THE ASTRONOMICAL SCHOOL ON GALAXIES FOUNDED BY ACADEMICIAN G. SHAJN AT THE CRIMEAN OBSERVATORY

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The first director of the Crimean Astrophysical Observatory academician G. A. Shajn actively studied the interstellar medium in the Galaxy and galaxies in the 1950s. He and his followers showed first that the interstellar medium consisting of gas and dust is important component of galaxies. Observational evidence in favour of the star formation from interstellar clouds were obtained.

INTRODUCTION

The first director of the Crimean Astrophysical Observatory (CrAO) academician Grigory Abtamovich Shajn at the end of his life in the 1950s actively studied the interstellar medium of the Galaxy. This work initiated studies under his leadership of the Galaxy and galaxies using data on gaseous nebulae, dust clouds, and stars. Observations were carried out near the settlement Simeiz – one of the resorts of the Great Yalta. At the beginning of the 1950s, G. Shajn and V. Gase fulfilled an imaging survey of the Milky Way in the hydrogen H_α emission line. Their program was published in [40, 45]. Before this survey, only about 80 emission nebulae were known. The Simeiz catalogue by V. Gase, G. Shajn [10] has listed 301 objects, the majority of which were new diffuse emission nebulae. Their "Atlas of diffuse gaseous nebulae" [47] was one of the most popular surveys at the time before the completion of the Palomar Sky Survey.

G. Shajn and V. Gase [48, 49] showed that the interslellar matter is important component of the Galaxy. It was thought before the 1950s that emission nebulae are stable objects with the irregular morphology. G. Shajn and V. Gase [45, 46, 51] found emission nebulae with different morphological properties. They discovered a principally new class of nebulae – supernova remnants, which are not excited by stars. An example is the Cygnus Loop. They found a filamentary nebula of such type, S 151 in Auriga [50]. S. Pikelner [20] proposed that an excitation mechanism of the supernova remnant is the collision of the intersected shocks.

G. Shajn and V. Gase suggested first the idea that the expansion and directed motion in diffuse nebulae are influenced by the Galactic interstellar magnetic field. G. Shajn [41–43] has shown first from the observations that the interstellar matter, consisting of gas and dust with a frozen magnetic field, is an important component of the Galaxy.

G. Shajn and V. Gase [48, 49] found first that diffuse gaseous nebulae have masses of hundreds and thousands solar masses and that nebulae are not ejected from the stars.

A wealth of data on the emission nebulae allowed Shajn to suggest the idea about their evolution [41, 42]. He found that gaseous nebulae are linked with the groups of young stars [43, 52]. Their evolution proceeds on different discrete spatial scales: about 10 pc, 100 pc, and several hundred pc [38, 43, 52]. In particular, G. Shajn [44] studied a large region in the spiral arm near the Sun. This region of 1000 pc in size, contains diffuse matter with the frozen magnetic field and can represent a place for future star formation.

Short reviews of the emission nebulae studies by G. Shajn and V. Gase are made by S. Pikelner [21, 22] and V. Pronik [34].

STRUCTURE OF THE GALAXY

Using the data of more than 300 diffuse gaseous nebulae with their exciting stars, V. Gase [9] first prepared the sketch of patches of the three nearest to the Sun spiral arms of the Galaxy in Orion, Perseus, and Sagittarius. A general picture of her sketch remains valid up to now.

To search for exciting stars of emission nebulae new catalogues of stars of early spectral type were needed. G. Shajn [40] described the research plan for this study: "Partly for that purpose spectroscopic observations of stars brighter than 12.2^m, by means of a 400 mm camera equipped with a 410 mm prism (6.9°) are being carried

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out at the Simeiz Observatory. Star magnitudes, colour indices, and colour excesses are also being determined, mainly in the regions with emission nebulae.” A short summary of the Shajn’s Plan was given by G. Shajn and V. Gase [45]. This plan was later transformed to the Plan of the Galaxy structure studies.

The Shajn’s Plan was fulfilled by 12 researchers. Seven researchers worked at the Crimean Astrophysical Observatory: E. Brodskaja, R. Ikhsanov, I. Kopilov, L. Metik, I. Pronik, P. Shajn, G. Sharapova. The remaining researchers were from various regions of the Soviet Union: A. Alksnis from Riga, N. Grigoreva from Moscow, A. Numerova from Leningrad, R. Raznik from Uljanovsk, V. Straizys from Vilnius. Stars of different spectral types were studied in 13 sky regions of $10^\circ \times 10^\circ$ along the Milky Way. The observational data for those regions were obtained in the Crimea. The galactic longitudes of the regions are shown at the bottom of Fig. 1 by thick horizontal bars. The general characteristics of the regions, authors, and years of publishing of results are shown in Table 1, where column 1 is a number of the region; columns 2 and 3 are right ascension α and declination δ at the epoch 1950.0; columns 4 and 5 are galactic longitude l' and galactic latitude b' in the old coordinate system; column 6 is the size of the region in square degrees; column 7 is the number of studied stars N; column 8 is the number of the O–B stars n; column 9 is the authors and years of publishing of the paper. The detailed references may be found in the reviews by I. Pronik [25] and by I. Pronik, L. Sharipova [33].

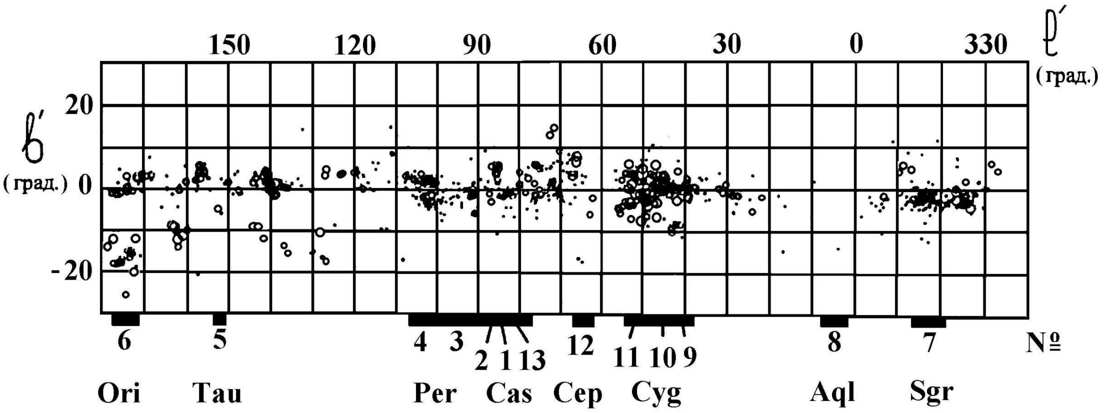

Figure 1. Distribution of the stars W–R, O, B0, B1 (dots) and emission nebulae (circles) in the Galaxy superposed by the grid with the old galactic coordinates (G. Shajn, V. Gase [52]). Thick horizontal bars and numbers at the bottom show longitudes of the Shajn’s Plan regions

Table 1. The characteristics of the studied Shajn’s Plan regions in the Milky Way

No.	α 1950	δ 1950	l'	b'	Area sq. degr.	N	n, type	Authors, years of publishing
1	2	3	4	5	6	7	8	9
1.	0^h00^m	$+66^\circ30'$	86°	+5.0°	15	605	44, O–B5	Raznik, 1963–1967
2.	0 30	+62 00	89	0.0	45	2816	500, O–B5	Brodskaja and Grigoreva, 1964; Grigoreva, 1964–1967
3.	1 25	+61 50	95	+0.5	85	3206	731, O–B5	Kopilov, 1953; Brodskaja, 1960–1961
4.	2 30	+58 00	104	−1.0	48	3340	835, O–B5	Brodskaja and Shajn, 1958; Brodskaja, 1961
5.	5 32	+22 00	153	−3.6	4	86	6, O–B5	Brodskaja, 1963
6.	5 32	−05 30	177	−17.6	56	1572	57, O–B6	Kopilov and Straizys, 1963; Straizys, 1963
7.	18 10	−15 00	343	−0.6	68	3914	276, O–B3	Pronik, 1958–1963
8.	18 54	+05 00	6.1	−0.7	36	1492	79, O–B3	Pronik, 1960–1961; Grigoreva *et al.*, 1971; Pronik and Sharapova, 1971
9.	20 05	+36 00	41.0	+1.1	36	5000	120, B0–B5	Numerova, 1958–1961
10.	20 16	+42 30	47.6	+3.0	30	952	952, O–A	Ikhsanov, 1959–1960
11.	20 44	+45 00	53	+0.6	42	3404	60, O–B2	Metik, 1960–1963
12.	21 24	+58 30	67	+5.6	25	2060	67, O–B5	Alksnis, 1958–1961
13.	23 25	+61 30	81	+0.8	64	5752	400, O–B5	Brodskaja, 1953–1956

More than 35 000 stars were studied and more than 4 000 stars among them were classified as the new O–B stars. The regions with the extinction in the optical range as high as 25^m per kpc were found in these studies. These data could be used to study the structure of dark matter, composition of clusters and associations of O–B stars in spiral arms in Orion, Perseus, and Sagittarius.

The Crimean archives include several hundred plates obtained with the H_α filter, more than 400 plates of $10° \times 10°$ regions with objective prism spectra of stars brighter than 13^m, and more than 100 plates of $10° \times 10°$ regions with the direct images of stars brighter than 18^m.

Reviews of the results on the Galaxy structure obtained in the course of the Shajn's Plan were made by I. Kolesnik [12], I. Pronik [25], and by I. Pronik and L. Sharipova [33].

A review of studies on the distribution of the interstellar extinction in the Galaxy in the wavelength range $0.1-5$ μm and the discussion on the shape of the reddening curve was made by V. I. Burnashev [4].

THE PROBLEM OF STAR FORMATION

The Shajn's Plan included also the star formation studies. G. Shajn and V. Gase [45] wrote: "It is very much possible that the role of the interstellar matter will also appear very considerable in the just outlining hypothesis on so-called protostars."

The interest to star formation was increased in 1940s–1950s. The question was whether stars are forming in the recent epoch or they were formed simultaneously with the Universe. If yet, how they are formed and whether it is possible to look at protostars. V. Ambartsumyan [1] showed that star associations are unstable, star formation is taking place in them continuously "almost on our eyes". It means that the age of luminous stars is by a factor 10 less than the age of the Universe.

B. Bok and E. Reilly [2] suggested that small dark objects, globulae, can represent an evolution stage preceding of star formation. A minimum extinction in globulae was estimated to be equal to 2^m–5^m.

B. Vorontsov-Velyaminov [56] wrote that the matter, from which young hot supergiants were formed, was beforehand disposed in spiral arms and thus there is a chance to reveal it.

The Shajn's Plan was fulfilled in the 1950s, 49 papers were published, 47 of them – before 1966. One of the important results of these studies were evidence for a link of early type stars and dark matter. The complexes of emission nebulae, young stellar clusters, and luminous stars were found to show the enhanced dust extinction. The distribution of O–B5 stars and dark clouds in the Galaxy were studied by E. Brodskaja [3] and I. Kopilov [13]. These are the two first papers in the frame of the Shajn's Plan. Figure 2 displays one of the striking examples of the dust extinction as high as $\Delta A_v = 5^m$ in the region No. 1 observed by R. Raznik [35].

R. Ikhsanov [11] studied 22 young stellar clusters connected with emission nebulae and showed that the presence of a large amount of dust is one of the important characteristics of very young nebulae. In particular, the extinction in the Orion nebula is found to be as high as $A_v \sim 9^m$–10^m.

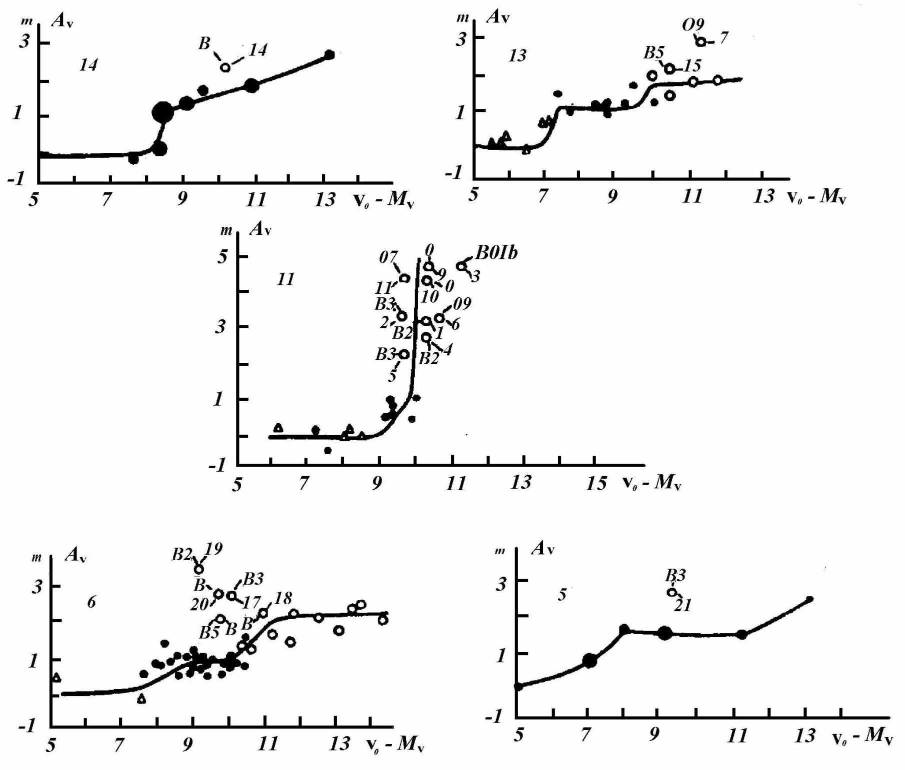

Figure 2. Dependence of the extinction A_v on the distance modulus v_0–M_v for five parts of the region No. 1 studied by R. Raznik [35]. Figures at the top show number of the part of the region No. 1

Table 2. A hierarchy of sizes of star forming regions and complexes of young stars and emission nebulae

Star forming regions (P. Solomon *et al.* [54])		Emission regions (Shain's Plan)	
object	size, pc	object	size, pc
clusters	10–15	separate nebulae	8–50
associations	30–200	groups of nebulae	100
superassociations	500	large groups of nebulae	to 300
complexes of star formation	1000	detail of the regular magnetic field near the Sun	1000

R. Raznik [36, 37] studied the reddening of O5–B3 stars in 31 young open clusters and found that many of them exhibit anomalously high colour excesses.

It is believed now that a progress in understanding of star formation processes was achieved after the discovery in 1963 of the hydroxyl radio line at the wavelength of 18 cm [57], and later discoveries of the lines of other molecules. "Only in 1970, it turned out finally that cold molecular gas is collected in massive clouds which serve as the "maternity hospitals" of stars" [55]. All molecules exist in the dense clouds connected with the dust, which protect molecules from the destruction by interstellar ultraviolet radiation.

However, a genetic link of gas nebulae, dust clouds, and clusters of young stars was observationally established one decade before the discovery of the hydroxyl radio line. It was justified in all papers by G. Shajn and V. Gase (for example [53]) and by those who fulfilled the Shajn's Plan. A basic view on the star formation remains unchanged since those studies and can be summarized as follows:

1. Stars are formed by groups in the regions of accumulation of gas nebulae [52].
2. Clouds, from which stars are formed, are essentially more massive than the star clusters [48, 49, 52].
3. A hierarchy of the characteristic sizes for star forming regions [54] is similar to a hierarchy of the sizes discovered by G. Shajn [39] for the gas–star groups (Table 2).
4. Stars are formed in the cocoons consisting of very dense interstellar matter. It was shown that the O–B stars in young star clusters are often surrounded by more dense dust clouds, than the stars of the later spectral types.
5. Clusters of giant clouds with H_α emission and young clusters associated with them are located in the spiral arms of galaxies [39, 43, 48, 52].

Thus, it is possible to express a confidence that the observational evidence for genetic connection of young stars, emission diffuse, and dark nebulae obtained by G. Shajn and other astronomers under his leadership will be assessed at its true value in the history of star formation studies.

INDIVIDUAL GALAXIES

Studies of individual galaxies have been begun by G. Shajn at the Crimean Astrophysical Observatory in the 1950s. He revealed 82 diffuse nebulae and more than 200 luminous clumps of stellar nature in spiral arms of the galaxy NGC 598 (M33) [39]. The clumps were brighter than 16^m or absolute magnitude -5.5^m. G. Shajn showed that the population I stars in M33 are numerous.

It was shown that the masses of 13 gaseous nebulae in the galaxy M33 and of three nebulae in the galaxy M31 are in the range from $0.5 \cdot 10^4\,M_\odot$ to $3 \cdot 10^5\,M_\odot$ [49]. G. Shajn concluded first that interstellar matter in galaxies is dominant component by mass inside the complexes of gaseous nebulae and young stars.

In the 1960s, the observations of normal and active galaxies at the Crimean Astrophysical Observatory have been carried out under the leadership of A. Severny, V. Nikonov, and K. Chuvaev [5] using the imagetube and 5–9 filters in the spectral region 3700–7100 Å in the prime focus of the 2.6-m Shajn telescope. Several thousand plates were obtained for more than 200 extragalactic objects and are collected in the archive of the Crimean Astrophysical Observatory. Some of the results obtained using these observational data are outlined in this section.

K. Chuvaev and I. Pronik [6] studied more than 200 clumps consisting of blue star forming regions and gaseous nebulae inside spiral arms of the Sc galaxies NGC 628, NGC 4254, and of the galaxy pair NGC 5194/5195. Figure 3 shows spiral arm patches revealed in the interacting pair NGC 5194/5195. Sizes, luminosities, masses, and colour–colour diagrams of the clumps in all galaxies were obtained in this study.

I. Pronik [23] showed that a star population of bars in SB galaxies is younger in comparison with that of the central regions of normal galaxies of the same morphological types. It was interpreted that current star formation processes in bars are more active.

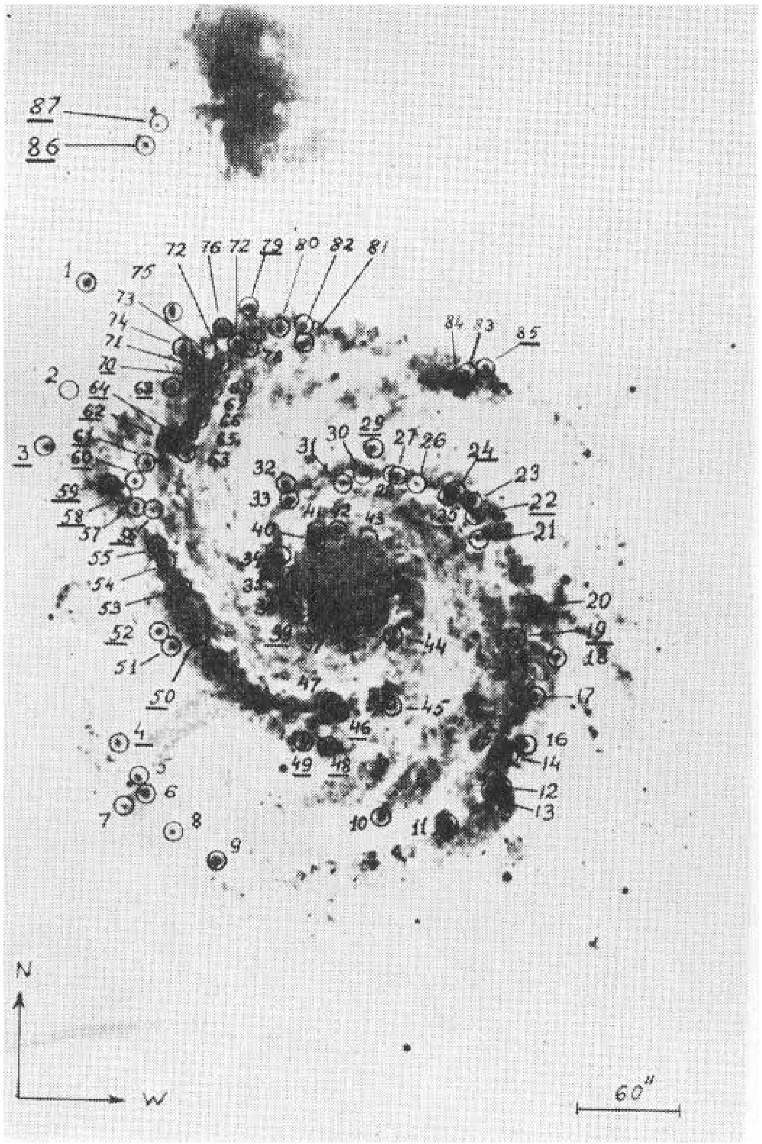

Figure 3. Spiral arm patches in the NGC 5194/5195 system (K. Chuvaev and I. Pronik [6]). The image was obtained with the filter centered on the H_α line. The underlined figures correspond to the blue patches without H_α emission

It was shown that for each galaxy the larger the distance of the spiral arm clump from the galaxy center is the bluer this clump is in the colour–colour diagram. The galaxies with the bluest central regions contain also the bluest patches of spiral arms [26].

The multicolour photometry of 31 superassociations with gaseous nebulae in the peculiar pair of galaxies NGC 4038/4039 (the "Antennae") was carried out by O. Dobrodij and I. Pronik [7]. It was shown that the superassociations of the Antennae differ from star forming regions in normal galaxies by their higher sizes, higher masses of neutral hydrogen, and higher masses of young star populations. The properties of superassociations of NGC 4038/4039 are close to those of blue dwarf galaxies which have the excess of blue hot stars.

L. Metik and I. Pronik [14–19] carried out the multicolour photometry of nine elliptical (E) galaxies containing Seyfert nuclei: Mkn 34, Mkn 42, Mkn 69, Mkn 205, Mkn 279, Mkn 290, Mkn 298, NGC 1275, and NGC 7469. It was shown that the rate of current star formation in the central regions of galaxies with Seyfert nuclei is appreciably higher compared to that of normal galaxies of the same morphological types.

Star-like objects near the nuclei of the Seyfert galaxies NGC 1275, NGC 7469, Mrk 290, Mrk 298, 3C 120, and 3C 390.3 having signs of interaction with the nuclei were revealed (see Fig. 4). Absolute magnitudes of these objects are about -16^m–17^m, and their masses are about $10^8\,M_\odot$. Spectral energy distributions of some of the revealed objects is similar to that of quasars or galaxies with the ultraviolet excess in spectra.

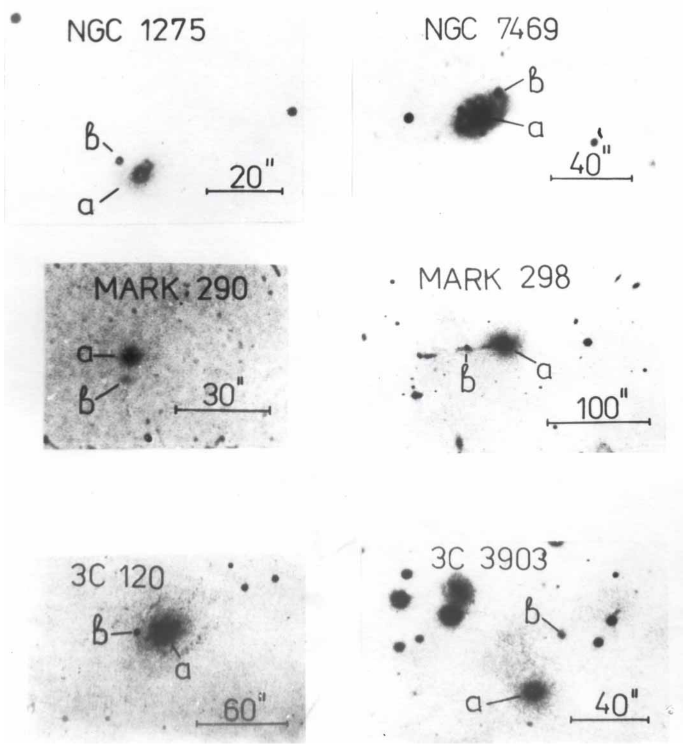

Figure 4. Star-like objects which were revealed by I. Pronik and L. Metik [30] near the active galactic nuclei; **a** – nucleus of a galaxy, **b** – a star-like object

Analysis of the 6-m telescope spectra of some compact objects supported the results of the multicolour studies [14–16, 18, 19, 30].

I. Pronik, V. Prokof'eva, and L. Sharipova [31] performed the *BVR* photometry of compact objects near the nuclei of Seyfert galaxies revealed by L. Metik and I. Pronik (Fig. 4) using the TV-complex of the 0.5-m telescope of the Crimean Astrophysical Observatory. It was shown that these objects consist of both early-type and late-type stars.

L. Metik and I. Pronik [17] studied physical and kinematic characteristics of components of 47 galaxy pairs of different morphological types. Three groups of pairs were revealed. They differ by relations of radial velocity differences and colour indices of pair members. It was concluded that there is a difference in the origin and/or evolutionary phase of these groups.

The study of the emission regions in galaxies was performed using not only multicolour photometry but also the spectra obtained with the high speed spectrograph at the prime focus of the 2.6-m Shajn telescope. Emission regions and stellar populations of the central regions of 17 E, S, and Irr normal galaxies were studied by I. Pronik [24]. Figure 5 shows the dependence of equivalent widths of the H_α line on the colour indices $(U-B)$ for normal and Seyfert galaxies. One can see that the dependence for the normal galaxies is continuously prolonged by Seyfert galaxies. It was concluded that the brightness of the H_α emission of each central region is caused by the colour index of the star population rather than by the morphological type of the galaxy. Thus, the main mechanism of H_α emission in central regions of normal galaxies is recombination of hydrogen which is ionized by ultraviolet radiation of blue stars.

In the 1960s, V. Pronik with E. Dibay from the Crimean Laboratory of the Sternberg Astronomical Institute (Moscow), just after the identification in 1963 by M. Schmidt of emission lines in the spectrum of the star-like high-redshift object (QSO) 3C 273, began a new page in the study of galaxies in the Crimea – a study of active galactic nuclei (AGNs) with the brilliant star-like nuclei and very broad emission lines in their spectra. The history of the AGN study at the Crimean Astrophysical Observatory is described by Yu. Efimov *et al.* [8].

I. Pronik, N. Merkulova, L. Metik, and V. Pronik [27] studied stellar populations in central regions with sizes of 0.2 – 20 kpc of 20 normal galaxies of morphological types from Irr to E using the spectra in the range 1800–3400 Å. These data were obtained with the space telescope "Astron". The analysis of the observed line and continuous spectra permits one to conclude that the main contribution into the near *UV* spectrum of the central regions of Sc and Irr galaxies and extragalactic H II regions with O–B associations is caused by O, B, and A main sequence stars. It was shown that the near *UV* spectrum of the central regions of early morphological type

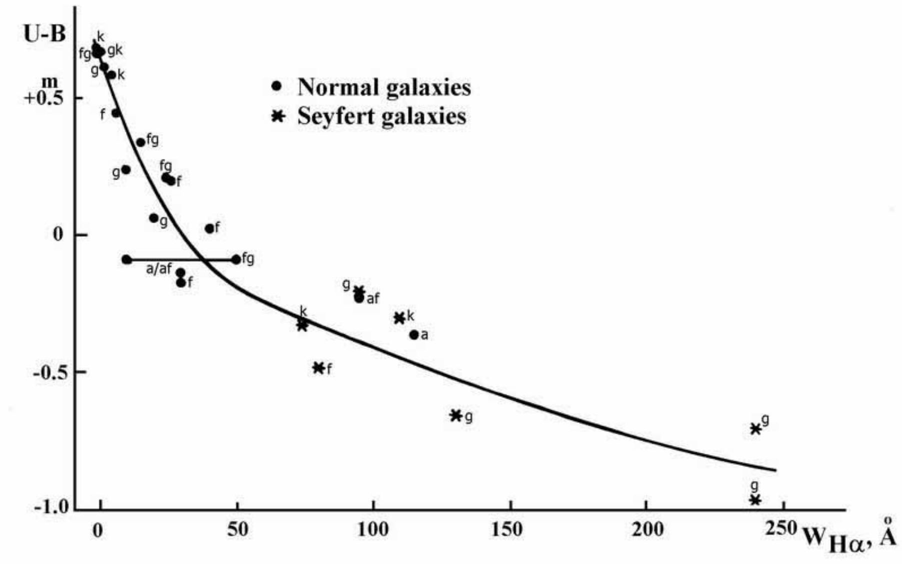

Figure 5. Dependence of equivalent widths of the H_α emission line on the colour indices $(U-B)$ for the central regions of normal and Seyfert galaxies according to the paper by I. Pronik [24]. Small letters indicate the classes after Morgan

galaxies is caused mainly by stars of the horizontal and post-asymptotic branches of the Hertzsprung–Russell diagram. Spectra of two Markarian galaxies and two extragalactic H II regions with O–B associations were interpreted as showing the regions of current star formation [28, 29].

A review on the star formation characteristics of central parts of normal and peculiar galaxies was published by I. Pronik and V. Pronik in 1988 [32]. A classification of these regions according to the level of current star formation (the weak, moderate, and intense types) was proposed:

1. Central regions with weak star formation are observed almost in normal E and S galaxies. Their surface brightness decreases from the center to periphery according to the power law $B \sim r^{-1/4}$ and colour index decreases too. The colour variation gradient decreases from E to the lenses of S galaxies. The main photometric and spectroscopic parameters vary smoothly along the sequence of morphological types, reflecting smooth variations of star contents.
2. Centers of moderate star formation cannot be revealed from the structure inhomogeneities of the central regions, but only from the spectroscopic and photometric characteristics. In general, they differ from the characteristics of central regions of normal galaxies. Bars of SB galaxies, members of interacting galaxies, and most of Markarian galaxies which are, in general, bluer than the central regions of normal galaxies show examples of centers of moderate star formation. Bluer colours in all these cases favour a higher stellar content of earlier spectral types compared to the normal galaxies.
3. The regions of intense star formation are observed as large H II regions named "hot spots". Short intense episodes of star formation are present in M82, in the pair of interacting galaxies NGC 4038/4039, and in galaxies with high infrared emission. Observations showed that more than 40% of nearly normal galaxies have high emission at 10 μm. Stellar populations of all these galaxies can be interpreted in the frame of models including the bursts of star formation.

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