Long-term Photometric and Spectral Study of Planetary Nebula Variability

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In 1968 at Crimean Station of Moscow University was started the study of planetary nebula variability. During long-term examination we revealed several planetaries with well – marked variations of the integral *UBV*-brightness, viz.: NGC 6572, IC 4997, NGC 6891, Hu 2-1, and NGC 6543. The photoelectric observations (1968-1996) of seven nebulae were published in three catalogs (Kostyakova 1990, 1991, Arkhipova et al. 1994) and by Kostyakova (1997). The method and analysis were described by Kostyakova et al. (1973).

A systematic spectral study (1972-2004) of the same objects showed also noticeable changes in their spectra. The integral fluxes in the brightest nebular emission lines and in continua of central stars were measured on objective prism spectrograms got with 50-cm Maskutov meniscus telescope *(D/F* = 1: 4). The examined spectral region was ~ 3400-5100 A.

In our spectral study, as in photoelectrical one, we tried to keep common procedure of observations, technique and reduction of material in order to obtain an extended, homogeneous series. We cannot to reveal short-period variations of energy fluxes; our individual published results are averaged through every observational moonless season.

The most remarkable photometric and spectral behaviour was found for the well-known extremely young planetary nebula IC 4997. Over several years (1968-1985) it exhibited a gradual decline in the total *UBV*-brightness which, on the whole, reached 0.4-0.5 mag. This decline had abruptly ceased in 1985-1986, but since the late 1986 till the present days the nebula was brightened almost linearly in all three bands.

Most spectral characteristics of IC 4997 – the brightest emission lines and the continuum of the central star – were found to change in time. Over 1972-1992 an increase of excitation and ionization degrees of the nebula was detected.

The most representative ratio *R* – the ratio of the [OIII] λ4363 and Hγ fluxes, well indicating the excitation degree of nebular spectra, exhibited the greatest change: between 1972 and 1992 its value increased by more than a factor of 3, and had reached a maximum (log *R* = +0.28) in 1992 , whereupon (1993-2004) it began to decrease. It appears, that real maximum could be observed in 1991.

Figure 1 shows the variations of ratio *R* over the last 66 years: from 1938 up to 2004. In addition to our results (filled circles), the data from the published works and surveys (Vorontsov-Vel'aminov 1960, 1961; Liller and Aller 1957; Aller and Liller 1966; Ferland 1979, Feibelman et al. 1979; Purgathofer and Stoll 1981; Feibelman et al. 1992, and Hyung et al. 1994) are plotted (asterisks).

The detailed spectral analysis showed that over the period 1972-1992 the nebular integral electron density increased from $N_e \cong (2\text{-}6) \times 10^5$ cm^{-3} to $N_e \cong (1\text{-}3) \times 10^6$ cm^{-3}, and the integral electron temperature rose from $T_e \cong 12\,000$ K to $T_e \cong 14\,000$ K.

It should be noted, that above estimates of N_e *and* T_e*,* and their temporal variations should be considered as mean, integrated estimates which characterize the object as a whole. Since this nebula has complicated structure (Miranda et al. 1996, 1997), the parameters of its individual components can markedly differ from means.

The changes in continuous spectrum of IC 4997 indicate that the effective temperature of the central star and its ultraviolet flux are increased. The measuring of continuum, together with examination of earlier estimates of T_*, permits to conclude that over the period 1972-1992 T_* was increased from $T_* \cong 40\,000$ K to 60 000 K or even more.

Such rise T_* and thus the rise of the ultraviolet flux from the central star can testify to instability of this star; no doubt, that it had caused the revealed increase of N_e *and* T_e in the nebula.

Our observations showed that intensification of the spectral activity of IC 4997, which started in the late 1960s, appears to have terminated in 1990-1992, while in 1993-2004 the activity began to decrease.

The detailed results of this study, concerning IC 4997 and its variability, are published in (Kostyakova 1999, 2002).

The bright elliptical (~7" $\times$ 16") planetary nebula NGC 6572 had also shown marked fluctuations of brightness and spectrum.

Our photoelectric data revealed that over first ten years of observations (1968-1978) the visual (*V* and *B*) brightness had undergone marked increase, which, on the whole, reached 0.4-0.5 mag. Other authors (e.g. Feibelman et al. 1992) also noted the rapid rise of the nebula brightness over the period 1966-1973: it reached ~ 0.3-0.4 mag in filter *V* and 0.2 mag in *B*. Over following 25 years the visual brightness of NGC 6572 had undergone quasiperiodic (of order of two decades) fluctuations in the range of 0.2 mag.

The examination of spectrum showed that the nebula had demonstrated essential spectral activity over the whole observational period. So, over 1972-2004 the flux in [OIII] λ 4363 become about 1.5 times stronger, whereas the flux in [OII] λ 3727 – about 2 times weaker. Certain increase was observed in the HeI λ 4471 flux: on the whole, it become about 1.5 times stronger. Over the whole period under consideration the above mentioned ratio *R* was almost doubled. All these facts together indicate the increase in the degrees of excitation and ionization in the nebula spectrum.

The rose of spectral activity of NGC 6572 during considered period may be confirmed by the results of Mendez et al. (1988): they have revealed a dramatic intensification of HeII λ 4686 line in the nebular spectrum. The authors supposed that it was caused by the rose of central star temperature.

The analysis of our spectral data, analoguous with that, undertaken by Kostyakova (1999), shows that over the whole period of observations the integral electron density of nebula N_e was approximately increased tenfold: if in 1960s it was of order $n \times 10^4$ cm^{-3}, while over 1972-2004 it rose from

$n \times 10^5$ cm^{-3} to $n \times 10^6$ cm^{-3}. More exact estimation is difficult because of complexity of this nebula (see below).

The integral electron temperature of nebula over the whole observational period changed from $T_e \cong 12\,000$ -13 000 K to $T_e \cong 14\,000$ - 15 000 K., i.e. had increased by ~ 2 000 K. However, in period of maximum activity (1987-1991) T_e could be even higher and could reach 16 000-20 000 K.

The examination of NGC 6572 continuum led to conclusion that the central star become somewhat bluer; that means, its ultraviolet energy flux had increased. We can assume that the effective temperature T_* had increased from ~ 48 000 K to ~ 53 000 K, i.e. increased at least by 5 000 K.

Our observations, made in 2004 (Sept.), showed that majority of spectral characteristics had changed: the brightest emission lines and the flux in continuum became strongly increased. Further observations are need to confirm the reality of this phenomenon.

Novadays is known, that the nebula NGC 6572 has very complicated structure and peculiar kinematics caused, evidently, by different types of winds and collimated bipolar outflows from the central star (Miranda et al. 1999). That confirms the necessity of further monitoring of the nebula and its behaviour.

The nebulae NGC 6891 and Hu 2-1 over the period 1968-2004 have undergone rather irregular fluctuations of the *UBV*-brightness in the range 0.2-0.3 mag. Their spectra are not changed essentially.

The nebula NGC 6543, being observed since 1979, showed a small but monotonous decrease of brightness in *V* and *U* filters.

It is necessarily to note that the nebulae IC 3568 and NGC 6720, suspected earlier to be variable, over the whole period 1968-2004 showed no fluctuations of integral *UBV*- brightness exceeding 0.1 mag. The changes in their spectra are within the errors limits.

Finally, we can conclude, that the studied variable planetaries are in an active stage of their development; therefore, they can serve as tools for examing the evolution of planetary nebulae and their progenitors, and our stellar system as a whole.

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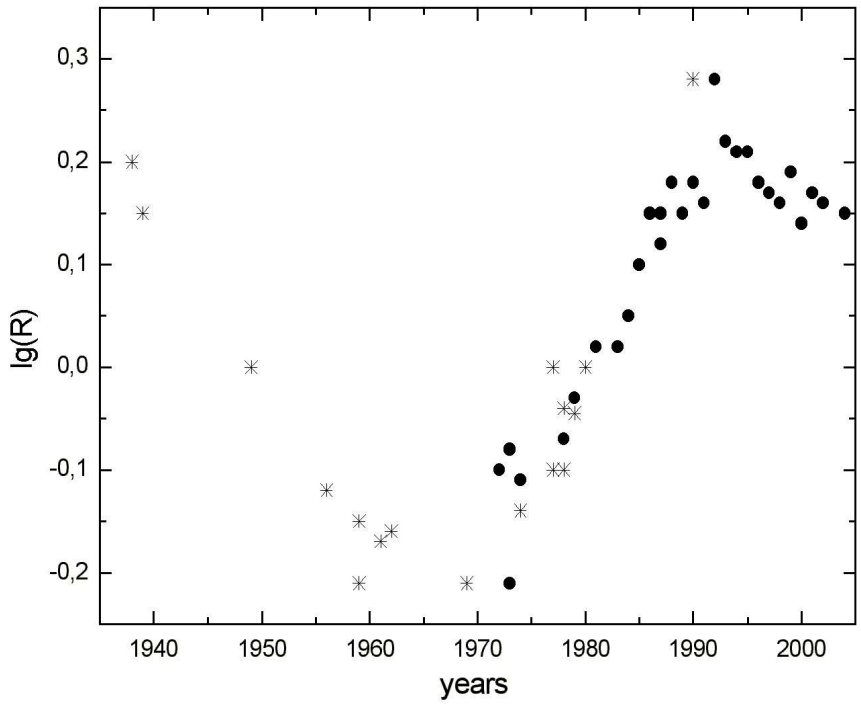

Figure 1. The temporal behaviour of the ratio lg(*R)*=lg(*F(*λ 4363[OIII])/*F*(Hγ)) in
IC 4997 spectrum over period 1938-2004. The filled circles – results of present work, the asterisks – data of other authors and reviews.