Ly-α RADIATION DENSITIES IN PLANETARY NEBULAE

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1. Introduction

The average Ly-α radiation densities are calculated for 9 planetary nebulae from the observed $\lambda 10830/\lambda 5876$ line-intensity ratios under the assumption that the 2^3S state of He I is depopulated via photo-ionization by Ly-α radiation. Three of the nebulae are probably optically thick in their respective hydrogen Lyman continua. For these objects, the Ly-α radiation densities as determined from the $\lambda 10830/\lambda 5876$ line-intensity ratios may represent the actual Ly-α radiation densities. If they do, then the Ly-α radiation pressures exceed the respective gas pressures in these objects. For the remaining nebulae, it seems that the observationally determined Ly-α radiation densities are representative only if either one or both of the following conditions is fulfilled in each case:

(1) The object is essentially optically thick in the hydrogen Lyman continuum when other properties show it to be optically thin in the hydrogen Lyman continuum.

(2) We are viewing the object during a specific 100-year time span during the course of its evolution.

For these objects, the gas pressures probably exceed the respective Ly-α radiation pressures.

2. Lyman-α Radiation Densities

In recent years, much attention has been turned to the dynamical structure and the origin of the condensations of the planetary nebulae. Mathews (1966) and Sofia and Hunter (1967) have constructed theoretical dynamical models under the assumption that the gas pressure is the driving force. The studies of the origin of the condensations as a thermal instability phenomenon by Zanstra (1955), Daub (1963), Sofia (1966), and Harrington (1967) are all based on the assumption that the total pressure is essentially equal to the gas pressure. However, Ly-a radiation is imprisoned in the planetary nebulae to the extent that it may, in some cases, be greater than the gas pressure. Here, we report on estimates of the ratios of the Ly-a radiation pressure and the gas pressure for 9 planetary nebulae.

Münch (1963, private communication) suggested that photo-ionization by Ly-α radiation is the most important mechanism working in the depopulation of the 2^3S state of helium in the planetary nebulae. O'Dell (1965), following this suggestion, was

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able to estimate for each of 9 planetary nebulae the mean distance (in units of the nebular radius) traveled by a Ly-α photon before it is lost by the radiation field in the nebula if the 2^3S state of helium is depopulated through photo-ionization by Ly-α radiation. These estimates were obtained indirectly from the observed $\lambda 10830/\lambda 5876$ line intensity ratios. The $\lambda 10830$ line is excited by collisions to the 2^3P state from the 2^3S state as well as by capture-cascade processes, while the $\lambda 5876$ line is excited almost entirely by capture-cascade processes. The observed $\lambda 10830/\lambda 5876$ line-intensity ratios are then measures of the relative population densities of the 2^3S state of neutral helium. O'Dell also showed that two-photon transitions to the ground state and collisional transitions to the ground state and the 2^1S state are too slow to account for the observed values of the relative population densities of the 2^3S state. In this manner, support was lent to the idea that photo-ionization by Ly-α radiation is the chief mechanism for the depopulation of the 2^3S state.

We denote the mean distance (in units of the nebular radius) traveled by a Ly-α photon before it is lost by the nebular radiation field by f. f is also the mean Ly-α radiation density in units of the Ly-α radiation density for the case where the mean transit time of a photon is R/c. R is the nebular radius and c is the speed of light. Column 2 of Table 1 lists values of f calculated by O'Dell (1965).

It may appear that one could apply any theoretical model to the objects listed in Table 1 and obtain matching values of f by simply adjusting the optical thickness in

Table 1

Interpretations of the data under the assumption that the 2^3S state of helium is depopulated through photo-ionization by Ly-α radiation

Object	f	$1/\lambda$	P(Ly-α)/P(gas)	t
IC 418*	$1{\cdot}3 \times 10^2$	$4{\cdot}0 \times 10^8$	15	32
IC 2149	$7{\cdot}3 \times 10^2$	$3{\cdot}9 \times 10^8$	31	41
NGC 2392	$4{\cdot}0 \times 10^2$	$6{\cdot}6 \times 10^8$	16	120
IC 4997*	$5{\cdot}3 \times 10$	$2{\cdot}5 \times 10^8$	10	0·25
BD + 30°3639	$5{\cdot}2 \times 10^3$	$6{\cdot}6 \times 10^8$	80	310
NGC 6572	$8{\cdot}3 \times 10^2$	$6{\cdot}6 \times 10^8$	7·5	480
NGC 7009	$1{\cdot}5 \times 10^3$	$5{\cdot}8 \times 10^8$	46	110
NGC 7027*	$3{\cdot}8 \times 10^2$	$5{\cdot}8 \times 10^8$	5·2	230
NGC 7662	$6{\cdot}7 \times 10^2$	$8{\cdot}1 \times 10^8$	9·0	430

* Has measurable [OI] lines in spectrum.

the Ly-α line. In attempting to represent real planetary nebulae by theoretical models, however, one must keep in mind the fact that Ly-α photons can be lost by the radiation field through conversion to the two-photon continuum. The third column in Table 1 lists values of the inverse of the probability that a Ly-α photon will be converted to the two-photon continuum as a result of a single scattering. These values are

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denoted by $1/\lambda$. The number of scatterings suffered on the average by a Ly-α photon before it is lost by the radiation field is bounded by the value of $1/\lambda$. Therefore, for a given model, there is a largest possible value of f, and this value of f is set by the value of $1/\lambda$. Of the objects listed in Table 1, only IC 418 and IC 4997 can be represented by isothermal models, although the value of f for NGC 7027 is close to the range of values allowed by an isothermal model. In all other cases, the values of f listed in Table 1 are far too large to be consistent with an isothermal model. It is interesting to note that IC 418, IC 4997 and NGC 7027 have measurable [O I] lines in their spectra. The existence of these lines indicate that neutral oxygen atoms co-exist with electrons having thermal velocities corresponding to a temperature of the order of 10^4 °K. Hydrogen has the same ionization potential as oxygen and the presence of [O I] lines indirectly indicates that substantial amounts of neutral hydrogen co-exist with electrons near 10^4 °K. For example, Osterbrock (1964) estimated that roughly 26% of the hydrogen in NGC 7027 is neutral in regions where the electron temperature is of the order of 10^4 °K. It could well be that isothermal models represent fairly well the conditions in IC 418, IC 4997 and NGC 7027, and that the values of f listed in Table 1 are representative of the Ly-α radiation densities in these objects.

O'Dell (1965) suggested that a Yada-Osaki (1957) type model might represent the objects under consideration. This model consists of an H II region at 10^4 °K and a surrounding H I region at 10^2 °K. Indeed, the maximum values of f allowable for Yada-Osaki models are greater than the respective values of f listed in Table 1.

Let us suppose for a moment that the values of f computed from the He I lines are really representative of the Ly-α radiation densities in the 9 objects under consideration. Column 4 of Table 1 lists the values of the ratios of the mean Ly-α pressure and the mean gas pressure estimated under the latter supposition. In each case, the Ly-α pressure is greater than the gas pressure. One must conclude, therefore, that if the values of f estimated under the assumption that the 2^3S state of helium is depopulated through photo-ionization by Ly-α radiation are representative of the true Ly-α radiation densities, then the Ly-α pressure dominates over the gas pressure in each case.

There is reason to believe, however, that the values of f listed in Table 1 are not representative of the Ly-α radiation densities for the objects under consideration with the possible exceptions of IC 418, IC 4997, and NGC 7027. Suppose that Yada-Osaki models apply to the objects in Table 1. One can then estimate for each object the length of time t, in years, in which it would take the surrounding H I region to be accelerated to a given speed, say 200 km/sec, under the driving force of the Ly-α pressure. The fifth column of Table 1 lists values of t. For a given object, the velocity gradient would become so large in a time t that the effective optical thickness in Ly-α would be greatly reduced. The Ly-α radiation density would then be much smaller than the initial value of f. The largest value of t listed in Table 1 is 480 years. We conclude that if the blanketing of Ly-α radiation by a surrounding H I region is the cause of the large observed values of f for a nebula, then this blanketing could occur for a short time when compared to the lifetime of the nebula. We feel that the probability of viewing a planetary nebula during this stage of development would be too small to account for the number seen to have the observed values of f.

For IC 418, IC 4997 and NGC 7027, isothermal models may be applicable. The Ly-α pressure gradient for isothermal models is small except in the outermost layers. These outermost layers of small mass can be accelerated to great speeds in a short time. However, contrary to the case of the Yada-Osaki model, the outer layers in the case of an isothermal model play an insignificant role in the trapping of Ly-α radiation. Therefore, the length of time involved before the Ly-α pressure is greatly reduced is much larger in the case of an isothermal model than in the case of a Yada-Osaki model having the same optical thickness in Ly-α. Furthermore, as pointed out above, evidence that large amounts of neutral hydrogen co-exist with electrons at temperatures of the order of 10^4 °K in IC 4997, IC 418 and NGC 7027 appears in the form of [O I] lines in the spectra. One knows that each of these objects is very probably optically thick in the Lyman continuum and that the optical thickness in Ly-α could well be large enough so that the values of f and P(Ly-α)/P(gas) listed in Table 1 are representative for IC 4997, IC 418, and NGC 7027.

The work of Harman and Seaton (1966) provides us with relevant results. They have estimated the black-body temperatures of the central stars of 35 planetary nebulae under the assumption that in each case there is a complete absorption of the radiation emitted by the central star in the Lyman continuum of He^+. NGC 2392, BD +30°3639, NGC 6572, NGC 7009 and NGC 7662 are among these objects. For each of these 5 objects, estimates of the black-body temperatures of the central stars under the assumption that there is a complete absorption in the hydrogen Lyman continuum yield values that are lower than the temperatures determined by Harman and Seaton. One interpretation is that there is incomplete absorption by neutral hydrogen (Würm and Singer, 1952; Harmon and Seaton, 1966). Capriotti (1967*a*) estimated upper and lower limits to the optical thicknesses in the hydrogen continua for NGC 2392, BD + 30°3639, NGC 6572, NGC 7009, and NGC 7662 as well as for other objects under the latter assumption. The upper limits to the optical thicknesses in the hydrogen Lyman continua are used in order to estimate the values of f and P(Ly-α)/P(gas) for each of the 5 objects. These values are listed in Table 2. In each case, the gas pressure dominates.

Table 2

Characteristic values of f and P(Ly-α)/P(gas)

Object	f	P(Ly-α)/P(gas)
NGC 2392	13	0·49
BD + 30°3639	12	0·19
NGC 6572	40	0·37
NGC 7009	27	0·85
NGC 7662	24	0·34

We conclude that high surface brightness objects, like NGC 7027, IC 418 and IC 4997 with [O I] lines in their spectra, are probably optically thick in their Lyman continua. The trapping of Ly-α radiation in such an object could be strong enough so that the Ly-α pressure exceeds the gas pressure. For objects that show evidence that they are optically thin in the hydrogen Lyman continua, we conclude that the gas pressure exceeds the Ly-α radiation pressure.

The values of the parameters (electron density, collision cross-sections, etc.) needed in order to make the calculations reported in this work were taken from O'Dell (1965) and Osterbrock (1964). The theoretical models were constructed by using available theories of Ly-α radiation transfer. In particular, we adopted the treatments of Osterbrock (1962) and Yada and Osaki (1957) (Capriotti, 1967*b*).

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