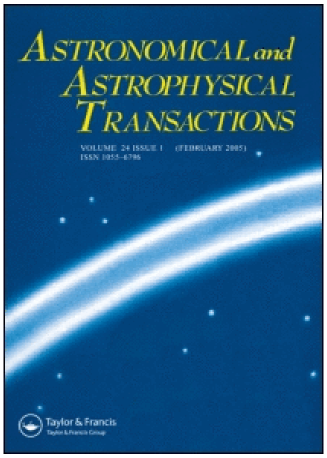

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A search for spectral variations of planetary nebulae and related objects

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A search for spectral variations of planetary nebulae and related objects

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The results of long-term spectral observations were used to search for changes in planetary nebulae and emission-line stars. A significant increase in the degree of excitation is found for two objects: M1-6 and M1-11.

Keywords: Planetary nebulae; Variability of spectra

1. Introduction

It is widely known that physical parameters of planetary nebulae and their central stars change gradually during evolution, but these effects are rather difficult to detect in a short time interval Sometimes much more unusual processes, such as the formation of a secondary envelope, jets and so on, take place in planetary nebulae. Similar processes cause appreciable changes in spectra, but these events are rare and unpredictable. In other words it is well-know that planetary nebulae are changing, but these effects are difficult to discover. The problem is more complicated, because results obtained simultaneously but by different workers may sometimes differ substantially. We decided to use the fact that spectral observations of the large group of planetary nebulae and other emission objects have been carried out at the Astrophysical Institute for a long time and with the same equipment. The very first spectrograms were obtained in 1970–1973, and the last observations were conducted in 2004–2005. The aim of this paper is to search for any variations in the spectra of chosen objects over 30–35 years. We expected that even small fluctuations in $T_{\rm eff}$, $T_{\rm e}$ or $N_{\rm e}$ in some young objects can affect essentially the intensities of forbidden lines. We also hoped to find any traces of fast dynamic processes, such as a jet, if they occurred within the specified period.

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2. The series of objects

Objects of different types and ages were chosen for this study. There are three classical planetary nebulae of high and moderate excitation (K3-58, K3-3 and M1-5), three low-excitation planetary nebulae (M1-6, M1-11 and M1-12) and M1-77. The last object has a very-low-excitation spectrum with [O II], [N II] and [S II] emission lines, and weak emission and absorption lines of neutral metals. It was identified as a young planetary nebula in [1]. Later, some irregular changes in brightness and radial velocity were found in [2, 3]. Our observations showed that there are TiO bands in the spectrum of M1-77, and it was considered to be a nebula around a symbiotic star [4]. In addition, three emission objects were included in our programme: MWC 137, M1-15 and He2-446.

3. Observations

All observations were been carried out by the author with the 70 cm telescope of the Astrophysical Institute (Almaty, Kazakhstan). We used a slit spectrograph, equipped with a three-cascade image tube until 1998, and with a charge-coupled device matrix ST8 since 1999. A series of gratings and objective lenses provided a spectral range from 3700 to 8200 Å, with a dispersion in the range of 20–200 Å mm and with 0.3–1.1 Å pixel after 1998. Wavelength calibration was performed using a laboratory source of He I, neon and argon emission lines.

The earlier database was obtained in 1970–1975, and most of the results (but not all) were published. Later, observations of objects were continued but quite irregularly until 2005.

4. Observational data for the planetary nebulae

At the first stage of our study we compared the results of the earliest and the latest observations. One or two rows of data for the middle of the specified period were included as well (table 1). The ratios of $I(\text{O III}, 4959 + 5007\text{ Å})/I(\text{H}\beta)$, and $I(\text{N II}, 6548 + 6583\text{ Å})/I(\text{H}\alpha)$ were used as the initial criteria. These lines were chosen because firstly, as a rule they are the strongest in the spectrum and, secondly, the influence of interstellar absorption on these ratios is minimal. The designation of the objects, observation date and ratios of line intensities are given in the first to fourth columns of table 1. Corresponding references are presented in the last column. Our unpublished results are denoted AFI.

One can see that the line ratios for most of the objects in table 1 do not show significant changes, *i.e.* the ratios of the maximal to minimal values do not exceed 1.05. Incidentally this result confirms the reliability of our method of observations and measurement. However, the spectra of two objects (M1-6 and M1-11) have undergone essential changes: I(O III, $4959 + 5007\text{ Å})/I(\text{H}\beta)$, increased during the specified period by 40 and 110 %, respectively. A slightly smaller increase in this ratio (about 14 %) is noticed in the spectrum of K3-58. Below we shall consider the spectral changes of M1-6 and M1-11 in detail. In table 2, three results of spectral observations for these objects are presented. The year of observation is given in the first row; the next row contains references. All values of emission line intensities have undergone 'dereddening'.

The last six rows contain the available parameters of nebulae and central stars: EW, the equivalent widths; $\log[F(\text{H}\beta)]$, logarithm of the absolute flux at Hβ (in erg cm^{-2} sec^{-1}); N_e, the electron density determined from the [S II], 6717 Å-to-6731 Å line ratio, T_e, the electron temperature calculated from the [N II] line ratio and/or [O III] line ratio; T_{eff}, the temperature

Table 1. Spectral data for the chosen planetary nebulae.

Name	Date	I(O III)/I(Hβ)	I(N II) /I(Hα)	Reference
K3–58	1974–1975	14.5 ± 2.0	1.73 ± 0.24	AFI
	1988	15.2 ± 1.5	1.62 ± 0.16	[5]
	2004–2005	13.3 ± 1.0	1.59 ± 0.10	AFI
M1–5	1972–1973	4.82 ± 0.48	0.44 ± 0.05	[6]
	1971–1973	5.02 ± 0.50	0.43 ± 0.04	[7]
	2004–2005	5.08 ± 0.45	0.44 ± 0.04	AFI
M1–6	1971–1973	1.25 ± 0.12	0.60 ± 0.07	[8]
	1986	1.60 ± 0.16	0.68 ± 0.07	[5]
	2004–2005	1.72 ± 0.11	0.76 ± 0.04	AFI
M1–11	1986	0.10 ± 0.02	0.88 ± 0.10	[9]
	1996	0.14 ± 0.01	0.98 ± 0.10	[10]
	2004–2005	0.21 ± 0.04	0.95 ± 0.05	AFI
M1–12	1975	0.26 ± 0.06	0.74 ± 0.06	[8]
	1993	0.25 ± 0.04		[11]
	2004	0.25 ± 0.03	0.72 ± 0.04	AFI
M1–77	1972–1973		0.37 ± 0.05	AFI
	1983		0.33 ± 0.06	[1]
	1988		0.41 ± 0.05	[5]
	2004–2005		0.41 ± 0.04	AFI
M3–3	1972–1974	11.8 ± 1.2	4.45 ± 0.60	AFI
	1987	11.6 ± 0.9	4.36 ± 0.40	[12]
	2005	12.1 ± 0.8	4.40 ± 0.40	AFI

determined by the Zanstra method. Analysis of table 2 shows that in M1-6 the first essential increase in [O III] intensities took place between 1975 and 1986 and, at that time, changes did not occur in other zones of the nebula. The strengthening of the He I lines began rather later, and a decrease in [S II] was recorded only in 2004. All these facts give evidence of a gradual increase in the degree of excitation of the nebula. However, we do not know the reason for this. Both the temperature $T_{\rm eff}$ of the central star, and the electron density $N_{\rm e}$ in the S^{+}, region seem to be like rather constant. Some other parameters, such as EW(Hβ), and F(Hβ), show

Table 2. Results of spectral observations on M1-6.

Date of observations reference	1971–1975 [8]	1986 [5]	1989–1990 AFI	1995 AFI	1996 [10]	2004–2005 AFI
4101 Å, Hδ	23.6 ± 3.0		25 ± 4			25.2 ± 2.5
4340 Å, Hγ	47 ± 3.0		48 ± 3	47.5 ± 5		44.0 ± 3.2
4471 Å, He I	7.9 ± 1.0					10.1 ± 1.5
4861 Å, Hβ	100 ± 3	100	100 ± 3	100 ± 4	100 ± 2	100 ± 3
4959 Å, [O III]	29.0 ± 3.0		42 ± 4	39.4 ± 4		44.1 ± 2.3
5007 Å, [O III]	86.7 ± 7.7	122	117 ± 7	122 ± 6		128 ± 6.7
6548 Å, [N II]	47.2 ± 3.5		46.4 ± 4.0		45.8 ± 4.1	48.5 ± 3.5
6563 Å, Hα	285 ± 15	285	285 ± 7		286 ± 20	286 ± 11
6583 Å, [N II]	124 ± 10	140	130 ± 11		135.6 ± 11.1	146 ± 8
6678 Å, He I	2.1 ± 0.5		2.3 ± 0.5			4.2 ± 0.4
6717 Å, [S II]	5.4 ± 0.5	1.11	4.8 ± 0.6		5.04 ± 0.5	2.9 ± 0.3
6731 Å, [S II]	7.9 ± 0.7	2.46	8.4 ± 0.9		7.16 ± 0.7	4.2 ± 0.4
EW(H$_{\beta}$)	260 ± 60		187 ± 23		257 ± 20	230 ± 20
EW(5007 Å)			213 ± 23			260 ± 30
log F(Hβ)	−12.20 ± 0.10				−12.269 ± 0.005	
$N_{\rm e}$(S II)	8300 ± 1000		8000 ± 1000		7500 ± 1000	8000 ± 1000
$T_{\rm e}$(N II)	12 000 ± 1000					
$T_{\rm eff}$	⩾30 000					⩾29 300

Table 3. Results of spectral observations on M1-11.

Date of observations Reference	1971–1973 [8]	1984 [13]	1986 [9]	1989–1989 AFI	1996 [10]	1999 AFI	2004–2005 AFI
4101 Å, H_δ	24.2 ± 3.2		23.1 ± 0.5			25.8 ± 2.7	26.4 ± 1.7
4340 Å, H_γ	51 ± 5.2		43 ± 0.6			45.5 ± 4.9	44.0 ± 3.3
4861 Å, H_β	100 ± 3	100	100 ± 4	100 ± 2	100 ± 3	100 ± 4	100 ± 3
4959 Å, [O III]	6.0 ± 2	5.2 ± 2	2.2 ± 0.1	3.4 ± 0.5	3.3 ± 0.04	5.5 ± 0.7	5.3 ± 0.3
5007 Å, [O III]	19 ± 8		6.8 ± 0.2	10.2 ± 1.4	10.4 ± 0.1	15.4 ± 1.9	15.6 ± 0.7
6548 Å, [N II]	62.5 ± 5.5		63.7 ± 2.2	65 ± 6	66 ± 4	69.5 ± 8	65.5 ± 3.5
6563 Å, H_α	285 ± 15	285 ± 7	285 ± 10	286 ± 14	285 ± 10	286 ± 20	285 ± 10
6583 Å, [N II]	186 ± 10	192 ± 5	187 ± 10	190 ± 12	201 ± 10	200 ± 20	204 ± 10
6678 Å, HE I	0.8 ± 0.4		0.85 ± 0.04	1.05 ± 0.10	1.19 ± 0.05	1.1 ± 0.2	1.3 ± 0.1
6717 Å, [S II]	0.42 ± 0.08		0.63 ± 0.04	0.70 ± 0.09	0.46 ± 0.03	0.46 ± 0.03	0.51 ± 0.05
6731 Å, [S II]	0.96 ± 0.15		1.1 ± 0.04	175 ± 30	0.96 ± 0.05	0.95 ± 0.11	1.06 ± 0.08
EW($H\beta$)				18 ± 1.4	173 ± 17	175 ± 20	175 ± 18
EW(5007 Å)					19 ± 2	40 ± 10	30 ± 7
log $F(H\beta)$]	-11.76 ± 0.10	-11.839 ± 0.005	11.85 ± 0.05		-11.781 ± 0.003		
N_e(S II)	10000 ± 2000		4500 ± 500	5100 ± 900	9300 ± 900	8300 ± 900	8300 ± 800
T_e(N II)	10500 ± 1000	9800 ± 1000	10300 ± 400		22800 ± 800		
T_e(O III)			11300 ± 400		22000 ± 800		
T_{eff}	$\geqslant 26\,500$	$29\,000$	$27\,000$				$\geqslant 27\,000$

fluctuations, but without any tendency. It appears that the emission spectrum is more sensitive to the changing conditions in a nebula than the usual methods of parameter estimation.

The spectral data for M1-11 are presented in table 3. In spite of the low precision there is good agreement between our earliest values of [O III] intensities, and the data in [13]. Then some weakening of the [O III] intensities was recorded, and errors were decreased significantly. The intensity of [O III] lines has begun to increase gradually since 1988. Up to now no other lines have show, essential changes. Only the intensity of He I has increased a little. In other words the increase in degree of excitation occurs in only the inner most region of nebula M1-11. Some physical parameters of M1-11 have undergone fluctuations. The fact that T_e(O III), increased twofold after 1986 is very interesting. This may be the result of any dynamic process (shock wave?) in the inner zone of the nebula. On the other hand, the high value of T_e, may be the reason for the strengthening of the forbidden lines. The value of EW(Hβ), is almost constant, but EW(5007 Å) increases in accordance with the intensity behaviour.

5. Spectra of related objects

Three other objects from our list are identified as B[e] stars. Their spectra contain a strong continuum and the Balmer emission lines of hydrogen. In addition, there are the [O I] 6300 and 6364 Å lines in the spectrum of He2-446 and the weak emission lines of Fe II in the spectrum of M1-15 and MWC 137. All three objects are embedded into large H II regions and have infrared excesses due to warm dust. The emission lines Hα, and Hβ, are broad in all three objects.

Filter photometric and high-resolution spectral observations has been carried out in order to study the stellar brightness and profiles of emission lines. The corresponding procedure has been described in detail in [14].

Selective data for these objects are presented in table 4. This information, is not complete, but it allows us to estimate the behaviours of the studied stars.

He2-446, is classified as a B[e] star [15]. It shows a photometric variability within a magnitude of 0.2. There is no correlation between the change in brightness and EW values. One can see that, between 1988 and 1995, EW(Hα), and EW(Hβ), have increased up to two

Table 4. Spectral data for the chosen B[e] stars (FW HM, full width at half-maximum).

Name	Date of observations	EW(Hβ) (Å)	EW(Hα) (Å)	FWHM(Hα) (Å)	V Magnitude	Reference
He2-446	1971–1973	36 ± 5	280 ± 30	6.6 ± 0.4	14.7 ± 0.03	AFI
	1988	35 ± 4	330 ± 30		14.6 ± 0.2	AFI
	1995–1996	70 ± 15	700 ± 40			AFI
	2004–2005	68 ± 7	730 ± 60			AFI
M1-15	1971–1973		2453 ± 30	7.8 ± 0.4		AFI
	1991		230 ± 17			AFI
	2004–2005		245 ± 12			AFI
MWC 137	1971–1973	47 ± 10	300 ± 40	5.5 ± 0.4		AFI
	1977–1980	46 ± 10			11.67–11.98	[15]
	1981		311 ± 15			AFI
	1988	54.7 ± 10	240 ± 25	4.8 ± 0.4		AFI
	1989-1994		254 ± 27	4.6 ± 0.4		[16]
	1993	60 ± 10	295 ± 10			AFI
	1996		550 ± 10		11.2	[17]
	1998	39 ± 10	200 ± 20			AFI
	2004–2005	37 ± 5	196 ± 10	5.0 ± 0.3		AFI

fold. At the same time the full width at half-maximum has remained almost unchanged. The profile of Hα, consists of two components with the following ratio of their intensities: $I_{\rm blue}/I_{\rm red} = 0.70 \pm 0.05$. It may be explained as a result of stellar wind and rotation. Variations in EW are probably connected with the gradual increase in the ionized mass of the stellar envelope.

M1-15, is the faintest of the chosen stars, and thus it has been poorly studied. All that we know are the values of EW(Hα), and thus their changes are within the errors.

MWC 137 is the central star of the H II region Sh2-266. According to [16], it is an evolved B[e] supergiant, probably of B0 spectral class. As is seen from table 4, EW(Hα) and EW(Hβ) show significant changes, as far as the V-magnitude is concerned. The spectral and photometric variabilities of the object may be affected by the change in stellar wind power.

6. Conclusions

Long-term spectral observations of planetary nebulae and some emission-line stars were carried out over 30–35 year. The results were analysed in order to determine any change in these objects. The fluctuations is some emission-line intensities in most objects did not exceed 5%. Essential changes were revealed in two planetary nebulae: M1-6 and M1-11. Significant strengthening of the [O III] and He I lines and weakening of the [S II] line (in M1-6) testifies to the change in physical conditions in the nebulae. It is reasonable to assume that all observable effects are caused by the increase in $T_{\rm eff}$, however, available estimate of this stellar parameter do not confirm this conclusion. In the case of M1-11, sudden increases in $N_{\rm e}$(S II), $T_{\rm e}$(O III) and $T_{\rm e}$(N II) were recorded in 1996. Probably these changes are connected with some dynamic events in the nebula.

Our study of the emission-line stars shows that MWC 137 has undergone photometric and spectral variability. All changes are irregular and have rather small amplitudes. M1-15 appeared to be quite a stable object. He2-446 showed a significant increase in the EW of hydrogen lines, connected probably with the increase in the ionized mass of the circumstellar envelope.

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