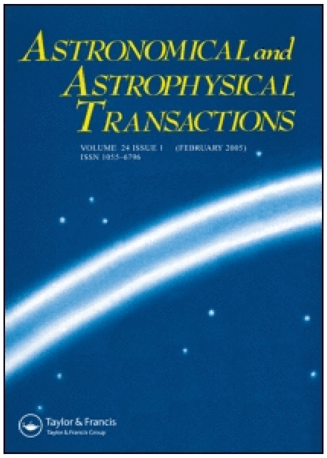

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SPECTRAL STUDY OF PLANETARY NEBULAE AT THE FESSENKOV ASTROPHYSICAL INSTITUTE

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SPECTRAL STUDY OF PLANETARY NEBULAE AT THE FESSENKOV ASTROPHYSICAL INSTITUTE

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A review of the long-term spectral investigation of galactic planetary nebulae carried out at the Fessenkov Astrophysical Institute within the last 20 years is presented. The main results are briefly discussed.

Keywords: Planetary nebulae; Emission line spectra; Age classification

1 INTRODUCTION

Planetary nebulae are always objects favoured for investigation. Firstly, they are at a certain stage of stellar evolution. On the other hand, gaseous envelopes represent a so-called natural laboratory with various and, sometimes, quite exotic physical conditions. A continuous increase in the number of discovered planetary objects is proof of the unremitting attention given to these objects. For example, *The Catalogue of Galactic Planetary Nebulae* published by Perek and Kohoutek (1967) contains 1036 objects, and the quantity of planetary objects included in *The Catalogue of Galactic Planetary Nebulae* published by Acker *et al.* (1992) increased to 1820. At the Fessenkov Astrophysical Institute the first spectrograms of planetary nebulae were obtained in 1968, and some time later a study of these remarkable objects became one of the Institute's main scientific subjects.

The main goal of our work was the search for objects at an earlier stage of evolution of a planetary nebula. It is clear owing to theory that such objects have to be rather dense and compact, and so most probably they may be found among planetary objects with small angular sizes. Thus, in 1970, at the beginning of this work, it was planned to carry out detailed spectral observations of a group of star-like objects in order to determine their physical parameters and evolution status. It was proposed to work out some observational criteria that would enable us to distinguish quickly the youngest planetary nebulae. Firstly a sample of 30 small objects was chosen, but then the primary list was increased little by little, and today it contains 74 objects. Besides that, a group of large planetary nebulae of low surface brightness was also included in the observational programme. Most of these are very old and

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represent the opposite end of the evolution scale. The others appeared to be interesting because of some peculiarities. The main results of this long-term work are presented in this paper.

2 SPECTRAL OBSERVATIONS

The main volume of observations has been carried out with a slit spectrograph, which was equipped with a three-cascade image tube and attached to 70 cm AZT-8 telescope. Special astronomical films (A-600, Kodak 103 OaG, etc.) were used as the flux receiver until 1998, and ST-4 and ST-7 charge-coupled devices (CCDs) have been employed since 1999. Various gratings and objective lenses provided a spectral range from 3700 to 8600 Å with dispersion in the range 10–300 Å mm^{-1} and with a spectral resolution $\Delta\lambda = 0.8$–20 Å. Wavelength calibration was made using a laboratory source with He I, Ne and Ar emission lines. Various spectral regimes were used depending on the aim of observations. For example, a dispersion of 300 Å mm^{-1} enables us to study the range up to about 4500 Å and is suitable for an initial diagnostic spectrogram or for measuring of a star's continuum. A moderate dispersion regime ($D = 100$–150 Å mm^{-1}) provides a wavelength range up to about 2200 Å and a spectral resolution of about 4 Å and is widely used for identification of emission lines and for measuring their intensities. Finally high-dispersion spectrograms were utilized to examine line profiles and to estimate radial velocities. A more detailed description of the spectrograph can be found in the paper by Denissyuk (2003) in this issue.

TABLE I List of Small Planetary Nebulae Studied at the Astrophysical Institute.

Number	*Designation*	*Name*	*Reference(s)*	$10^{-3}T_{eff}$	*log(EM)*
1*	000.1 + 17.2	PC12	Kondratyeva (1984b)	36	5.80
2*	0007.0 + 04.1	Th4-4	Kondratyeva (1998)	51	5.58
3	007.2 + 01.8	Hb6	Kondratyeva (1978)	58	6.90
4	008.3 − 01.1	M1-40		107	7.0
5	011.0 + 06.2	M2-15	Kondratyeva (1978)	50	6.10
6*	013.1 + 04.1	M1-33	Kondratyeva (1978, 1983)	56	6.00
7*	013.3 + 32.7	Sn1	Kondratyeva (1978, 1983, 1984a)	60	5.5
8*	015.9 + 03.3	M1-39	Kondratyeva (1984b, 1994)	30	6.00
9	016.4 − 01.9	M1-46	Kondratyeva (1984b, 1994)	33	5.60
10	017.7 − 02.9	M1-52		73	5.03
11*	018.0 + 20.1	Na 1	Kondratyeva (1978, 1983)	51	5.80
12	019.4 − 05.3	M1-61	Kondratyeva (1984c)	43	6.00
13	019.7 + 03.2	M3-25		52	7.02
14	021.7 − 00.6	M3-55		35	5.36
15	021.8 − 00.4	M3-28		50	6.36
16	026.3 − 02.2	Pe1-16		111	5.89
17	028.5 + 01.6	M2-44	Kondratyeva (1984c)	63	5.05
18	031.0 − 10.8	M3-34	Kondratyeva (1984c)	60	5.0
19	032.7 + 05.6	K3-4		60	5.35
20	038.2 + 12.0	Cn3-1	Kondratyeva (1979, 1983, 1994)	32	6.80
21*	039.5 − 02.7	M2-47	Kondratyeva (1978, 1983)	39	6.00
22	043.0 − 03.0	M4-14		113	5.96
23*	043.1 + 03.8	M1-65	Kondratyeva (1978, 1983, 1994)	33	6.70
24	048.0 − 02.3	PB 10		93	6.45
25	048.7 + 01.9	He2-429	Kondratyeva (1978, 1983)	40	6.00
26	049.4 + 02.4	He2-428		36	4.84
27	053.3 + 24.0	Vy1-2	Kondratyeva (1978, 1983)	59	5.43
28	055.5 − 00.5	M1-71	Kondratyeva (1978, 1983)	38	6.50
29*	055.6 + 02.1	He1-2	Kondratyeva (1978, 1983, 1994)	33	4.60
30	059.0 − 00.1	He2-446	Kondratyeva (1975)	20	5.50

TABLE I *Continued.*

Number	*Designation*	*Name*	*Reference(s)*	$10^{-3}T_{eff}$	*log(EM)*
31	061.9+41.3	DdDm 1		35	7.02
32	066.9−05.2	PC24		52	5.44
33*	068.3−02.7	He2-459	Kondratyeva (1981, 1983, 1994)	30	7.09
34	069.2+02.8	K3-49		30	5.38
35	069.6−03.9	K3-58		87	6.11
36	071.6−02.3	M3-35	Kondratyeva (1978)	39	6.60
37*	075.0−04.1	He2-468	Kondratyeva (1987)	35	
38*	079.9+06.4	K3-56		103	5.53
39	086.5−08.8	Hu1-2	Kondratyeva (1978, 1983)	110	6.26
40	089.3−02.2	M1-77	Kondratyeva (1984a, 1994)	22	6.26
41*	089.8−00.6	Sh1-89	Glushkov and Kondratyeva (1986)	115	5.53
42	093.5+01.4	M1-78		34	7.14
43*	095.2+00.7	K3-62	Kondratyeva (1978, 1983)	45	7.07
44*	096.3+02.3	K3-61	Kondratyeva *et al.* (1980); Kondratyeva (1983)	50	5.13
45	097.6−02.4	M2-50	Kondratyeva (1978)	53	5.30
46	098.1+02.4	K3-63	Kondratyeva (1978, 1983)	115	5.08
47	107.6−13.3	Vy2-3	Kondratyeva (1978, 1983, 1984a)	40	5.00
48	107.7−02.2	M1-80	Kondratyeva (1978, 1983)	85	5.16
49*	108−05.1	K4-46	Kondratyeva (1992)	60	
50	111.8−02.8	HB12		40	6.40
51	118.0−08.6	Vy1-1	Kondratyeva (1978, 1983, 1984a)	40	5.54
52	119.6−06.7	Hu1-1	Kondratyeva (1978, 1983)	58	6.11
53	129.5+04.1	K3-91		36	0.00
54	130.4+03.1	K3-92		50	5.28
55	142.1+03.4	K3-94		94	5.57
56	146.7+07.6	M4-18		22	7.58
57	147.8+04.1	M2-2		45	5.20
58	147.4−02.3	M1-4		60	6.97
59	151.4+00.5	K3-64		60	5.40
60	166.4−06.5	CRL618		30	5.57
61*	184.0−02.1	M1-5	Kondratyeva (1978, 1983, 1984a)	35	7.31
62*	211.0 3.5	M1-6	Kondratyeva (1979, 1983)	33	6.60
63*	212.0+04.3	M1-9	Kondratyeva (1978, 1983)	45	7.30
64	221.7−05.3	M3-3		60	6.00
65*	227.6+05.6	M1-16	Kondratyeva (1978, 1983)	61	6.65
66	228.8+05.3	M1-17	Kondratyeva (1978, 1983)	54	6.69
67	232.4−01.8	M1-13		60	5.60
68*	232.8−04.7	M1-11	Kondratyeva (1979, 1983, 1984a)	33	7.00
69*	234−00.1	M1-15	Kondratyeva (1984a); Balbekov *et al.* (1988)	22	—
70*	234.9−01.4	M1-14	Kondratyeva (1978)	36	6.60
71	235.3−03.1	M1-12	Kondratyeva (1979, 1984a)	30	7.40
72	278.8+04.9	PB 6		114	5.16
73	342.1+27.5	Me2-1		104	5.44
74*	343+11.1	H1-11	Kondratyeva (1978, 1983)		42

At the end of the 1960s, when our observational programme began, only the brightest planetary nebulae were studied in detail. Our spectral apparatus enabled us to obtain spectrograms of rather faint objects with a limited surface brightness equal to a magnitude of 16–16.5 per squared arcminute. Thus planetary nebulae previously unstudied were chosen for further work. A final list of objects studied is presented in Tables I and II. Designations and names are in accordance with the work of Acker *et al.* (1992) or Perek and Kohoutek (1967) and are given in the second and third columns. The asterisks in the first column mean that the very first detailed study of object's spectrum was made at the Astrophysical Institute. The fourth column contains references to papers published by the Institute. Of course many of these objects were also studied by other researchers. The corresponding references may be

TABLE II List of Planetary Nebulae (with $R \geqslant 6''$) Studied at the Astrophysical Institute.

Number	*Designation*	*Name*	*Reference*	$10^{-3}T_{eff}$	*log(EM)*
1	006.0 + 03.1	M1-28		56	5.82
2	010.8 + 18.0	M2-9		32	5.06
3	036.0 + 17.6	A43	Kondratyeva (1980)	110	3.72
4	040 + 00.4	A53	Kondratyeva (1980)	72	6.22
5	045.6 + 24.3	K1-14	Kondratyeva (1980)	116	2.50
6	045.4 − 02.7	Vy 2-2		43	5.40
7	047.1 − 04.2	A62	Kondratyeva (1980)	56	5.46
8	059.7 − 18.7	A72	Kondratyeva (1980)	111	3.23
9	061 + 08.1	K3-27	Kondratyeva (1980)	107	3.73
10	069.2 + 03.8	K3-46	Kondratyeva (1980)	40	5.93
11	075.7 + 35.8	Sa4-1		60	4.55
12	079.6 + 05.8	M4-17		59	5.82
13	081.2 − 14.9	A78	Kondratyeva (1980)	120	3.10
14	084.9 + 04.4	A71	Kondratyeva (1980)	74	2.12
15	093.3 − 02.4	M1-79		66	6.04
16	103.2 + 00.6	M2-51		70	4.69
17	103.7 + 00.4	M2-52		115	5.60
18	104.4 − 01.6	M2-53		50	5.90
19	112.9 − 10.2	A84	Kondratyeva (1980)	78	4.00
20	114.0 − 04.6	A82	Kondratyeva (1980)	70	4.00
21	116.2 + 08.5	M2-55		45	5.25
22	121.6 − 00.1	BV5-2		50	3.89
23	122.1 − 04.9	A2	Kondratyeva (1980)	102	3.64
24	131.4 − 05.4	BV5-3		64	3.83
25	133.1 − 08.6	M1-2		39	5.52
26	144.3 − 15.5	A 4		78	3.79
27	174.2 − 14.6	H3-29		114	5.02
28	195 − 00.1	Sh2-266	Kondratyeva (1975)	22	2.90
29	197.2 − 14.2	K1-7		60	4.24
30	204.0 − 08.5	A13	Kondratyeva (1980)	75	2.05
31	208.5 + 33.2	A30	Kondratyeva (1980)	115	1.30
32	210 + 01.9	M1-8	Kondratyeva (1978)	79	4.87
33	219 + 01.1	K1-9		45	2.35
34	238.0 + 34.8	A33	Kondratyeva (1978)	94	2.09

found in *The Catalogue* published by Acker *et al.* (1992) and in some later publications. The aim of this paper is to show the contribution of our Institute to the investigation of planetary nebulae; thus we concentrate attention on the work of our researchers. Data about the effective temperature of the central star and the brightness of a nebula (log(EM) where EM is the emission measure) are given in the last two columns.

3 RESULTS OF SPECTRAL OBSERVATIONS

Altogether about 3500 spectrograms of planetary nebulae were obtained during 1970–2001. Data obtained for bright objects, which were used as standards, are not included in this quantity.

3.1 Nebular Spectra

As a rule, about 30 spectrograms were obtained for an object. Various exposures allow us to cover a rather wide dynamic range of intensities. The wavelength sensitivity dependence of our optical system was examined using an energy distribution of standard stars and bright planetary nebulae, such as NGC 7027, with known emission line fluxes. Relative intensities of all recorded emission lines were measured for all objects. The precisions of our data are 10%, 15% and 50% for moderate, strong and faint lines respectively. The absorption constant $C(\mathrm{H}\beta)$ was calculated as usual, using the $\mathrm{H}\delta$-to-$\mathrm{H}\beta$, $\mathrm{H}\gamma$-to-$\mathrm{H}\beta$ and $\mathrm{H}\alpha$-to-$\mathrm{H}\beta$ ratios. The [N II] and [O III] line intensities were used to estimate the electron temperature, and such traditional ions as [S II], [O II], [C III] and [Ar IV] gave the values of electron densities. The majority of these data have already been published; the results for the other objects are in preparation.

Besides the main physical parameters, some other additional data were obtained. The fluxes $F(\mathrm{H}\beta)$ in absolute energy units were measured for 12 planetary nebulae. The chemical abundance of 19 objects (Kondratyeva, 1983) was estimated in the usual manner, described, for example, by Barker (1978). Profiles of H I broad emission lines in the spectra of Sh2-266, He2-446, M1-15 and Th4-4 were investigated. The width of profiles was determined with a precision of 0.1–0.3 Å and the radial velocities were evaluated for some objects (Kondratyeva, 1992, 2001; Balbekov *et al.*, 1988).

3.2 Spectral Study of Central Stars

Low-dispersion spectrograms were used to study the central star's continuum. Measurements of the intensity were carried out in some chosen points, which were free of a nebular emission. All necessary corrections (atmosphere's extinction, wavelength dependence of sensitivity) have been made. A flux calibration was performed through observations of standard stars (ζ Tau, 62 Tau, 55 Cyg and ζ Cas) (Kharitonov *et al.*, 1978). The energy distribution in absolute units for a wide wavelength range was obtained for 15 objects (Kondratyeva, 1984a, 1994). Several central stars have emission line spectra. Seven Wolf–Rayet (WR) central stars and three symbiotic objects were revealed. It appeared that all WR nuclei are connected with low-excitation planetary nebulae. Values of the effective temperature $T(\mathrm{He\ II})$ and/or $T(\mathrm{H\ I})$ were obtained for all central stars studied. In some peculiar cases, when objects have broad emission lines, the slope of the energy distribution of the continuum was used to estimate T_{eff}.

4 PHOTOMETRIC STUDY OF PLANETARY NEBULAE

Our spectrograph has a special device, that projects the area of the sky under study on to the input photocathode of the image tube and allows us to obtain photographic images of the studied object and surrounding stars. As a rule such photographic images are taken for each object simultaneously with the spectral observations. They may be used to control by eye the comparison of an object's stability with surrounding stars and, if necessary, to measure photometrically a star's magnitude. Our colour system is dictated by the characteristics of the photocathode of the image tube. It is centred at 5460 Å and has a pass band at 800 Å, that is close to Johnson's V band. The sizes of the projected field of sky are $250'' \times 250''$ (or $150'' \times 150''$); the scale of image was about $15''$ (or $9''$) per millimetre. Exposure times of 10–30 s are sufficient to obtain good quality images of stars up to magnitude 20.

In order to determine the brightness of an object, differential photometry relative to the comparison stars was carried out. The intrinsic precision of results was of magnitude 0.03–0.07 depending on the star's magnitudes. Primary standards, for example those from the catalogue published by Kharitonov *et al.* (1978) or from that of Acker *et al.* (1992), are used for absolute calibration. A photometric variability was recorded for the objects K4-46, K1-9 and Th4-4 (Kondratyeva, 1992, 2001).

5 MODEL CALCULATIONS

Several models for the evolution of planetary nebulae were employed for calculations at the Astrophysical Institute, using the tracks recorded by Schonberner (1979, 1981) for star's parameters. The values of the mass M^* of a star and the mass M_n of the envelope were set as initial parameters. The envelope was considered to expand with time with a velocity $V = 20\,\mathrm{km\,s^{-1}}$. The start of expansion was accepted as coinciding with the zero Schonberner moment and corresponded to a stellar temperature of 5000 K. For each definite moment t the external radius R_n of a nebula is determined as Vt. A nebula was divided into 20–40 thin layers. A column density for each of these layers was calculated from the expression

$$N(R) = \frac{A}{a^3}\left(\frac{R}{a}\right)^2 \mathrm{e}^{-(R/a)^2}, \tag{1}$$

where R is the current radius, $a = R_\mathrm{n}/2 = Vt/2$ is an evolution parameter and the value of A for a nebular mass was determined from

$$M_\mathrm{n} = 4\pi \int_0^{R_\mathrm{n}} N(R) R^2 \mathrm{d}R. \tag{2}$$

Then a system of ionization–recombination equations for H^0, H^+, He^0, He^+ and He^{2+} and a thermal balance equation was solved. As a result, the ionization degree, intensities of emission lines, Hβ fluxes, physical parameters and space configuration of the envelope were obtained for various stages of evolution. All calculations were carried out for $M^* = 0.64M_\odot$, $0.60M_\odot$ and $0.57M_\odot$ and $M_\mathrm{n} = 1.0M_\odot$, $0.3M_\odot$, $0.2M_\odot$ and $0.1M_\odot$. An analysis showed good agreement between model and observational data; in other words the results are reliable (Vilkoviskii *et al.*, 1983).

6 DISCUSSION

Now from all the observational parameters of the studied objects let us try to analyse them in terms of an age classification.

To start with, we present a few statistics: 74 small objects ($R_\mathrm{n} \leqslant 6''$) were studied, nine of which appeared to be not planetary nebulae: there are three symbiotic stars, one H II region, two Be stars and three very-low-excitation objects among them. The evolution status of the other planetary nebulae will be considered below.

A plot of log(EM) *vs.* T_eff is suggested with this aim in mind. The EM is the analogue of the surface brightness of an Hβ line. It does not depend on distance and may be calculated if the Hβ line flux and the angular size of an object are known. On the other hand the EM may be expressed through nebular parameters:

$$\mathrm{EM} = N_\mathrm{e}^2 R\varepsilon \ \mathrm{pc\ cm^{-6}}, \tag{3}$$

where R is the radius of the emission zone and ε is the nebular filling factor. Values of $F(\mathrm{H}\beta)$ are taken from the work of Acker *et al.* (1992) and Kaler (1990). T_eff was determined by the present author, and data from Preite-Martinez *et al.* (1991) and Kaler (1990) are also included.

The data from all the studied objects are given in Figure 1 and are denoted by various symbols: peculiar objects by full triangles, planetary nebulae with the very strong [N II] emission by full or open squares, and all other planetary objects by full circles. Model calculations

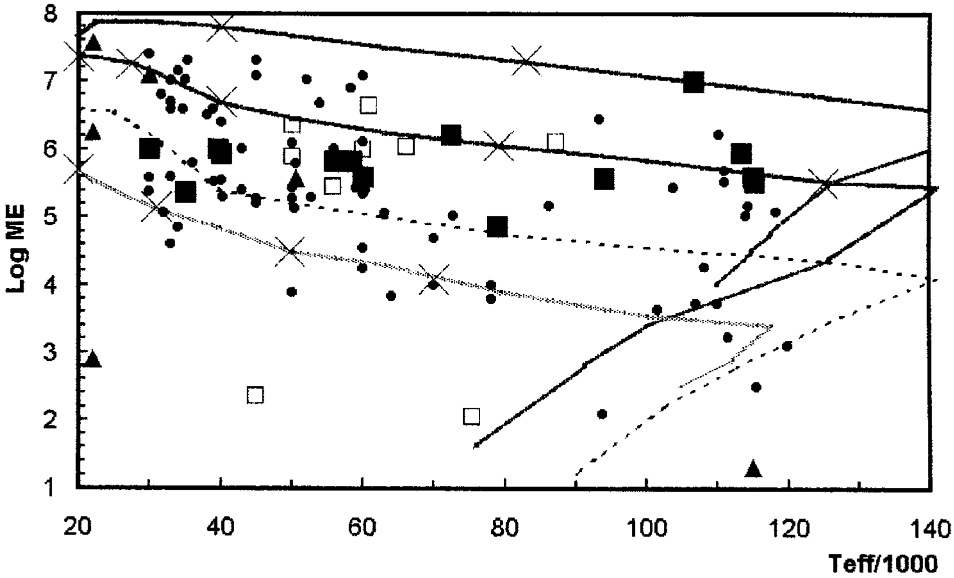

FIGURE 1 log(EM) *vs.* $T_{\rm eff}$ for the studied objects.

(Vilkoviskii *et al.*, 1983) were used to determine the effective temperature of the central star and the surface brightness of the nebula corresponding to a single age scale. There are some empirical relations between the mass of a nucleus and the mass of a nebula; the more massive central star has a more massive envelope. Figure 1 shows the curves for most real models: $M^* = 0.64M_\odot$ and $M_{\rm n} = 0.3M_\odot$; $M^* = 0.60M_\odot$ and $M_{\rm n} = 0.3M_\odot$ or $0.1M_\odot$; $M^* = 0.57M_\odot$ and $M_{\rm n} = 0.1M_\odot$. The rate of an evolution of a star depends on its mass. The points corresponding to ages of 2000, 3000, 4000 and 6000 years are denoted by crosses on the curves for $M^* = 0.64$ and $0.60M\odot$, and those for ages of 3000, 4000, 6000, 8000 and 10,0000 years on the curve for $M^* = 0.57M_\odot$.

It follows from the theory that a young nebula would be a dense compact object with a cold central star. In practice, extended objects of low density with cold nuclei and dense objects with hot stars are observed, but those with a density more than $5 \times 10^6\,{\rm cm}^{-3}$ are not found at all.

These facts can be explained if we take into account two main factors.

(i) The rate of stellar evolution depends on the star's mass.
(ii) An object may be identified as a planetary nebula only when [O III] emission appears in the spectrum.

Now let us examine the picture. It may be seen that a massive central star ($M^* = 0.64M_\odot$) during approximately 2000 years achieves $T_{\rm eff} = 40{,}000$ K; at this moment its massive nebula has too high a density, and no [O III] lines are observed in a spectrum. A similar object will be identified as a planetary nebula much later when its density is less than $5 \times 10^6\,{\rm cm}^{-3}$. Such a planetary nebula may be considered as young indeed.

A star with $M^* = 0.6M_\odot$ evolves more slowly; in 3000 years its temperature becomes equal to 30,000 K, and [O III] emission lines appear in the spectrum of the associated nebula. So the age of a group of objects with $T_{\rm eff} = 30{,}000$–$35{,}000$ K which lies between two curves for $M^* = 0.6M_\odot$ is about 3000–3500 years old. These are the youngest planetary nebulae that can be observed around stars with $M^* = 0.6M_\odot$.

The objects at the bottom left of the diagram have low massive central stars. Such a star evolves very slowly (in comparison with the more massive nuclei); thus it reaches a temperature of 30,000 K in approximately 6000 years; and this moment the nebula becomes an extended low-density object. Several similar objects (He1-2, for example) are presented in our diagram, and they are not young at all.

It is clear that our diagram does not indicate the exact age of objects, but it allows us to understand the infinite variety of observable characteristics and to single out really young planetary nebulae. Altogether only 11 planetary nebulae from our list may be considered as young objects. In Table I they are numbers 4, 8, 12, 20, 23, 31, 42, 61, 62, 68 and 71. Three objects, He2-459, M4-18 and M1-77, lie among the planetary nebulae on the diagram although they cannot be classified as members of this class. Two of these are related to the massive objects and the last certainly has a low-mass star.

Almost all the young nebulae have WR central stars with emission line spectra (Kondratyeva, 1994). The nebulae themselves have the following physical parameters: $T_e = 7000$–$9000\,\mathrm{K}$, $N_e = 10^4$–$2 \times 10^4\,\mathrm{cm}^{-3}$, $R = 0.02$–$0.04\,\mathrm{pc}$ and $\log(\mathrm{EM}) = 6.6$–7.4. In accordance with Figure 1, all of these belong to the sequence with $M^* = 0.6M_\odot$. M1-40 is the only exception, because it is connected with the massive star. The absolute age of all named objects is less than 3500 years; in other words they have been observed as planetary nebulae for no more than 500 years.

Some objects, numbers 14, 26, 29, 34 and 60, are connected with cold low-mass central stars. Their characteristics, $N_e \leqslant 10^3\,\mathrm{cm}^{-3}$, $R = 0.10$–$0.18\,\mathrm{pc}$ and $\log(\mathrm{EM}) \leqslant 5.5$, correspond to an age of 6000 years or more.

Now we should mention planetary nebulae with strong [N II] emission, for which $(I(6548 + 6583)/I(\mathrm{H}\alpha) \geqslant 1)$. They are denoted as large full squares in Figure 1. It is seen that these objects lie almost horizontally on the diagram showing that the more massive nebula, the more time is required for forming of low-excitation zone. For $M_n = 0.3M_\odot$ such low-excitation regions are observed up to $T_{\mathrm{eff}} = 100{,}000$–$120{,}000\,\mathrm{K}$. In general such a spectrum cannot be explained in the framework of a photoionization model for a nebula with a normal chemical composition. In some cases, if there are not any other low-excitation emissions except for [N II] in its spectrum an object is considered to be nitrogen enriched. Such planetary objects are denoted by open squares in Figure 1. The other objects that have high intensities of all low-excitation lines (in comparison with Hβ) are denoted by full squares. In order to interpret these spectra, one has to assume, specific conditions or mechanisms to act in a nebula. This may be shock excitation of hydrogen as in H II regions, a deficit of hydrogen in the nebular gas or some other feature.

6.1 Peculiar Objects

6.1.1 Stellar Objects

He2-446. This is a star-like object; its spectrum consists of [O I], [Fe II], Fe II emission lines and broad Hα. The half-width of the Hα profile is 6.62 ± 0.05 Å; the distance between two maxima is 3.4 ± 0.1 Å. It is most probably a Be star with $T_{\mathrm{eff}} = 20{,}000\,\mathrm{K}$ (Kondratyeva, 1975).

M1-15. This object is nearly identical with He2-446 but has a denser shell. Its spectrum consists of [Fe II], Fe II emission lines and broad Hα. The half-width of the Hα profile is 8.1 ± 0.03 Å. Most probably it is a Be star with $T_{\mathrm{eff}} = 22{,}000\,\mathrm{K}$.

Th4-4. Firstly, in 1970–1973 this star-like object looked like M1-15 and He2-446. Its spectrum showed a strong continuum, broad Hα and Hβ emission lines, weak He I emission lines and numerous weak Fe I absorption lines. The full width at half-maximum of the Hα profile is 5.5 ± 0.2 Å, and the wings extend over approximately 10 Å, implying a radial speed of up to 450 km s^{-1}. The object was classified as a Be star with $T_{\rm eff} = 22{,}000$ K. From 1975 the integral brightness of Th4-4 began to fall and He II and [O III] lines appeared in its spectrum with increasing intensity. Up to 1990 the object became fainter by a magnitude of 2.5 and then it entered a rather stable phase. It seems that some increase in visual luminosity is now observed. This object is considered to be a symbiotic nova (Kondratyeva, 2001).

He2-468. This star-like object shows a spectrum which consists of H I, He I and He II emission lines and a late stellar continuum with TiO absorption bands. It is concluded that He2-468 is a symbiotic star (Kondratyeva, 1987).

K4-46. This star-like object shows emission lines of H I, He II, [O III], N III and a strong continuum with TiO absorption bands. The integral brightness of the object changes from magnitude 16.7 up to magnitude 13.2 with a period of 286.6 days. This variable object consists of three components: a late star of spectral class M, a hot ionizing source with $T_{\rm eff} = 50{,}000$–$70{,}000$ K and a gaseous nebula with $N_{\rm e} = 10^5$ cm^{-3}. The photometric variation is demonstrated by the orbital movement of the hotter component (Kondratyeva, 1992).

6.1.2 Nebular Objects

M1-77. This nebula has a size of 7″ (Perek and Kohoutek, 1967). Its spectrum consists of a strong continuum. [N II], [O II], [S II], H I and [Fe II] emission lines, some absorption lines of H, K, Ca II, Ti II, Fe II, O I, S II and absorption bands of TiO ($\lambda = 4582$, 4620, 4770, 4806, 4935, 5005 and 5166 Å). $T_{\rm eff} = 20{,}000$ K was determined by the Zanstra method. Most probably the nucleus of this nebula is a symbiotic star. The data were presented in my dissertation, and the conclusions coincided with those of Sabbadin *et al.* (1983).

M4-18. There are low-excitation emission lines of H I, He I, [N II] ($\lambda = 6548$ and 6583 Å), [O II] ($\lambda = 7319$ and 7330 Å) and [S II] ($\lambda = 6717$ and 6731 Å) in the spectrum of this nebula. The central star has a strong continuum with some emission bands ($\lambda = 4700$, 5166 and 6830 Å). It was classified as WR11 (Goodrich and Dahari, 1985).

He2-459. This nebula has a very-low-excitation spectrum with [N II], [O II], [S II], [O I], and H I emission. The spectrum of the central star shows WR features and some emission bands: ($\lambda = 6125$, 6831 and 7088 Å). $T_{\rm eff} = 20{,}000$ K was determined by the Zanstra method. It was classified as a late WR star (Kondratyeva, 1981).

Sh2-266. Its spectrum consists of [Fe II], Fe II, [O II] and [N II] emission lines and broad Hα. The half-width of the Hα profile is 5.6 ± 0.1 Å. Most probably it is a B star surrounded by an H II region (Kondratyeva, 1975).

K1-9. This nebula of 28″ × 48″ shows emission lines of H I, He II, N III and [O III]. The intensities of all lines except H I have a ring-like distribution with two clear maxima. Hydrogen is observed in the ring and in the central hole. Some hydrogen outflow processes are recorded in the centre of the nebula.

7 CONCLUSIONS

During long-term spectral observations of planetary nebulae carried out at the Astrophysical Institute, data for 108 objects have been obtained. These data and the results of model calculations are used for an age classification of planetary nebulae. It is natural that the presented theoretical curves do not determine the exact age of an individual object because the initial parameters of the model may differ from the characteristics of real objects. These curves allow us to specify criteria for the early stage of evolution of planetary nebulae. It can be concluded that a low-excitation spectrum of a planetary nebula and a low temperature of its central star may be used as such criteria in most cases, with the following exceptions.

(a) Ionization of a massive ($M_\mathrm{n} = (0.5\text{–}1.0)M_\odot$) dense nebula requires about 1500–2000 years: during this time a central star, if it is massive ($M^* = 0.64M_\odot$), reaches a rather high temperature, about 60,000 K. Nevertheless such an object may be considered as a young planetary nebula. The earlier stages of evolution of a similar object if observed are identified as not a planetary nebula.

(b) A central star of low mass ($M^* = 0.57M_\odot$) may achieve an effective temperature of 30,000 K in 6000 years; only then will [O III] emission lines appear in its spectrum, and the object will be identified as a planetary nebula. It is evident that such an object is not a young planetary nebula, in spite of the low stellar temperature.

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