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COLLISIONAL EXCITATION OF THE λ10830 HE I LINE AND THE POPULATION OF THE 2^3S HE I STATE IN GASEOUS NEBULAE

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RESUMEN

A partir del estudio de las intensidades de las líneas λλ5876, 7065 y 10830 de He I en las nebulosas planetarias NGC 6572, NGC 6803, NGC 7009, NGC 7027, NGC 7662 e IC 418 se encuentra que el valor observado de I(10830)/I(5876) es menor que el predicho. Se demuestra que la absorción por polvo de fotones λ10830 de He I no es la responsable de este efecto. Las observaciones indican que el estado 2^3S está subpoblado por un factor de dos si se supone que se despuebla únicamente por medio de transiciones al estado 1^1S y por colisiones de intercambio entre tripletes y singuletes. La subpoblación del nivel 2^3S implica que la corrección a la abundancia de helio debida a colisiones es un factor de dos menor que lo supuesto anteriormente. Este resultado es importante para la determinación de la abundancia de helio en nebulosas gaseosas así como en la determinación de la abundancia pregaláctica de helio.

ABSTRACT

From the study of the λλ5876, 7065 and 10830 He I line intensities in NGC 6572, NGC 6803, NGC 7009, NGC 7027, NGC 7662 and IC 418 it is found that the I(10830)/I(5876) ratio is weaker than expected. It is found that dust absorption of λ(10830) photons is not the cause for the low I(10830)/I(5876) ratios. By assuming that the 2^3S He^0 state is depopulated only by radiative transitions to the 1^1S state and by triplet-singlet exchange collisions it is found that its population is about a factor of two smaller than expected. One of the main implications of the underpopulation of the 2^3S level is that the collisional effects in the determination of the N(He)/N(H) abundance ratios of planetary nebulae and O-poor extragalactic H II regions are smaller than previously thought. This result is important for the determination of the pregalactic helium abundance.

Key words: **ABUNDANCES – ATOMIC PROCESSES – COSMOLOGY – NEBULAE-PLANETARY STARS-EVOLUTION**

I. INTRODUCTION

The He I line intensities in gaseous nebulae are mainly produced by recombination but the emitted spectrum is also affected by three other processes: a) radiative transfer effects due to absorption from the 2^3S state, b) collisional excitation from the 2^3S state, and c) dust absorption within the nebula. Fortunately each He I line is affected differently by these three effects, therefore by studying three He I line intensity ratios, it is possible to evaluate each of these effects.

Once the relative importance of the different effects is established then it becomes possible to determine accurate N(He)/N(H) ratios which are paramount for the study of stellar evolution and galactic chemical evolution and for the determination of the pregalactic helium abundance which, within the framework of the big-bang theory, is related to the early stages of the expansion of the universe.

Ferland (1986) revived the interest on the collisional excitation from the metastable 2^3S He^0 state. Ferland based on the computations by Berrington *et al.* (1985) estimated that collisional effects reduced considerably the N(He)/N(H) abundances derived previously for planetary nebulae and O-poor extragalactic nebulae. The newer results by Berrington and Kingston (1987) reduced the collisional effects by about a factor of 1.6 for the λλ5876 and 6678 He I lines.

Moreover, Peimbert and Torres-Peimbert (1987, hereinafter paper I) based on observations of λλ3889, 4471, 5876, 6678 and 7065 He I line intensities in thirteen Type I PN have argued that, probably due to ionizations, the 2^3S level is underpopulated by about a factor of two. This result reduces by another factor of two the collisional effects for these objects.

Clegg (1987) based on the computations by Berrington and Kingston (1987) has also discussed the determination of $N(He^+)/N(H^+)$ abundance ratios in planetary nebulae; he has considered the collisional ionization of metastable helium and finds that it becomes significant at high temperatures, reaching 20% of all collisions out of the 2^3S level at 20000 K (see also Clegg and Harrington 1988). Clegg finds that the mean reduction in the N(He)/N(H) ratio of planetary nebulae due to collisional effects amounts to 10%, and that the He enrichment of Type I PN relative to H II regions is reduced from earlier values by about one third.

It has been known for a long time that the observed I(10830)/I(5876) line intensity ratio is smaller than predicted. From observations by O'Dell (1963) of the I(10830)/I(5876) ratio in 9 PN, several authors found that I(10830) was too weak by factors of 2.5 to 5 if only the D_A and D_C terms in equation (4) were included (e.g., Osterbrock 1964; O'Dell 1965; Capriotti 1967; Robbins 1968*a*; Persson 1970). Münch (1964), based on the fact that λ3889 of He I is rarely seen in absorption in PN, reached the conclusion that the 2^3S level is depopulated by ionizations due to the Lyman α radiation field. O'Dell (1965) and Capriotti (1967) considered that ionization by the Lyman α radiation field was responsible for the weakness of the I(10830) He I line, while Robbins (1970) and Persson (1970) advanced the idea that the weakness of I(10830) was due to dust absorption. Drake and Robbins (1972) with newer atomic data obtained good agreement between the observed and theoretical I(10830)/I(5876) ratios considering that the 2^3S level was depopulated by: photoionization, radiative decay and collisional exchange, and concluded that dust absorption was no longer necessary. Le Van and Rudy (1983) argued that the Lyman α radiation field was destroyed by dust absorption inside PN and that dust absorption of λ10830 photons was needed to explain differences in the 1.5 to 2 range between the observed and the computed I(10830)/I(5876) ratios. Pequignot, Baluteau, and Gruenwald (1987) considered that the difference of a factor of 1.47 between the observed and the computed I(10830)/I(5876) ratio in NGC 7027 could be due to five different causes: a) errors in the observed I(10830)/I(5876) ratio, b) an overestimate of the C(2^3S, 2^3P) rate, c) ionization from the 2^3S level due to the Lyman α radiation field, d) internal dust absorption of λ10830 photons, and e) underpopulation of the 2^3S state. Clegg and Harrington (1988) have made use of photoionization models to study the depopulation of the 2^3S level by the Lyman α radiation field and by stellar continuum photons, they find that photoionization can reduce the collisional effects on the He I line strengths by up to 30%.

Based on the higher quality of the atomic parameters involved and on the availability of *UV* observations gathered with the *IUE*, that permit us to determine the effect of internal dust absorption, we decided to study a group of planetary nebulae, with some of the best observed He I λλ10830, 7065 and 5876 line intensities, to try to test the result of paper I on the underpopulation of the 2^3S level.

II. OBSERVATIONAL DATA

a) *Line Intensities and Reddening Corrections*

In Table 1 we present the I(He I)/I(Hβ) line intensities, after correcting for reddening, for six of the best observed PN. The intrinsic line intensities were obtained from

$$\log [I(\lambda)/I(H\beta)] = \log [F(\lambda)/F(H\beta)] + \\ + C(H\beta) f(\lambda) , \qquad (1)$$

where F(λ) is the observed flux corrected for atmospheric extinction and C(Hβ) is the logarithmic reddening correction at Hβ presented in Table 1.

The observed F(5876)/F(Hβ) and F(7065)/F(Hβ) flux ratios come from Peimbert and Torres-Peimbert (1971). The observed F(10830)/F(Hβ) ratios come from: Peimbert and Torres-Peimbert for NGC 6572 and NGC 6803; Scrimger (1984) for NGC 7027, this ratio is in good agreement with those derived by Schwartz and Peimbert (1973) and Danziger and Goad (1973); an average of the values derived by Peimbert and Torres-Peimbert and by Scrimger for IC 418; and from Scrimger for NGC 7009 and NGC 7662.

The f(λ) values in Table 1 were derived from the Whitford (1958) reddening law and the C(Hβ) values from: Peimbert and Torres-Peimbert (1971), Torres-Peimbert and Peimbert (1977), Schwartz and Peimbert (1973), Scrimger (1984), Harrington *et al.* (1982), Le Van and

TABLE 1

LINE INTENSITIES[a]

λ	f(λ)	NGC 6572	NCG 6803	NGC 7009	NGC 7027	NGC 7662	IC 418
4861	0.000	0.00	0.00	0.00	0.00	0.00	0.00
5876	− 0.210	− 0.82	− 0.72	− 0.83	− 0.99	− 1.14	− 0.99
7065	− 0.400	− 1.01	− 1.00	− 1.32	− 1.22	− 1.51	− 1.27
10830	− 0.725	+ 0.07	+ 0.10	− 0.09	+ 0.02	− 0.25	− 0.11
C(Hβ)		0.44	0.56	0.17	1.38	0.20	0.35

a. Given by Log I (λ)/I(Hβ).

Rudy (1983), Kaler (1976) and Torres-Peimbert and Peña (1981).

It is estimated that the I(10830)/I(5876) and the I(7065)/I(5876) ratios in Table 1 are accurate within 0.04 dex (10%) at the 1σ level.

b) *Physical Conditions*

The O^{++} and the He^{+} zones almost coincide in all the theoretical models of H II regions and planetary nebulae, therefore to a very good approximation the electron temperatures of the He^{+} and the O^{++} zones are the same. Consequently, we will adopt for our computations the electron temperatures derived from the 5007/4363 [O III] ratio. For the electron densities we used a combination of those densities derived from the [S II], [O II], [Cℓ III] and [Ar IV] ratios. In Table 2 we present the adopted temperatures and densities, where the relevant references are those used for the line intensities in Table 1 plus the atomic data presented by Mendoza (1983). In addition for the electron density of NGC 7027 we used the value derived by Pequignot *et al.* (1987) which is in good agreement with that derived by Shields (1978) and Perinotto, Panagia, and Benvenuti (1980). The errors in the electron temperatures are of a few hundred degrees while the errors in the electron densities amount to about 0.10 dex; fortunately the density dependence is small for those objects with $N_e > N_c = 3229$ cm^{-3}.

TABLE 2

PHYSICAL CONDITIONS[a]

	NGC 6572	NGC 6803	NGC 7009	NGC 7027	NGC 7662	IC 418
t_4	1.05	1.00	1.00	1.30	1.30	1.00
n_4	2.1	0.90	0.60	8.0	0.40	1.5

a. $t_4 = 10^{-4}\ T_e$; $n_4 = 10^{-4}\ N_e$

III. POPULATION OF THE 2^3S HE^0 STATE

In principle we have two independent line intensity ratios: I(10830)/I(5876) and I(7065)/I(5876), and three unknowns: a) the fraction of the collisional contribution to the He I lines, b) the optical thickness of the He I triplet system to atomic absorption, and c) dust absorption within the nebula. For the time being we will assume that dust absorption is negligible, we will come back to this assumption later on.

Robbins (1968*a*) has computed the effect that atomic absorption has on the He I line intensity ratios and has used as a parameter the λ3889 He I optical depth, $\tau_A(3889)$. For convenience we will use $\tau_A(3889)$ which is related to the λ10830 optical depth by: $\tau_A(10830) = 23.6\ \tau_A(3889)$ (e.g., Robbins).

a) *Collisional Excitation*

From steady state considerations involving the 2^3S level we find

$$N(2^3S) = \frac{N_e N(He^+)\, \alpha_{tri}(T_e)}{D_T} \quad , \qquad (2)$$

where

$$\alpha_{tri}(T_e) = 2.04 \times 10^{-13}\ t_4^{-0.73}\ cm^3\ s^{-1} \qquad (3)$$

is the effective recombination coefficient to the triplet series (Brocklehurst 1972), $t_4 = T_e/10^4$ K; N_e, $N(He^+)$ and $N(2^3S)$ are the electron, singly ionized helium and 2^3S state densities. D_T is the total depopulation rate given by

$$\begin{aligned} D_T(2^3S) = {} & A(2^3S, 1^1S) + [C(2^3S, 1^1S) + \\ & + C(2^3S, 2^1S) + C(2^3S, 2^1P)]\, N_e + \\ & + D_i(Ly\alpha) + D_i(\text{stellar}) + D_i(\text{coll}) + D_e + \\ & + D_a(2^3S \rightarrow 2^3P, 1^1S) = \\ = {} & D_A + D_C + D_i(Ly\alpha) + D_i(\text{stellar}) + D_i(\text{coll}) + \\ & + D_e + D_a(2^3S \rightarrow 2^3P, 1^1S) , \end{aligned} \qquad (4)$$

where $A(2^3S, 1^1S) = 1.13 \times 10^{-4}\ s^{-1}$ is the Einstein transition coefficient (Drake 1971; Hata and Grant 1981). D_C is the triplet-singlet exchange collision rate, and can be approximated by (Berrington and Kingston 1987)

$$\frac{D_C}{N_e} = 3.50 \times 10^{-8}\ t_4^{0.24}\ cm^3\ s^{-1} \quad , \qquad (5)$$

over $1.0 \leqslant t_4 \leqslant 2.0$, where we did not consider terms involving levels with n = 3 since they contribute with less than 3% to D_C over the temperature range of interest; $D_i(Ly\ \alpha)$ denotes the ionization rate from the 2^3S state due to the Lyman α radiation field, D_i(stellar) denotes the ionization rate from the 2^3S state due to direct stellar radiation (e.g., Capriotti 1967; Persson 1972), D_i(coll) denotes the collisional ionization from the 2^3S state; D_e denotes the excitation rate of doubly excited autoionizing states of helium by line emission from the central star (Robbins 1968*b*) and D_a denotes the depopulation by the 2^3P, 1^1S intercombination transition

(Drake and Robbins 1972). Notice that in equations (7) and (8) of paper I, that correspond to equations (4) and (5) of this paper, N_e was inadvertently omitted.

From these approximations, equation (2) can be written as

$$\frac{N(2^3S)}{N(He^+)} = \gamma \frac{5.82 \times 10^{-6}\, t_4^{-0.97}}{(1 + 3229\, t_4^{-0.24}\, N_e^{-1})} , \qquad (6)$$

where

$$\gamma = (D_A + D_C)/[D_A + D_C + D_i(Ly\alpha) + D_i(\text{stellar}) + D_i(\text{coll}) + D_e + D_a(2^3S \rightarrow 2^3P, 1^1S)]$$

$$= \frac{D_A + D_C}{D_A + D_C + D_i(\text{total}) + D_a(2^3S \rightarrow 2^3P, 1^1S)} . \qquad (7)$$

The ratio of the collisional excitation rate to the recombination rate of λ10830 is given by

$$\frac{I(10830)_C}{I(10830)_R} = N(2^3S)N_e[C(2^3S, 2^3P) + C(2^3S, 3^3S) + C(2^3S, 3^3D)]/N(He^+)N_e\,\alpha(10830)_{eff} , \qquad (8)$$

where $\alpha(10830)_{eff}$ is the effective recombination coefficient in $cm^3\ s^{-1}$ and the C terms are the collisional rates in $cm^3\ s^{-1}$. From the work of Berrington and Kingston (1987) the collisional rates in the $1.0 \leqslant t_4 \leqslant 2.0$ range can be approximated by

$$C(2^3S, 2^3P) = 7.52 \times 10^{-7}\, t_4^{0.31}\, e^{-1.330/t_4} , \qquad (9)$$

$$C(2^3S, 3^3S) = 7.11 \times 10^{-8}\, t_4^{-0.48}\, e^{-3.364/t_4} , \qquad (10)$$

and

$$C(2^3S, 3^3D) = 6.16 \times 10^{-8}\, t_4^{0.22}\, e^{-3.776/t_4} . \qquad (11)$$

From the C values in equations 9–11, the $\alpha(10830)_{eff}$ value by Brocklehurst (1972) and equation (8), it follows that

$$\frac{I(10830)_C}{I(10830)_R} = \gamma(2.99 \times 10^1\, t_4^{0.21}\, e^{-1.330/t_4} + 2.82\, t_4^{-0.58}\, e^{-3.364/t_4} + 2.45\, t_4^{0.12}\, e^{-3.776/t_4})/(1 + 3229\, t_4^{-0.24}\, N_e^{-1}) , \qquad (12)$$

the contribution of the $C(2^3S, 3^3S)$ and $C(2^3S, 3^3D)$ terms to the total collisional rate is in the 2% to 4% range for the temperatures of interest; C terms involving collisional excitation to higher energy levels followed by the production of 10830 photons are negligible in comparison to the $C(2^3S, 2^3P)$ term. It should be noted that the $C(2^3S, 2^3P)$ term computed by Berrington and Kingston (1987) differs by less than 1% in the $0.5 \leqslant t_4 \leqslant 1.5$ range from that computed by Berrington *et al.* (1985).

Similar expressions can be derived for the $\lambda\lambda$5876 and 7065 He I lines and they are (see paper I).

$$\frac{I(5876)_C}{I(5876)_R} = \gamma\ (7.27\, t_4^{0.39}\, e^{-3.776/t_4} + 3.01\, t_4^{-0.04}\, e^{-4.544/t_4}) \times (1 + 3229\, t_4^{-0.24}\, N_e^{-1})^{-1} \qquad (13)$$

and

$$\frac{I(7065)_C}{I(7065)_R} = \gamma(58.3\, t_4^{-0.94}\, e^{-3.364/t_4} + 4.39\, t_4^{-0.84} \cdot e^{-3.698/t_4} + 2.92\, t_4^{-0.79}\, e^{-4.511/t_4}) \times (1 + 3229\, t_4^{-0.24}\, N_e^{-1})^{-1} . \qquad (14)$$

In Figure 1 we present the behavior of $I(10830)_{R+C}/I(10830)_R$ as a function of N_e and T_e for $\gamma = 1$. In Figure 2 we present the $[I(10830)/I(5876)]_{R+C}/[I(10830)/I(5876)]_R$ behavior as a function of N_e and T_e for $\gamma = 1$.

In Table 3 we present the ratio of the observed to the computed line intensity ratios for $\gamma = 1$ and $\tau_A(3389) = 0$. As can be seen from this table the 10830/5876 ratios are smaller than predicted while the 7065/5876 ratios are higher than predicted.

b) *Optical Depth Effects due to Atomic Absorption*

The dependence of the 10830/5876 and 7065/5876 intensity ratios on $\tau_A(3889)$ has been computed by Robbins (1968*a*). Robbins starts with the recombination ra-

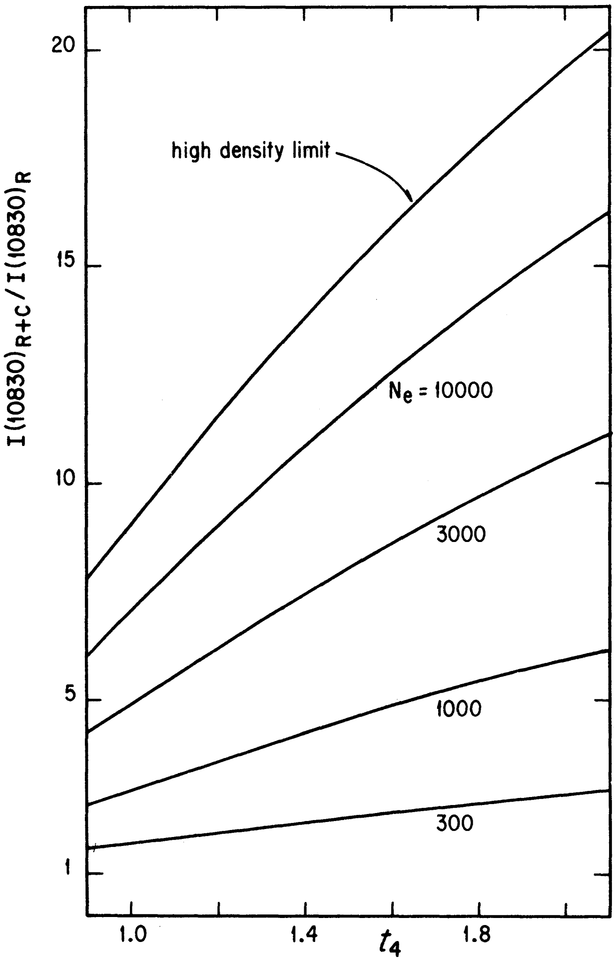

Fig. 1. Density and temperature dependence of the total I(10830) line intensity, recombination plus collisional terms, relative to the recombination term for $\gamma = 1$.

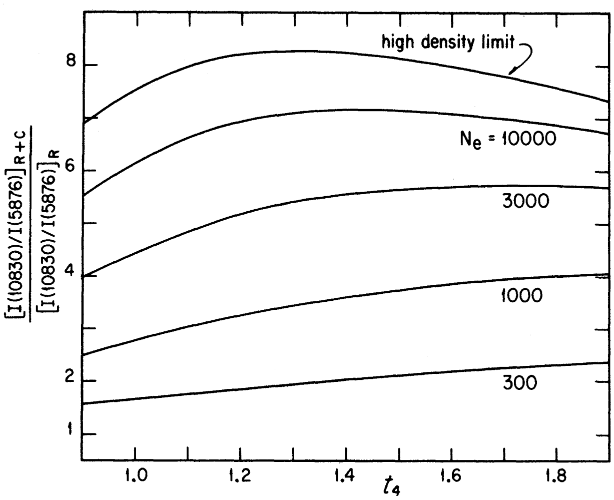

Fig. 2. Density and temperature dependence of the total I(10830)/I(5876) intensity ratio, recombination plus collisional terms, relative to the recombination ratio for $\gamma = 1$.

TABLE 3

OBSERVED TO PREDICTED LINE RATIOS FOR $\gamma = 1$ AND $\tau_A = 0$

Line Ratio	NGC 6572	NGC 6803	NGC 7009	NGC 7027	NGC 7662	IC 418
I(10830)/I(5876)	0.68	0.68	0.62	0.73	0.77	0.72
I(7065)/I(5876)	2.05	1.96	1.28	1.38	1.27	1.85

tios for the He I triplet series, $\tau_A(3889) = 0$, and computes the changes in the line ratios for different values of τ_A. Even if the recombination ratios for $\tau_A = 0$ adopted by Robbins differ somewhat from those by Brocklehurst (1972) we consider that the relative changes computed by Robbins are accurate enough to constitute a very good first approximation to this problem.

Both line intensity ratios, 10830/5876 and 7065/5876, depend on different functions of γ and τ_A, therefore for each object we have a system of two equations and two unknowns. In Table 4 we present the γ and τ_A (3889) values needed to reach agreement for both line ratios.

TABLE 4

γ AND τ_A (3889) VALUES FOR AGREEMENT BETWEEN THEORY AND OBSERVATIONS

	NGC 6572	NGC 6803	NGC 7009	NGC 7027	NGC 7662	IC 418
γ	0.50	0.52	0.47	0.55	0.62	0.57
τ_A (3889)[a]	38	29	9.5	10.5	6.5	22
τ_A (10830)[a]	897	684	224	248	153	519

a. Optical depth for V(R)/V(th) = 3, from Robbins (1968*a*)

In Figures 3 and 4 we present γ versus τ_A diagrams for NGC 7009 and NGC 7027. NGC 7009 and NGC 7027 represent two extreme cases of our sample, NGC 7009 is a low N_e, low T_e object while NGC 7027 is a high T_e and the highest N_e object. From Figures 3 and 4 it follows that an error of 500 °K in the adopted T_e produces an error of only 0.02 to 0.05 in the γ value; on the other hand an error of 10% in the 10830/5876 line intensity ratio introduces an error of about 0.10 in γ while an error of 10% in the 7065/5876 line intensity ratio introduces an error smaller than 0.02 in γ for the objects in our sample. If instead of using the 10830/5876 line intensity ratio given in Table 1 for NGC 7027 we had used the one presented by Pequignot *et al.* (1987) the γ value would have been reduced from 0.55 to 0.51.

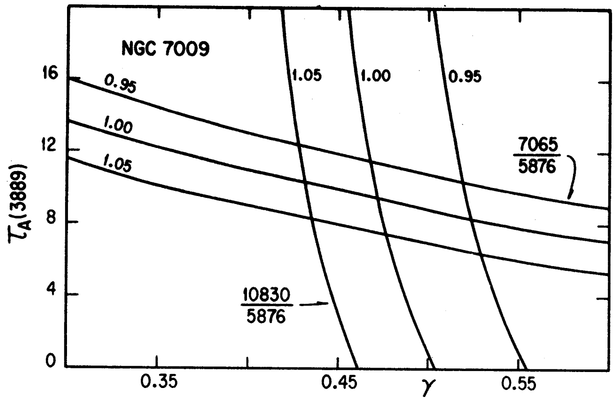

Fig. 3. NGC 7009 γ versus $\tau_A(3889)$ diagram for different values of t_4, the electron temperature.

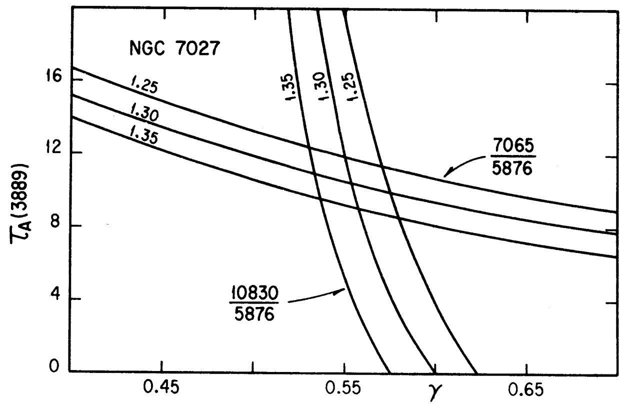

Fig. 4. Same as Figure 3, but for NGC 7027.

c) *Internal Dust Absorption*

Inside gaseous nebulae a very small amount of dust can cause significant absorption of radiation in optically thick lines because of the increased path length travelled by the photons as they are scattered by atomic absorption, this could be the case for the λ10830 He I line.

From infrared observations, it has been found that the M_{dust}/M_{gas} ratio diminishes as the size of PN increases (e.g., Natta and Panagia 1981; Pottasch *et al.* 1984). Moreover, even if M_{dust}/M_{gas} were constant, τ_D would decrease like $1/r^2$ as the nebula expands for a matter bounded nebula. Due to these two effects, dust destruction and expansion, we would expect a correlation of γ with N_e in the sense that the higher the N_e value the lower the γ value. Since there is no correlation between N_e and γ it can be concluded that dust is not affecting substantially the I(10830)/I(5876) line intensity ratio.

A similar argument can be made from the fact that there is no correlation between γ and $\tau_A(3889)$, where again we would expect a lower value of γ for a higher value of $\tau_A(3889)$.

In addition to these qualitative arguments, it is possible to make a quantitative estimate of $\tau_D(10830)$ for IC 418. For this object the He^+ zone almost coincides with the C^{++} zone (e.g., Flower 1969), therefore the same amount of dust will be affecting the C^{++} zone and the He^+ zone. Clavel, Flower, and Seaton (1981) found that the calculated ratio of the flux in C II λ1335 relative to that in C II λ4267 (both lines produced by recombination in the C^{++} zone) is about 0.54 times smaller than the observed ratio. They suggest that the discrepancy is probably due to some absorption of the C II λ1335 resonance lines by dust internal to the nebula. Clavel *et al.* estimated that $\tau_A(1335) \sim 10^4$; therefore, from the computations by Hummer and Kunasz (1980) they found that the required dust optical depth at λ1335 is $\tau_D(1335) = 0.08$.

From the reddening law by Seaton (1979) in the λ1335 to λ4861 range and that by Whitford (1958) in the λ4861 to λ10830 range, it is found that the absorption ratio is given by A(10830)/A(1335) = 0.114, therefore it follows that $\tau_D(10830) = 0.009$. From this value of τ_D the $\tau_A(10830)$ for IC 418 presented in Table 4 and the computations by Hummer and Kunasz (1980) it is found that the I(10830)/I(5876) decrease is smaller than 3%.

If instead of the C(Hβ) value of 0.25, adopted by Clavel *et al.* (1981), the value of C(Hβ) = 0.35 adopted in this paper is used, then the calculated I(1335)/I(4267) C II ratio over the observed ratio becomes about 0.94. Therefore $\tau_D(1335)$ becomes about 0.01 and $\tau_D(10830) \sim 0.001$ which produces a negligible effect on the I(10830)/I(5876) line intensity ratio.

Pequignot *et al.* (1987), from a model of NGC 7027 and the predicted intensity of the λ1550 C IV resonance lines, have estimated that $\tau_D(1550) \sim 0.05$ which implies a $\tau_D(10830) \sim 0.007$. The C^{+++} zone, where the C IV lines originate, is internal to the He^+ zone, but if the M_{dust}/M_{gas} ratio is the same in both zones, we would expect a similar $\tau_D(10830)$ value in the He^+ zone and consequently a decrease in the I(10830)/I(5876) of a few per cent at most. Note that the ionized part of NGC 7027 is surrounded by a neutral region; this neutral region has a high τ_A(Ly α) but $\tau_A(10830) = 0$ since most of the helium atoms are in the 1^1S state. Moreover, the contribution to $\tau_D(10830)$ by this zone has already been considered by the reddening correction made in Table 1.

Harrington, Lutz, and Seaton (1981), and Harrington *et al.* (1982) by comparing the C III λ2297 to C IV λ1549 fluxes in NGC 7009 and NGC 7662 found that $\tau_D(1549) \sim 0.1$, which implies that in the C^{+3} zone $\tau_D(10830) \sim 0.013$. The C^{+3} zone in the models of Harrington *et al.* (1982) for NGC 7662 (see their figures 12 and 13) is larger than the He^+ zone (and includes it); furthermore, at the external edge of the nebula the $N(C^{+3})/N(C)$ ratio is still about 20%; therefore, for these two objects, $\tau_D(10830)$ would be even smaller than 0.013 in the He^+ zone. From the computations by Hummer and Kunasz (1980), the $\tau_A(10830)$ values in Table 4 for NGC 7009 and NGC 7662 and $\tau_D(10830) < 0.013$ it follows that the I(10830)/I(5876) ratios would be reduced at most by a few percent due to internal dust absorption.

From the previous considerations we have neglected the internal dust absorption effect on the I(10830)/I(5876) line intensity ratios.

III. DISCUSSION AND CONCLUSIONS

From the *UV* resonance line intensities, C II λ1335 and C IV λ1550, estimates of $\tau_D(10830)$ were made. It was found that for IC 418 the expected reduction of the I(10830)/I(5876) ratio due to dust absorption is negligible, while for NGC 7009, NGC 7027 and NGC 7662 amounts to, at most, a few percent. From these and other considerations we conclude that the effect of internal dust absorption on the I(10830)/I(5876) observed ratios is negligible.

By comparing the observed and predicted I(10830)/I(5876) and I(7065)/I(5876) ratios we found γ values in the 0.47 to 0.62 range with an average value of 0.54 for the six objects considered in this paper. This value of $\langle \gamma \rangle$ is in good agreement with the value of $\langle \gamma \rangle = 0.37$ found from six PN of Type I in Paper I.

The value of $\langle \gamma \rangle$ implies that the 2^3S He^0 level is underpopulated by about a factor of two if only the $(D_A + D_C)$ term in equation (4) is taken into account.

There are at least three explanations for the underpopulation of the 2^3S level: a) that the computations by Berrington and Kingston (1987) overestimate the collisional contribution to the λλ3889, 4471, 5876, 6678, 7065 and 10830 He I lines by about a factor of two, which is unlikely; b) that the $(D_A + D_C)$ term has been underestimated by about a factor of two, which also is unlikely (notice that if this were the case $\gamma \sim 1$ but $N(2^3S)$ still would be smaller by a factor of two and consequently that the collisional effects would be smaller by the same amount), and c) that the ionizations from the 2^3S level, the D_i(total), in equation (7), plus the D_a term are comparable to the depopulations due to the $(D_A + D_C)$ term. This last possibility should be explored further.

The reduction of the collisional rates involved in the λλ5876 and 6678 line intensities by about a factor of 1.6 plus the reduction by about a factor of 2 due to the γ value reduce the collisional effects by about a factor of 3 with respect to the equations presented by Ferland (1986). This result, combined with the low electron densities found in O-poor extragalactic H II regions, makes the reduction of the N(He)/N(H) ratios due to collisional effects almost negligible (see also the discussion in Paper I). On the other hand, the reduction of the N(He)/N(H) abundances in PN of Type I is small but significant and should be taken into account.

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