THE ULTRAVIOLET EMISSION SPECTRA OF PLANETARY NEBULAE

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ABSTRACT

Calculations show that high-excitation planetaries emit about the same total intensity of collisionally excited radiation in the unobserved ultraviolet part of the spectrum as in the visible. This ultraviolet radiation emanates from a central zone where the electron temperature is high due to absorption of He II Ly-α photons. Intensities of lines which one might expect to detect in the ultraviolet have been calculated using revised atomic data and a detailed model of the ionization and thermal structure of the central zone. Relative line intensities are presented for a wide range of excitation in the nebula. In particular, the absolute intensity of the C IV doublet at 1550 Å has been calculated for 4 selected planetaries.

Calculations have been made of the intensities of the ultraviolet lines emitted by planetary nebulae. The spectral region considered extends from 912 Å to about 3500 Å. Interstellar hydrogen and helium will absorb all radiation shortwards of 912 Å, and 3500 Å is taken as defining the short-wavelength edge of the visible part of the spectrum.

There are several reasons to justify a theoretical study of the ultraviolet spectra of planetaries. In particular, observations of these lines from space vehicles should become possible in the near future and predictions of wavelengths and absolute line intensities will be useful. Observations of B stars in the ultraviolet have already been made and the results reported at the I.A.U. Symposium No. 23 (Heddle, 1964). A comparison is made of the absolute flux at the detectors in the observations of B stars with the predicted absolute flux from high-excitation planetary nebulae.

The physical processes responsible for the production of emission lines in planetaries are well known. The lines can be due either to radiative recombination followed by cascade or due to collisional excitation followed by radiative decay. Osterbrock (1963) has already considered in some detail the ultraviolet lines produced in planetary nebulae due to both processes. However, he did not calculate the actual intensities of the lines. To do this, a model of both the ionization and thermal structure of the nebula is essential. Here we shall be concerned with the intensities of the collisionally excited lines which constitute a very large fraction of the nebular radiation both in the visible and the ultraviolet.

To illustrate the physical arguments involved in the calculations, we shall consider Ne^{3+} as an example of an ion which emits collisionally excited radiation. The expected

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ultraviolet lines, which are produced in transitions between the terms of the ground configuration, are marked in Figure 1. The ^2D and ^2P states may be excited collisionally or by radiative recombination. In all of this work it is assumed that the rate of excitation by radiative recombination is negligible compared with the collisional excitation rate. The assumption is probably valid in almost all cases at the electron

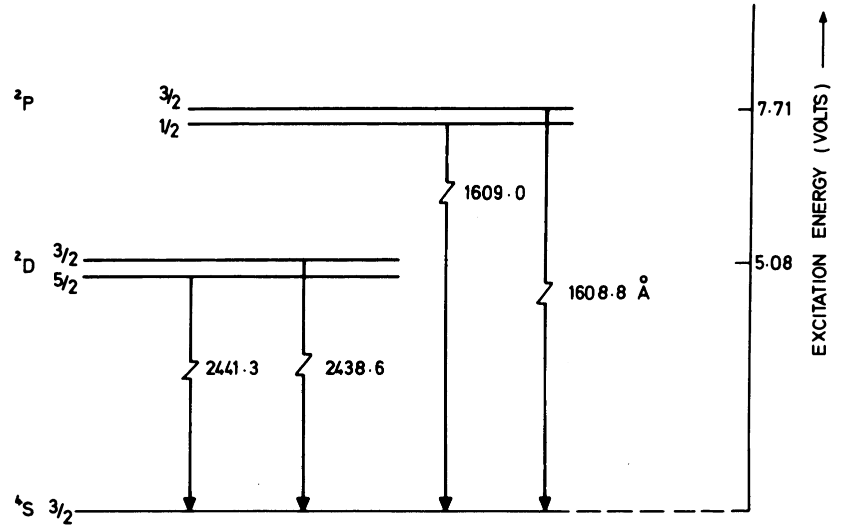

FIG. 1. *Terms of the ground configuration of Ne^{3+}. The wavelengths of expected ultraviolet transitions are marked in Å.*

temperatures considered. To be quite specific, we consider collisional excitation of the ^2P state from the ^4S ground state. The excitation rate is given by

$$X_c = N_e N(\mathrm{Ne}^{3+})\, q(1 \rightarrow 3) \tag{1}$$

where

$$q(1 \rightarrow 3) = 8{\cdot}63 \times \frac{10^{-6}\Omega(1, 3)}{\omega_1 T_e^{1/2}} \exp\left(\frac{-\Delta E(1, 3)}{kT_e}\right). \tag{2}$$

1 represents the ^4S state, 3 represents the ^2P state. N_e is the electron density, $N(\mathrm{Ne}^{3+})$ is the density of Ne^{3+} ions, $\Omega(1, 3)$ is the collision strength, and $\Delta E(1, 3)$ the energy of the transition, ω_1 is the statistical weight of the ground state, and T_e is the electron temperature.

Equation (2) clearly shows why a model of the thermal structure of the nebula is essential to any calculation of line intensities. The argument of the exponential, $-\Delta E/kT_e$, is approximately -8 for $T_e = 1 \times 10^4\,°\mathrm{K}$ and -4 for $T_e = 2 \times 10^4\,°\mathrm{K}$. So a factor of 2 difference in the electron temperature introduces a factor of about 50 in the value of the line intensity.

The electron temperatures of planetary nebulae are often obtained by measuring the intensities of the nebular and auroral lines of O III. It is important to note that the value obtained yields the electron temperature only in that part of the nebula which contains O^{2+}. In high-excitation planetaries, this will be the outer part of the nebula, furthermost from the central star. It is proposed here that, in high-excitation objects, there exists a central zone where the electron temperature is high, about $1{\cdot}8\text{–}2{\cdot}0 \times 10^4\,°K$. The value of the electron temperature in this region is not reflected in the intensities of the [O III] lines because there is very little O^{2+} in the central zone.

In using the term 'central zone', we mean quite specifically a central ionization zone. We follow the procedure of Hummer and Seaton (1964) and divide a planetary into a number of ionization zones. In any particular planetary, one or more of the possible ionization zones may not be present at all, but the general trend of the degree of excitation increasing towards the centre of the nebula is certainly supported by observations (e.g. Wilson, 1950). In the central zone, most of the helium is He^{2+} and most of the hydrogen is H^+. There is very little O^{2+} in this region of the nebula and so the electron temperature must be calculated.

The calculation of the theoretical electron temperature of the central zone involves all the physical processes of the thermal balance of that part of the nebula (Hummer and Seaton, 1964; Aller, 1956). The source of energy of all planetaries is the radiation emitted by the central star. This radiation is absorbed in the processes of ionization in the nebula when the electrons gain energy from the radiation field. For an element X in the qth state of ionization the process may be written as

$$X^{q+} + h\nu \rightarrow X^{(q+1)+} + e^- . \tag{3}$$

The electrons can lose energy in a number of ways, notably in inelastic collisions with positive ions when collisionally excited radiation can be produced:

$$X^{q+} + e^- \rightarrow X^{q+*} + e^- \tag{4}$$

$$X^{q+*} \rightarrow X^{q+} + h\nu . \tag{5}$$

In general, a balance is attained between gain of electron kinetic energy from the radiation field and loss of kinetic energy in processes such as the inelastic collisions with positive ions. However, Hummer and Seaton (1964) consider the importance of He II Ly-α radiation which is produced in the central zone. They propose that this radiation is absorbed in the central zone in maintaining the ionization of hydrogen:

$$\underset{\phantom{40{\cdot}8\text{ eV}}}{H^0} + \underset{40{\cdot}8\text{ eV}}{h\nu(\text{He II Ly-}\alpha)} \rightarrow H^+ + \underset{27{\cdot}2\text{ eV}}{e^-} . \tag{6}$$

Because of the very large energy of the He II Ly-α photon, the electron released in the process given by Equation (6) has a large energy. These electrons are thermalised by elastic collisions in the central zone and the electron temperature in this region is high as a consequence.

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Computer programmes have been developed to solve the thermal balance equation in the central zone of planetary nebulae. Allowance is made for heating by radiation from the central star and by He II Ly-α radiation. The usual cooling processes of radiative recombination, free-free transitions, and inelastic collisions are taken into account. In Figure 2, electron temperature is plotted as a function of radius for two

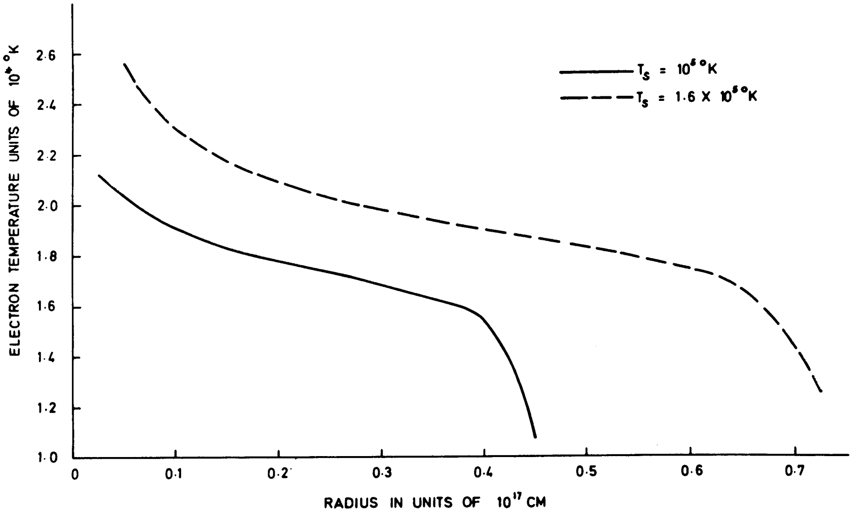

FIG. 2. *Electron temperature of the central zone as a function of radius. Plots are given for two values of central star temperature,* T_S.

values of central-star temperature, T_s, where it is assumed that the star radiates as a black-body. The electron temperature is seen to be insensitive to the value of T_s.

The computer programmes also solve for the ionization equilibrium of ions of the following elements in this zone: He, C, N, O, and Ne. Figure 3 is typical of the results obtained for oxygen. It is clear that there is very little O^{2+} in the central zone. The electron density is also obtained as a function of radius. Figure 4 shows the result for an assumed hydrogen density of $1{\cdot}0 \times 10^4$ cm^{-3} and He–H abundance ratio (Aller, 1964) of 0.18.

The results obtained are given in Tables 1–4. For each ion, the wavelengths and identifications of the ultraviolet transitions are given (Osterbrock, 1963). For Ne^{3+} and Ne^{4+}, some transitions which can be observed from the ground are also included; this makes possible a limited comparison between theory and observation. The ratio, Ω/ω, of the collision strength for the transition to the statistical weight of the ground state is also given. The best available values of collision strengths have been used (Czyzak *et al.*, 1968; Bely *et al.*, 1963). The most uncertain values are marked by an asterisk.

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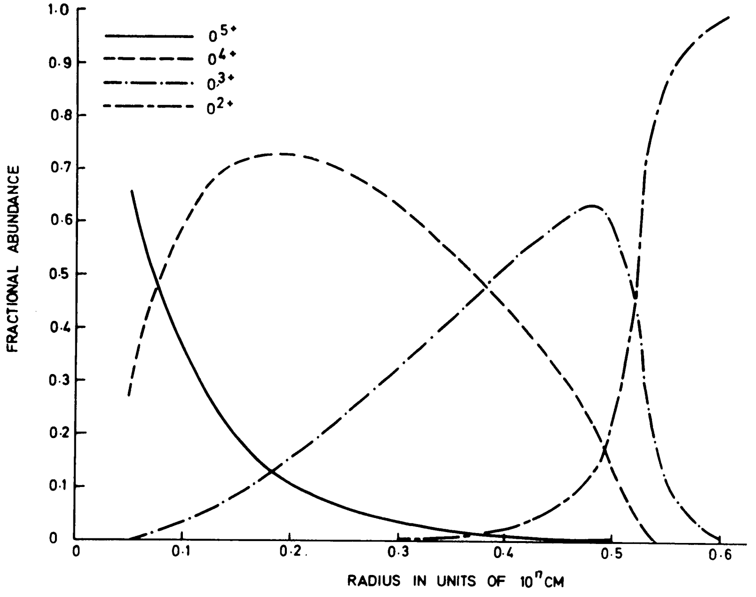

FIG. 3. *Ionization of oxygen in the central zone. The fraction of oxygen in each ionization stage is plotted as a function of radius.* $T_S = 12 \times 10^4 \,^\circ K$.

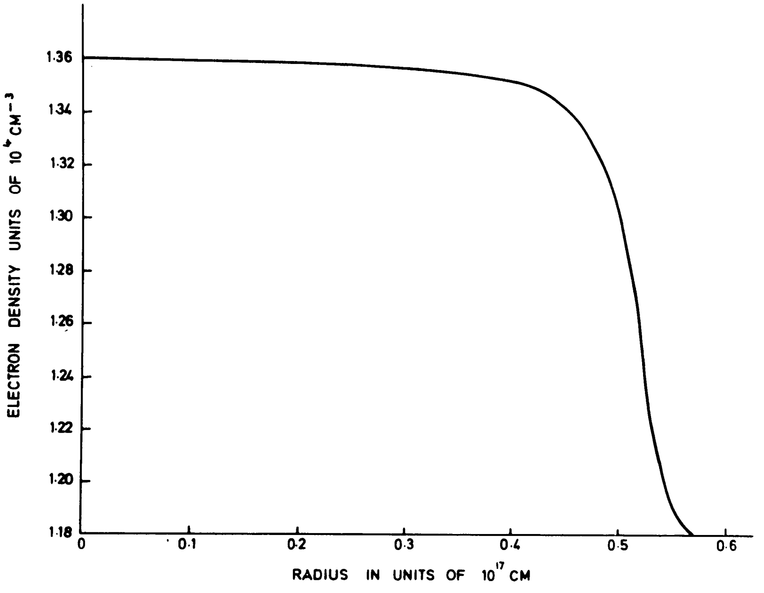

FIG. 4. *Electron density in the central zone as a function of radius.* $T_S = 12 \times 10^4 \,^\circ K$.

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Table 1

Ions of the C group of elements. Ω is the collision strength for the transition and ω the statistical weight of the ground state. The most uncertain values of the ratio Ω/ω are marked by an asterisk

Ion	Transition	Wavelength (Å)	Excitation Potential (volts)	Ω/ω
C^{+3}	$2s^2S_{1/2}$ – $2p^2P^0_{3/2}$	1548·2	8·00	5·5
	$^2S_{1/2}$ – $^2P^0_{1/2}$	1550·8		
N^{+3}	$2s^2\,{}^1S_0$ – $2s2p^3P^0_1$	1488·1	8·34	0·30*
N^{+4}	$2s^2S_{1/2}$ – $2p^2P^0_{3/2}$	1238·8	10·00	3·6
	$^2S_{1/2}$ – $^2P^0_{1/2}$	1242·8		
O^{+3}	$2s^22p^2P^0_{1/2}$ – $2s2p^2\,{}^4P_{3/2}$	1402·4:	8·81	0·20*
	$^2P^0_{1/2}$ – $^4P_{1/2}$	1404·9:		
	$^2P^0_{3/2}$ – $^4P_{5/2}$	1406·3:		
	$^2P^0_{3/2}$ – $^4P_{3/2}$	1410·0:		
	$^2P^0_{3/2}$ – $^4P_{1/2}$	1412·6:		
O^{+4}	$2s^2\,{}^1S_0$ – $2s2p^3P^0_1$	1215·7	10·21	0·30*
O^{+5}	$2s^2S_{1/2}$ – $2p^2P^0_{3/2}$	1037·6	11·99	2·6
	$^2S_{1/2}$ – $^2P^0_{1/2}$	1031·9		
Ne^{+3}	$2s^22p^3\,{}^4S^0_{3/2}$ – $2s^22p^3\,{}^2D^0_{3/2}$	2438·6	5·08	0·26
	$^4S^0_{3/2}$ – $^2D^0_{5/2}$	2441·3		
	$2s^22p^3\,{}^4S^0_{3/2}$ – $2s^22p^3\,{}^2P^0_{3/2}$	1608·8	7·71	0·107
	$^4S^0_{3/2}$ – $^2P^0_{1/2}$	1609·0		
	$2s^22p^3\,{}^2D^0_{5/2}$ – $2s^22p^3\,{}^2P^0_{3/2}$	4714·3	7·71	0·107
	$^2D^0_{5/2}$ – $^2P^0_{1/2}$	4715·6		
	$^2D^0_{3/2}$ – $^2P^0_{3/2}$	4724·2		
	$^2D^0_{3/2}$ – $^2P^0_{1/2}$	4725·6		
Ne^{+4}	$2s^22p^2\,{}^3P_2$ – $2s^22p^2\,{}^1S_0$	1592·7	7·83	0·024
	$^3P_1$ – $^1S_0$	1575·2		
	$2s^22p^2\,{}^1D_2$ – $2s^22p^2\,{}^1S_0$	2972	7·83	0·024
	$2s^22p^2\,{}^3P_2$ – $2s^22p^2\,{}^1D_2$	3425·9	3·66	0·153
	$^3P_1$ – $^1D_2$	3345·8		

* Where mean wavelength of a multiplet is uncertain it is marked with a colon. The spacing between the lines of the multiplet should be correct.

In all these calculations it is assumed that once a state has been collisionally excited it may decay only radiatively, i.e. collisional de-excitation is negligible. This assumption will be fairly justified for the electron-density values encountered in planetary nebulae. The function G, which is tabulated is then the product of Ω/ω with the branching ratio for the particular transition of the multiplet. Transition probabilities are taken from Allen (1964) for permitted transitions and from Garstang (1968) for forbidden transitions. All intensities are given relative to the He II λ 4686 line, which is the most intense He II line in the visible. The results for the ions of S and Ar will not

Table 2

Relative line intensity values for ions of the C group of elements. The function G is the product of Ω/ω with the branching ratio for the transition

Ion	Wavelength	G	Line intensities relative to He II λ 4686 $T_s = 6 \times 10^4$	10×10^4	14×10^4	18×10^4 °K
C^{+3}	1548·2	3·67	24	25	28	34
	1550·8	1·83	12	13	14	17
N^{+3}	1488·1	0·1	0·41	0·42	0·38	0·39
N^{+4}	1238·8	2·4	0·27	2·7	4·9	6·3
	1242·8	1·2	0·14	1·3	2·5	3·1
O^{+3}	1402·4:	0·04	0·34	0·39	0·37	0·36
	1404·9:	0·02	0·17	0·20	0·19	0·18
	1406·3:	0·07	0·51	0·60	0·57	0·55
	1410·0:	0·04	0·34	0·39	0·37	0·36
	1412·6:	0·02	0·17	0·20	0·19	0·18
O^{+4}	1215·7	0·1	0·027	0·29	0·56	0·70
O^{+5}	1037·6	1·73	$6{\cdot}2 \times 10^{-5}$	0·070	0·83	2·7
	1031·9	0·87	$3{\cdot}1 \times 10^{-5}$	0·035	0·42	1·3
Ne^{+3}	2438·6	0·22	5·3	7·6	5·6	4·1
	2441·3	0·035	0·85	1·2	0·89	0·66
	1608·8	0·053	0·27	0·44	0·34	0·25
	1609·0	0·011	0·056	0·091	0·070	0·053
	4714·3	0·016	0·081	0·13	0·10	0·076
	4715·6	0·0022	0·011	0·018	0·014	0·011
	4724·2	0·018	0·089	0·14	0·11	0·084
	4725·6	0·0078	0·040	0·064	0·050	0·037
Ne^{+4}	1592·7	$2{\cdot}4 \times 10^{-5}$	All intensities less than 10^{-4}			
	1575·2	0·015	$7{\cdot}7 \times 10^{-4}$	0·045	0·13	0·17
	2972	0·0092	$4{\cdot}7 \times 10^{-4}$	0·028	0·079	0·11
	3425·9	0·11	0·051	2·5	6·6	8·2
	3345·8	0·041	0·019	0·93	2·4	3·0

Table 3

Ions of S and Ar. The most uncertain values of Ω/ω are marked by an asterisk

Ion	Transition	Wavelength (Å)	Excitation Potential (volts)	Ω/ω
S^{+4}	$3s^2\,{}^1S_0 - 3s3p\,{}^3P_1{}^0$	1198·6:	10·32	0·3*
S^{+5}	$3s\,{}^2S_{1/2} - 3p\,{}^2P_{3/2}{}^0$	933·4	13·20	6·83
	${}^2S_{1/2} - {}^2P_{1/2}{}^0$	944·5		
Ar^{+4}	$3s^23p^2\,{}^3P_1 - 3s^23p^2\,{}^1S_0$	2691·4	4·70	0·0157
	${}^3P_2 - {}^1S_0$	2784·4		
Ar^{+5}	$3s^23p\,{}^2P_{1/2}{}^0 - 3s3p^2\,{}^4P_{3/2}$	992·0	12·49	1·2*
	${}^2P_{1/2}{}^0 - {}^4P_{1/2}$	1000·0		
	${}^2P_{3/2}{}^0 - {}^4P_{5/2}$	1001·8		
	${}^2P_{3/2}{}^0 - {}^4P_{3/2}$	1014·3		
	${}^2P_{3/2}{}^0 - {}^4P_{1/2}$	1022·6		

Table 4

Relative line intensity values for ions of S and Ar

Ion	Wavelength (Å)	G	Line intensities relative to He II λ 4686 $T_s = 10^5$ °K
S^{+4}	1198·6:	0·1	0·060
S^{+5}	933·4	4·55	0·49
	944·5	2·28	0·25
Ar^{+4}	2691·4	0·010	0·010
	2784·4	$1{\cdot}2 \times 10^{-4}$	$1{\cdot}2 \times 10^{-4}$
Ar^{+5}	992·0	0·27	0·0035
	1000·0	0·13	0·0017
	1001·8	0·40	0·0052
	1014·3	0·27	0·0035
	1022·6	0·13	0·0017

be as good as for the C group of elements because the detailed ionization structure for S and Ar has not yet been calculated.

In a high-excitation planetary, the He II λ 4686 line is about one half as intense as the Hβ line (the customary intensity standard). A simple calculation shows that the total intensity of the radiation emitted in the strongest ultraviolet lines is approximately the same as the total intensity of the radiation emitted in the visible. So high-excitation planetaries such as NGC 7027 and NGC 7662 are emitting a large fraction of their total radiation in the ultraviolet.

The absolute intensity of the C IV doublet at 1550 Å has been calculated for four planetary nebulae, and the results are presented in Table 5. The 4 objects considered

Table 5

Values of the absolute flux of the C IV doublet at 1550 Å for four selected planetaries. The flux is in photons cm^{-2} sec^{-1} rather than ergs cm^{-2} sec^{-1}

NGC	Absolute flux photons cm^{-2} sec^{-1}
1535	10
2392	26
7009	24
7662	17

were taken from a list of 47 planetary nebulae compiled by Harman and Seaton (1966). They were chosen because they satisfy the following criteria:

(a) the value of the absolute Hβ flux is fairly high and the intensity of the He II λ 4686 radiation is significant compared with the Hβ line intensity;

(b) the reddening constant for the nebula is small; and

(c) the nebula completely surrounds the central star.

The value of the reddening function, $f(\lambda)$, at 1550 Å was obtained by extrapolation of the values given by Seaton (1960). $f(\lambda)$ was plotted against $1/\lambda$ and a linear extrapolation made to 1550 Å. By this means we obtain $f(1550) = 2{\cdot}2$. The values of absolute intensity of the C IV doublet, allowing for space absorption, are seen to be of the order of 10 photons cm^{-2} sec^{-1}.

The procedure adopted in the ultraviolet observations of B stars reported by Heddle (1964) was to view the continuum of the star through a filter of typically 200 Å bandwidth. The flux at the detectors under these conditions was of the order of 10^4 photons cm^{-2} sec^{-1}. If the bandwidth of the filter was reduced to 0·1 Å, the flux would be reduced to about 10 photons cm^{-2} sec^{-1}. So the problem of observing the strongest ultraviolet lines of bright planetary nebulae seems comparable with the problem of viewing the ultraviolet continuum of B stars under quite high resolution. It is to be hoped that experiments of this sensitivity will become possible in the near future.

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DISCUSSION

Aller: The calculations pertaining to [Ne IV] ultraviolet lines are amenable to direct observational check for many high-excitation planetaries. The ^2P–^2D auroral transitions fall near λ 4725 and have been measured in a number of planetaries in our program at Lick. Thus without any theoretical model at all we can predict some of the ultraviolet intensities. The electron temperatures are usually higher than 10000 °K. Values of 15000 °K – 17000 °K would be more typical.

Hummer: Collisional excitation of ultraviolet lines is of course caused by high-energy electrons.

It is important to realize that there may be some deviation from an exact Maxwell-Boltzmann distribution at high energies, because photo-ionization of H by He II Ly-α (λ 304) photons produces electrons with energy about 30 eV each, which are only very slowly thermalized.

Underhill: The He II λ 304 quanta have sufficient energy to ionize atoms in relatively low-lying levels, of the first, second, and third stages of ionization of the light elements. Such ionizations may help to create a more rapid thermalization of the energy of He II λ 304 than is possible by ionization of H only.

Seaton: However, the number of ionizations of H is larger than the number of ionizations of heavy elements, because the number of recombinations of hydrogen is greater.