is associated with one of these clusters, which is a new star-forming region.

IC434 The exciting star σ Ori is surrounded by a well-studied cluster of 15 PMS stars (Garrison, 1967).

A similar arrangement of OB and PMS stars is observed also in IR stellar clusters detected in many compact H II regions. A compact H II region itself can be considered as a secondary star-forming region.

All these results allow us to understand better the very complicated structure of the nebulae discussed here.

Signatures of sequential star formation are most prominent in NGC 7538 which contains a classical H II region excited by an O6–O7 star (IRS6), a compact H II region with an O8 star (IRS5), and also three ultra-compact H II regions forming a cluster similar to the Trapezium (NGC 7538G).

A spectroscopic binary O star (S152.2) detected by us against the center of the brightest clump in S152 is a secondary star-forming center in this nebula. Secondary star-forming centers are observed also in the nebulae NGC 2024, S138, S159 and S269, and also in the outer regions of the nebulae S93 and S186 (Glushkov *et al.*, 1979), S128 (Ho *et al.*, 1981), S235 (S235AB), NGC 2068 and NGC 2023.

In a number of the nebulae (S83, S226, NGC 1931 and NS14), OB stars represent the core of a cluster, and they form Trapezium-like system.

However, most of the nebulae discussed here contain a single OB star surrounded by a cluster of the σOri type. The nebula S252A apparently represents an early stage of the evolution of these clusters which, possibly, accompany exciting stars of the nebulae S61, 148, 152, 156, 235, 257 and 297.

5.2 Electron density, absorption and the structure of the nebulae

Electron density is one of the basic indicators of the age of a nebula. For all ultra-compact H II regions, $N_e \simeq 10^4$–10^5 cm^{-3} (Churchwell, 1990), whereas in compact

H II regions the electron density is smaller by an order of magnitude. All of the objects considered here (except three of them) have average N_e[S II] values of order 500 cm^{-3}; at the same time, all the objects have regions with N_e[S II] $> 10^3$ cm^{-3}.

The values of N_e[S II] do not always characterize the true density of the ionized gas. As follows from our optical observations, the ultra-compact H II regions MonR2, NGC 7538G, S157B and W3 (IRS5) have N_e[S II] $< 10^3$ cm^{-3}, although their densities obtained from radio observations are about 10^5 cm^{-3}; this happens because the bulk of the ionized gas does not emit forbidden lines.

Regions with $N_e > 3 \times 10^3$ cm^{-3} are observed in S138, 146, 226 and some other nebulae in the radio range; for these regions N_e[S II] $< 5 \times 10^2$ cm^{-3}. This can be explained by the following two reasons: either these regions are completely screened out by absorbing clouds or they contain several clumps with $N_e \simeq 10^5$ cm^{-3} but a small filling factor leads to the values of N_e inferred from radio observations being a few times 10^3 cm^{-3}. The following third possibility applies to S226: dense regions revealed in the radio range may emit in optical [S III] lines, since the exciting stars are O5–O6, so that [S II] lines are very weak. Dense [S III] regions may be present also in the nebulae NGC 6618, S83 and S128.

Low values of N_e[S II] are typical of the nebulae NGC 2068 and NGC 2023, but here the Lc emission flux of their exciting stars (in comparison with that produced by O stars) is too weak to provide sufficiently high ionization degree of the molecular gas as to make them bright in both radio and optical ranges. This applies also to some nebulae with B0.5 stars.

Comparison of optical and radio data, especially at angular resolutions of order or better than about 5″ reveals one more important feature of the nebular emission. Some regions having N_e[S II] $\simeq 10^3$–10^4 cm^{-3} do not emit in the radio range. These are plausibly neutral clumps that reflect the light of bright, ionized regions of the nebulae. This effect is most pronounced in NS14 where only a small central region is ionized, whereas the whole nebula has an emission spectrum. S106 also provides a good example of this effect. This probably occurs, to a certain extend, in all H II regions containing dense molecular gas and dust. However, one should take into account that regions with low emission measure may avoid to be detection in radio observations at high angular resolution.

Inspection of individual regions with known electron densities in Hα photographs shows that some bright regions are indeed clumps with densities 10^3–10^4 cm^{-3}. At the same time, there are bright regions with densities 10–100 cm^{-3}. Their high brightness is a result of their large size along the line of sight. Some of these regions look like clumps, for example those in NGC 2024, NGC 7635 and NGC 1931. In these cases we apparently observe rarefied filaments extended along the line of sight. Many high-density regions are hardly distinguished in Hα photographs, and they probably represent localized regions of absorbing matter. In many objects, the highest density and the highest extinction are observed at interfaces between ionized regions and various molecular features.

Long ($\simeq 0.8$ pc), narrow ($\simeq 0.07$ pc), dense ($\simeq 10^5$ cm^{-3}) molecular fingers recently revealed at some depth in the Orion Nebula (Rodriguez–Franko *et al.*, 1992) are especially interesting. They extend radially from the region of the Trapezium and BN/KL object. We note in this connection that numerous dark channels, especially well pronounced in M20 and NGC 2024, have their vertices in the vicinities of their respective exciting star. It seems quite plausible that these are molecular fingers observed at later evolutionary stages. Another reason for the very complicated structure of some dark channels might be shadows cast by molecular fingers and cloudlets. Many dark cones observed in S228, NS11 and, especially, in NGC 6618 and NGC 6611 also can be shadows of dense molecular features.

Inspection of the POSS plates indicates that many of the objects in our list are surrounded by rings of absorbing material. Therefore, the values of A_v obtained by us for individual nebulae contain contributions from absorption in interstellar matter, in molecular gas/dust and HI envelopes of the nebula, and also from a highly variable absorption within the nebulae. The comparison of A_v and A_v^* indicates that all stars in compact H II regions are surrounded by disks whose material makes the stellar brightness as low as 10^m. Such an additional absorption in the neighborhood of the exciting stars occurs in S148, 152, 226, 235 and NGC 2068. For the other nebulae $A_v > A_v^*$. This can be understood as an indication that the exciting star is located near the nebula boundary closer to the observer. Of source, the amount of absorption for an exciting star depends on the spatial orientation of the rotation axis of the circumstellar disk, its density, and the degree of its integrity. All these factors also affect the observed structure of the nebula. If S106 were observed along the rotation axis of IRS4 and its disk, the exciting star would be visible in optics and the nebula would resemble IC1170.

Observations of the last few years indicate that only rough outlines of the future studies of star-forming regions are being established now. Observations of the Orion Nebula at the HST and in the radio range at angular resolution $0''.1$–$10''.0$ imply an extremely complicated structure that incorporates dense ($\simeq 10^5$ cm^{-3}) clumps of ionized gas, both related to stellar envelopes and independent of stars, and thin ($\simeq 0''.1$–$1''.0$) dense filaments representing either jets from individual stars or narrow strips extended along interaction regions where ionized gas and stellar winds meet with molecular filaments and condensations (Hester *et al.*, 1991; Yusef–Zadeh, 1990; Felli *et al.*, 1993).

5.3 The exciting stars

Based on the analysis of the spectra of the nebulae and their exciting stars, we have suggested approximate empirical criteria for the determination of the spectral classes of the exciting stars from the observed nebula spectra. These criteria are especially important for those H II regions where the exciting stars are not visible in optics. Indirect estimates of the stellar spectral class are very contradictory. For example, the following estimates are available for the compact H II region NS11: about B2 from IR observations, about B0.5 from radio data (White and Gee, 1986) and about O7 from optical observations.

The criteria suggested here may become more important once a theoretical model of the nebular emission is available, which incorporates the joint action of the stellar wind and Lc emission on intensities of the emission lines.

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Analysis of the spectra of the nebulae which have a strong continuum, i.e. those containing large amounts of dust, shows that hydrogen emission lines of the Balmer series are invisible or very weak, in some cases starting from Hβ. This happens not only because of a strong absorption within the nebula, but also because the stellar absorption spectrum reflected by dust is superimposed on the nebula emission spectrum. This effect should be taken into account when the Balmer decrement is estimated and the intensity ratio of hydrogen and forbidden lines is analyzed.

The spectral class of a star exciting the emission of a given nebula, as obtained by different authors at different times and also implied by our observations, indicate that the spectral class may vary by 1 or 2 subclasses in average. This variation is especially strong for the Trapezium stars in Orion. We believe that practically all stars associated with nebulae are spectrum variables with deviations within one subclass around the mean value.

Our observations performed with the 6m telescope confirm this conclusion. These observation also imply that practically all stars are spectroscopic binaries. Extensive observational series obtained at high spectral resolution are required to clarify the character of the variability and to obtain more precise estimates of the spectral class. This is a very complicated task, since the brightness of the exciting stars in our list is $12–20^m$.

6 CONCLUDING REMARKS

We have presented generalized results of our observations of the spectra of 40 diffuse nebulae. Ten of them are compact H II regions, the others are intermediate evolutionary stages differing from classical H II regions in smaller sizes and greater electron densities. Many of them contain secondary star-forming centers both within the nebulae and in their immediate neighborhood.

A considerable amount of information on the spectra of diffuse nebulae has been collected, but most of this information is based on the analysis of 2 or 3 sections across a nebula with the width of the spectrograph slit of $1–4''$, whereas the minimum size of a nebula is about $1–2'$. Therefore, this should be considered only as a preliminary stage of collecting the optical data.

In fact, we have information on the nebula emission in a restricted spectral range centered on the Hα and Hβ lines. The blue and ultraviolet spectral ranges are only poorly explored. The continuum is largely unexplored. Photometric studies of the intensities of weak emission lines are available only for a few bright nebulae. Thus, quantitative estimates of the degree of ionization and determinations of chemical composition should await future studies.

Stars in the nebulae remain practically unexplored. We are confident that investigations of these stars will provide no less information on the nature of the nebulae than a direct study of the diffuse matter.

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