ULTRAVIOLET OBSERVATIONS OF PLANETARY NEBULAE

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1. INTRODUCTION

The ultraviolet spectra of gaseous nebulae have for long been arresting the attention of astrophysicists. The 60's saw the first attempts at plotting the expected spectra of planetary nebulae between 3000 and 912 Å (Code 1960; Aller 1961). This was followed by an examination of the expected forbidden lines (about thirty of them) in the ultraviolet, and of their relation to physical parameters (Gurzadyan 1965; Osterbrock 1963). Even more accurate calculations were made for the intensities of stronger lines in highly excited nebulae (Flower 1968). At the same time preliminary estimates were being made of atomic parameters for various transitions - the collision strengths, the probabilities of forbidden transitions, etc. (Czyzak et al. 1968; Garstang 1968). The computations of various models for planetary nebulae also bear on the above studies (Harrington 1968; Kirkpatrick 1970).

Despite such activity of the theoreticians, space astronomy was still in its infancy, and we were in no position to obtain UV spectra of planetary nebulae. This was due to the faintness of these objects (the brightest of them barely attaining eighth magnitude) and to the difficulties in locating and tracking them from spaceship or vertical rocket. Still, upon the first serious attempt in December 1973, the ultraviolet spectrogram of IC 2149 was obtained with the help of the space observatory "Orion-2" installed on board the spaceship SOYUZ-13 (Gurzadyan et al. 1974). Then in 1974 an Aerobee rocket took the electronographic picture of the short-wave spectrum of NGC 7027, and a little later, that of NGC 7662 (Bohlin et al. 1975).

Such are the data at our disposal to date (the beginning of 1977), to which should be added two attempts at wideband ultraviolet photometry of a number of planetary nebulae, made from orbital observatories OAO-2 (Holm 1972) and ANS (Wesselius 1975).

Yervant Terzian (ed.), Planetary Nebulae, Observations and Theory, 79-91.

2. SHORTWAVE SPECTRA OF THE PLANETARY NEBULAE

The spectrum of IC 2149. An ultraviolet spectrogram of the planetary nebula IC 2149 (near β Aur, 10th magnitude, excitation class 4) was obtained at the Cassegrain focus of the 24-cm meniscus telescope, using an objective prism of medium dispersion, and Kodak 103-0-UV film. The accuracy of the guidance system of the stabilized platform of "Orion-2" during the 15 minute exposure time (±7") limited the spectral resolution to about 18 Å at 2500 Å and about 36 Å at 3000 Å. The angular size of the nebula is 6" x 12", which results effectively in a point-like image at the effective focal length, 1000 mm (for the details see Gurzadyan et al. 1976).

During the observing run only one successful spectrum was obtained for this nebula. A tracing of it is given in Figure 1; its short wavelength limit for useful measurements is 2400 Å. Unfortunately, the central part of this spectrum, from 3300 Å to nearly 2800 Å, has superimposed on it the long wavelength spectrum of a nearby faint star, probably red in colour and of photographic magnitude $11^m.5$. IC 2149 is one of the rare nebulae for which the central star is a little brighter ($\sim 9^m.5$ photographic) than the nebula itself ($\sim 9^m.9$), and the continuum from the 07 nucleus was superimposed on the spectrum of the nebula.

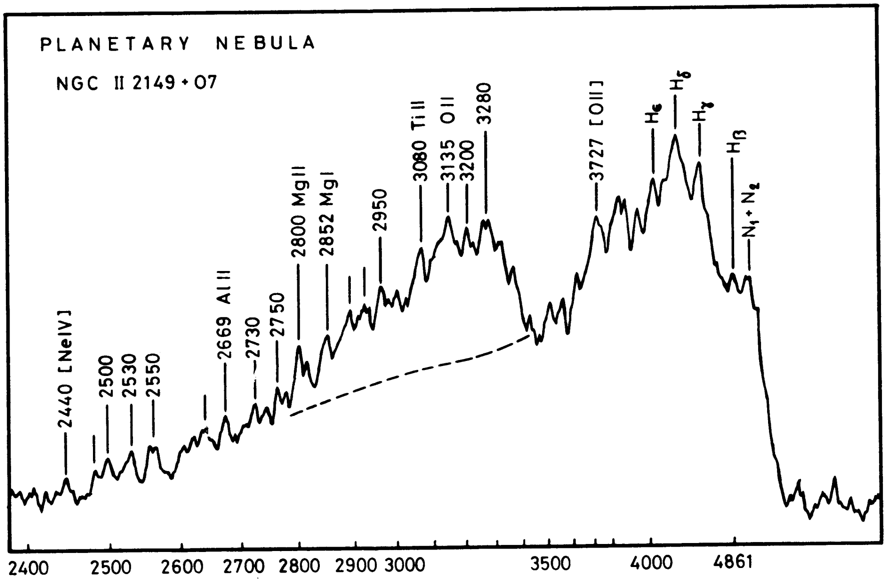

Figure 1. The ultraviolet spectrogram of the planetary nebula IC 2149. The broken line shows the part of the spectrum affected by the nearby faint star.

In spite of the extremely small dispersion at 5000 Å (∿ 3000 Å mm^{-1}), the lines N_1 + N_2 [OIII], H_β and some of the higher terms of the Balmer series are visible on the tracing; λ3727 [OII], which is among the shortest wavelength lines seen in this nebula by ground-based observations (Aller 1951), is distinctly present. Many features are also present, down to 2400 Å, some of which may be due to fluctuations of plate density; others are certainly real emission lines of the nebula. The proposed identifications for some of these lines are given in Table I together with very approximate estimates of their relative intensities (in units $E(H_\beta)$ = 10, we have E (λ3727 [OII]) = 11); a detailed discussion of each follows.

Table I

Ultraviolet Emission Lines in the Spectrum of Planetary Nebula IC 2149

Wavelength λ (Å)	Relative intensity ($E(H_\beta)$ = 10)	Identification
2440	20:	2439 + 2441 [Ne IV]
2670	20	2669 AlII
2800	10	2795 _ 2802 MgII
2850	10	2852 MgI
2945	15	2945 HeI
3080	13	3080 TiII
3135	10	3135 O II

λ2440. This line is identified as λ2439+2441 [Ne IV] ; its presence in the spectra of planetary nebulae had been predicted earlier (Gurzadyan 1965; 1969). The doublet itself arises from the transitions $^2D_{3/2,\ 5/2} \rightarrow {}^4S_{3/2}$ which are isoelectronic with λ3726 + 3729 [OII].

λ2669 AlII. The correctness of this identification is supported by the fact that λ2669 AlII is a resonance transition; its presence as a strong line has been predicted theoretically (Aller 1961). Its intensity is comparable with that of H_β. This will have been the first observation of aluminum in a planetary nebula, if the identification is correct.

λ2800 and λ2852. These are identified as the well-known resonance lines λ2852 MgI and λ2795 + 2802 MgII. Both identifications are believed to be correct but their intensities are a little uncertain (Table I); that of λ2852 MgI is probably overestimated.

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Only in the case of NGC 7027 is there an observation of the very faint λ4575 [MgI] (Aller et al. 1955). The present identification of λ2800 MgII is the first observation of Mg^{+} in planetary nebulae, and it provides additional evidence for the existence of Mg in these objects. These lines are also interesting because they are not forbidden transitions, and are excited by electronic collisions.

λ2945. This is identified as one of the strongest recombination lines of neutral helium. It looks as if another line, λ2829 HeI, is also present.

λ3080. This line we identify as a blend of four lines of TiII at 3066, 3073, 3078, and 3088 Å, all belonging to a quintuplet of TiII.

λ3135 O II. This is identified as one of the strongest recombination lines of ionized oxygen predicted in planetary nebulae (Aller 1961).

Thus, the list of identifications in Table 1 includes nearly all types of emission lines - resonance, forbidden, recombination - each of which is important for information on the physics of planetary nebulae.

Spectrogram of NGC 7027. The short-wave spectrum of the highly excited planetary nebula (class 10) was obtained during one of the launchings of an Aerobee rocket in 1973 (Bohlin et al. 1975), with the help of a 33-cm telescope, using a concave diffraction grating as a dispersing element, and recording the spectrum on Kodak IIa-O after photoelectric intensification and transmission along fibre optics.

In this case, too, only one spectrogram was obtained; its microphotometric tracing is presented in Figure 2. The spectral range fit

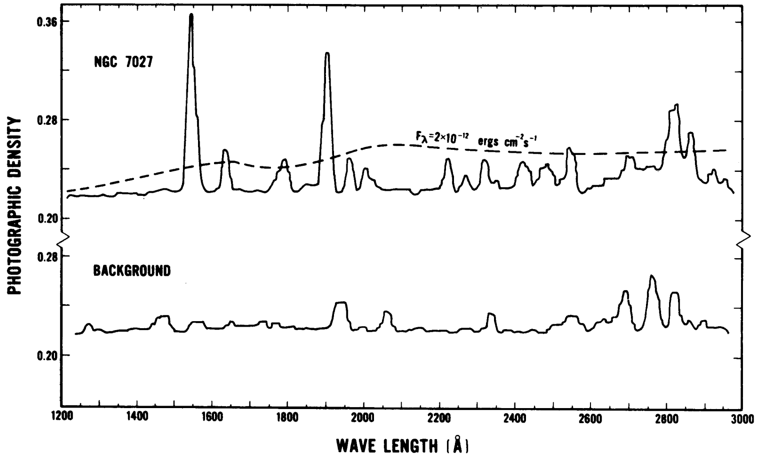

Figure 2. Ultraviolet spectrum of the planetary nebula NGC 7027 (upper solid line). The lower solid line is a typical noise level. The dashed line is proportional to the instrumental sensitivity.

for measurement stretches out from 1300 to 2900 Å. Some disturbance of the tracking system during the 90 second exposure on NGC 7027 resulted in the broadening of particular emission lines to 35 Å.

Table II

Shortwave spectra of the planetary nebula NGC 7027.
Observed fluxes

Å	Identification	Flux, F(λ) (10^{-11}erg $cm^{-2}s^{-1}$)	F(λ)/(H_β) (observed) *)	Interstellar extinction Aλ - A	F(λ)/F(H_β) (corrected)
1549	CIV	1.06	0.17	$5^m.00$	17.0
1640	HeII	0.28	0.045	4.77	3.6
1793	-	0.23	0.037	4.70	2.8
1909	CIII]	0.63	0.098	5.29	12.8
1964	-	0.18	0.029	5.60	5.0
2008	-	0.10	0.016	6.10	4.4
2224	-	0.17	0.027	6.31	9.0
2321	-	0.16	0.026	5.36	3.6
2424	-	0.16	0.026	4.57	1.7
2548	-	0.21	0.034	3.83	1.2
2821	-	0.39	0.063	2.72	0.8

*) F(H_β) = 6.25 • 10^{-11} erg cm^{-2} s^{-1}

Having conducted a preliminary energy calibration of the spectrograph with a telescope and a radiation reciever, the investigators present the results of their measurements in absolute energy units. Table II lists the values of fluxes in the emission lines both in units of 10^{-11} erg $cm^{-2}s^{-1}$ and in units of the intensity of H_β (F(H_β) = $6.62 \cdot 10^{-11}$erg $cm^{-2}s^{-1}$). Noteworthy is the exceptionally high interstellar absorption in the line of sight to NGC 7027.

Due to the high level of noise and the uneven background (lower recording in Figure 2), the authors believe that only four emission lines are very likely to be real, namely, λ1549 CIV, λ1640 HeII, λ1793 (unidentified) and λ1909 CIII]. The upper limits for the intensities of another four lines are offered: λ1240 N V, λ1334 CII, λ1407 OIV and λ1488 NIV. The theoretical intensities of these lines for highly excited nebulae had not been computed before. An examination of uniform spherical models for nebulae led us to the conclusion that the observed intensity of λ1909 CIII] is at least ten times greater than the expected value.

The following three circumstances call for an explanation:

1. The doublet λ2440 [NeIV], present in the spectrum of IC 2149, was not seen in that of NGC 7027. It can be argued that, because of the very high temperature of the central star ($T_* > 200{,}000°K$) of NGC 7027, the neon in it is mainly in a state of four-fold ionization and above; but λ2440 [NeIV] occurs strongly in NGC 7662, which is itself only insignificantly inferior to NGC 7027 as to excitation (class 8) (Bohlin et al. 1975).

2. There is no sign of the doublet λ2800 MgII in NGC 7027. If we question the line identification in IC 2149, λ2821 Å (Table II) was likely to have been mistaken for the doublet 2800 MgII. Alternatively, magnesium could be highly ionized in NGC 7027 and Mg^+ missing, again due to the high temperature. No information is available concerning λ2800 MgII in NGC 7662.

3. The continuous component in the ultraviolet of NGC 7027 is lacking altogether. This is probably due to interstellar absorption, leading to more than 100-fold reduction in intensities.

3. WIDE-BAND SHORT-WAVE PHOTOMETRY OF PLANETARY NEBULAE

Wide-band photometric measurements were made in the spectral range 1430-4250 Å (Holm 1972) with the help of OAO-2 for nine planetary nebulae-NGC 40, 246, 1535, 3587, 6543, 6826, 6853, 7293 and IC 418. They consisted in comparing the radiation flux of each nebula with that of the star 15 Mon (07, V = 4.65, B-V = -0.25) in each spectral band.

A preliminary discussion was mainly restricted to a comparison of the observed m(neb) - m(15Mon) with theoretical models, in particular for NGC 246 and NGC 6826, both relatively free of interstellar absorption. Figure 3 shows the results for NGC 246, where the dots stand for

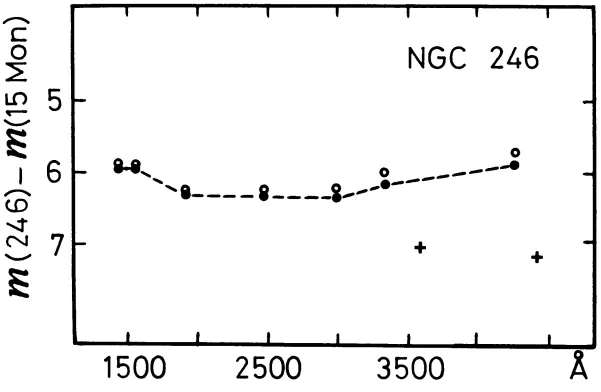

Figure 3. The wide-band seven-channel ultraviolet relative photometry of the planetary nebula NGC 246: points, observations of OAO-2, open circles calculations; crosses, the ground-based observations by Liller and Shao (1968).

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observations, while the circles represent the (simple) theoretical model. The fit is worse for NGC 6826, the discrepancy reaching 1 mag. at 1500 Å.

The results of six-channel photometry in the range 1550-3500 Å, conducted on seventeen planetary nebulae using another orbital observatory, ANS, were reported in a brief communication (Wesselius et al. 1975), according to which most of the nebulae proved reddened. When the angular dimensions of the nebula are fairly large, or the central star is weak enough, the photometric results should be meaningful to the investigation of the nebula. According to preliminary data two-photon radiation plays in such nebulae a far greater role than it was believed earlier; the impression is that almost all recombinations pass through the level 2s, or it may be that a true process of fragmentation of Lyman photons (Gurzadyan 1969), is going on in the nebulae.

The results of both attempts - OAO-2 and ANS - of wide-band photometry were not unexpected. One gathers the impression these observations are less informative for planetary nebulae than for their central stars. In future planning, preference should apparently be given to spectrophotometric investigations.

4. CONTINUOUS SPECTRUM OF THE CENTRAL STAR

The continuous spectrum of the central star of IC 2149 in the range 2400-2800 Å, is obtained (Fig. 4, open circles) from the measurements and processing of the "Orion-2" spectrogram. Mihalas' (1965) model for an effective temperature T_{eff} = 50,000°K (suggested by estimates of ∿43,000° by Gurzadyan (1969) and 66,000°K by O'Dell (1962)) is shown in Figure 4 as the solid line.

The difference between theory and observations is large and arises from interstellar absorption which seems to obey a λ^{-1} law (Gurzadyan 1975), at least down to 2500-2400 Å; the divergence from this law appears around 2400 Å, and reaches to a maximum at 2200 Å (Bless and Savage 1972). The corrected continuous spectrum of the central star is given in Figure 4 by filled circles. It exceeds the model values at wavelengths shorter than 2800 Å.

5. TWO-PHOTON EMISSION

We believe that the marked excess emission (shaded part on Figure 4) bears no relation to the central star and cannot be accounted for by dust particles in the nebula; part of this excess radiation can be two-photon emission, generated by hydrogen atoms in the nebula itself.

To separate the two-photon radiation from the observed nebular spectrum, a complete picture of the continuum of IC 2149 is reconstructed for wavelengths shorther than 3646 Å, using n_e = 3.2 10^3 cm^{-3},

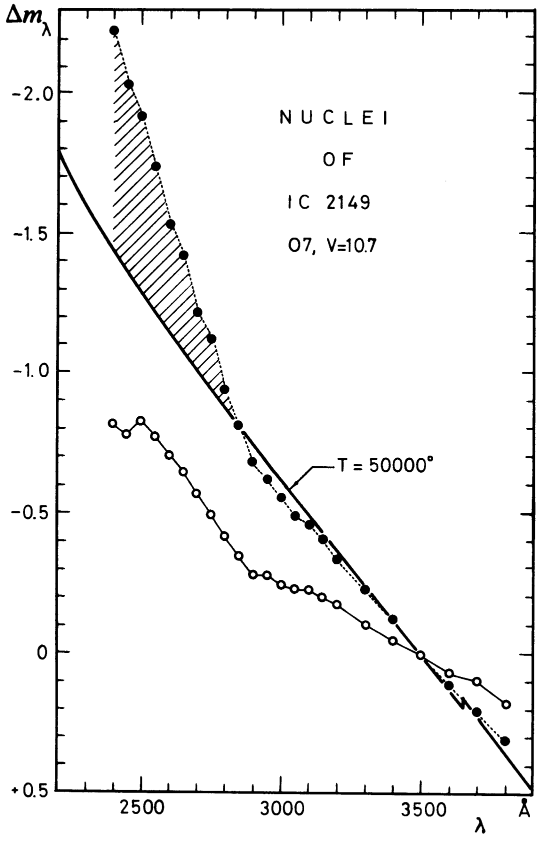

Figure 4. The continuum of the nucleus IC 2149; open circles are observations; filled circles, corrected for the effect of interstellar absorption; solid line, the theoretical model spectrum; shaded area, additional radiation.

obtained by the method of λ3727 [OII] doublet ratio (Osterbrock 1960), and T_e = 12,400° (Kaler 1970).

The optical emission line spectrum of IC 2149 indicates it is moderately excited (Aller 1951). This fact may be taken as a criterion that the role of ionized helium continuum is negligible because of the very small amount of ionized helium atoms. Therefore, we shall take into account only three components for the UV continuum of IC 2149: the Balmer continuum of hydrogen, J(HI), neutral helium, J(HeI), and 2-photon radiation of hydrogen, J(2q). As a result we obtain the picture shown in Figure 5 (solid line on the top). The radiation coefficient data by Brown and Matthews (1970) are used in our calculations.

Seaton (1955, 1960) was the first to make an attempt to identify

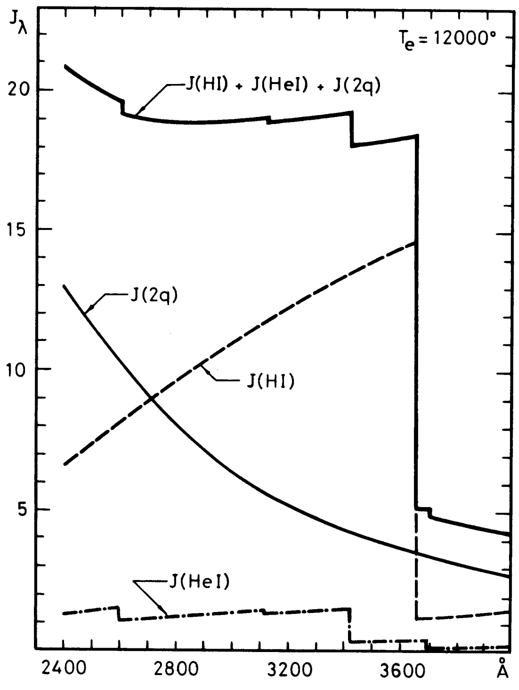

Figure 5. The calculated continnum of IC 2149 (the solid line from the top; T_e = 12000°K, N_e = 3.2 · 10^3 cm^{-3}). The ordinate is in the units 10^{-28}erg/cm^{3}s Å.

two-quantum process in the emission of nebulae by examining the magnitude of the Balmer jump. However, as is seen on Figure 5, the intensity of two-photon emission on λ = 3646 Å is at least 5-6 times smaller than the full intensity due to both hydrogen and helium continua at the jump, whereas the intensity of 2q-photon emission at λ = 2400 Å makes up 60% of the total intensity of the continuum. That limits severely the sensitivity of the Balmer-jump method.

Figure 6 compares the observed additional emission from Figure 4, with the theoretically recalculated spectrum (from Figure 5). Agreement may be considered quite good.

An alternative to check the plausibility of the conclusions drawn is based of the estimation of the total amount of the additional emission and its comparison with the theoretically expected value for 2q-radiation. For this we obtain at first the observed value of the ratio $Q(\lambda_1,\lambda_2)/N^*(\lambda_1,\lambda_2)$, where $Q(\lambda_1,\lambda_2)$ is the additional number of emitted photons in the interval from λ_1 to λ_2, and $N^*(\lambda_1,\lambda_2)$ is the number of photons emitted by the central star in the same wavelength region. Further, we can obtain the ratio $Q(2q)/Q(\lambda_1,\lambda_2)$ from the

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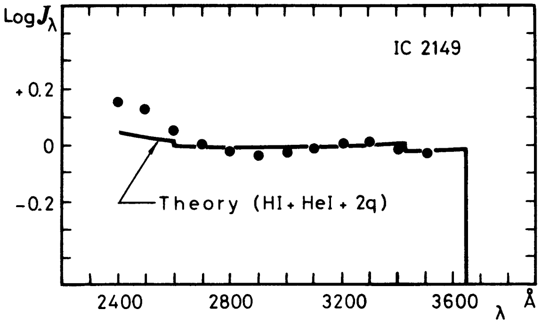

Figure 6. The comparison of observed and theoretical (solid line) continua for nebula IC 2149.

theoretical spectrum of two-photon radiation, where Q(2q) is the total number of 2q-photons from $\lambda = 1216$ Å to $\lambda \to \infty$.

Finally, denoting by N_c the number of photons in the Lyman continuum ($\lambda < 912$ Å) emitted by the nucleus per second, we can derive the following relationship between the ratio $Q(2q)/N_c$ and the temperature of the nucleus T_*, somewhat analogous to Zanstra's formula for two-photon emission:

$$\frac{Q(2q)}{N_c} = \frac{Q(\lambda_1,\lambda_2)}{N^*(\lambda_1,\lambda_2)} \frac{Q(2q)}{Q(\lambda_1,\lambda_2)} \frac{\int_{x_1}^{x_2} \frac{x^2\,dx}{e^x - 1}}{\int_{x_0}^{\infty} \frac{x^2\,dx}{e^x - 1}}$$

where $x = hc/\lambda k T_*$. In our case we have: $\lambda_1 = 2400$ Å, $\lambda_2 = 2850$ Å. Further, we obtain $Q(\lambda_1,\lambda_2)/N^*(\lambda_1,\lambda_2) = 0.50$ from Figures 4 and 5, and $Q(2q)/Q(\lambda_1,\lambda_2) = 14$ from the theoretical spectrum of 2q-photon emission. Using these data we derive from this formula for $Q(2q)/N_c$, at two probable values of the nucleus temperature:

T_*	$Q(2q)/N_c$
55,000°K	0.67
66,000°K	0.45

According to the theory, approximately 0,33 of the hydrogen atoms formed by recombination (at $T_e = 12{,}000$°K) to all levels starting with the

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second enter the 2s, inducing 2q-transitions. Therefore, we have for the theoretical ratio, $Q(2q)/N_c = 2 \times 0.33 = 0.66$, assuming of course $\tau_0 > 1$ for the optical depth of the nebula in the Lyman continuum and neglecting collisions. Taking into account the collisions we shall obviously have for IC 2149: $Q(2q)/N_c = 0.55$, which is in good agreement with the observations.

Thus, two independent methods, both the spectral distribution and the amount of radiation emitted, point to the existence of hydrogen two-photon emission in IC 2149.

As to NGC 7027, it is hard to trace signs of two-photon emission on the published spectrum. This was to be expected by the virtue, as was mentioned above, of the following two reasons . A first reason is the very large electron concentration leading to a rapid deactivation which will result in a sharp depression of the intensity of the two-photon emission. Secondly, and more importantly, interstellar obscuration suppresses the continuous spectrum of two-photon origin.

6. CONCLUSIVE REMARKS

The ultraviolet observations of planetary nebulae from space are only in their exciting beginnings. It seems the UV spectra of these objects are much more sensitive than the optical to physical conditions and to the central star.

The resonance lines of most atoms and ions have wavelengths shorter than 3000 Å, hence the importance for abundance studies of short-wave spectrography. Atomic parameters for most of those lines are already available; greater attention will be paid in the future to such calculations, as well as to computations of spectra for various models of nebulae.

Interstellar absorption exerts a great influence on the observed UV spectra of nebulae. Special attention should be devoted to obtaining spectrograms of absorption-free nebulae such as NGC 246, 1535, 2371-2, 3587, 4361, 6058, 6741, 6818, 6826, 6853, IC 3568, which will enable direct and reliable comparisons with model estimates.

Some planetary nebulae are interesting for their very high values of electron concentration, of the order 10^6 - 10^7 cm^{-3}: IC 4997, anon. 0 1^h52^m, anon. 19^h21^m (Gurzadyan 1969).

It is evident that the UV spectra are the only reliable means for the solution of the problem of two-photon emission. Clearly, the prospect of studying this problem can in full measure justify the efforts that will be spent on outer space experiments in deriving the short-wave spectra of planetary nebulae.

We are now facing the interesting possibility of using the observed properties of two-photon emission to completely characterize the physical conditions in the nebula. The spectrum of two-photon emission depends on the electron concentration and, to a lesser degree, on the electron temperature; its intensity depends also on the degradation process of Lyα photons in the given nebula. The fragmentation can take place either directly during the spontaneous 2p → 1s transitions (Kipper and Tilt 1958), or as a result of compulsory 2p→2s transitions (by means of electronic collisions) with subsequent two-photon 2s → 1s decay (Gurzadyan 1961). The total number of degraded Lyα photons depends then in turn on the total optical depth of the nebula, τ_α, on its dimensions, as well as its internal kinematics (the gradient of expansion velocity). 75% of all the Lyα continuum energy from the central star turns eventually into Lyα energy, thus making the Lyα photons a potentially powerful source of two-photon emission. In this connection the observations of planetary nebulae in the Lyman-alpha line must be of definite interest, too.

The resonance doublet λ2800 MgII and the resonance line λ2669 AlII, are excited not by fluorescence, but by inelastic electronic collisions. This entails the question - first, how often are those lines observed in planetary nebulae and how often are similar lines from other atoms?

The role of dielectronic recombination in planetary nebulae for various type of ions should also be examined.

It might also be possible to observe planetary nebulae that are either quite close to us (NGC 7293), or located high above the galactic plane, in wavelengths shorter than 300 Å or at least shorter than 100 Å.

Despite the achievements in theory and observations, we are still far from understanding the true essence of planetary nebulae and their nuclei; it is not an easy task to trace the genesis of the nebulae themselves. Under the circumstances, to set our hopes on the extensive space observations of planetary nebulae must be looked upon as more than natural and reasonable.

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