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Abstract

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ON ONE MECHANISM OF "SPLITTING" LYMAN-ALPHA QUANTA IN NEBULAE

(Presented by Academician V. A. Ambartsumian on 8 VIII 1961)

According to the theory of the luminosity of gaseous nebulae, of the total number of ultraviolet (L_c) quanta N_c absorbed by a nebula, on the average $2/3N_c$ quanta are produced in the hydrogen L_α line, while the remaining part, $1/3N_c$, goes into two-photon radiation. The question, however, of whether, under nebular conditions, the L_α-quanta existing in it can be split into two quanta by means of two-photon radiation constitutes an independent problem.

Until now two mechanisms of "splitting"of L_α-quanta have been known. The first mechanism, indicated by Spitzer and Greenstein ([1]), is as follows. A neutral hydrogen atom is transferred from the state $1S_{1/2}$ to the state $2P_{1/2,\,3/2}$ by absorption of an L_α-quantum. Because of the large density of L_α-radiation in nebulae, the relative population of the states $2P_{1/2}$ and $2P_{3/2}$ will not be a very small quantity. Therefore there is a certain probability that an atom excited in the states $2P_{1/2,\,3/2}$ is transferred, as a result of collisions with free electrons, to the level $2S_{1/2}$, whence the atom returns to the normal state $1S_{1/2}$ by two-photon radiation. It subsequently became clear ([2]) that, in transferring atoms from the states $2P_{1/2,\,3/2}$ to the state $2S_{1/2}$, collisions with protons are more effective. The probability of splitting of an L_α-quantum by this mechanism (cycle $1S \to 2P \to 2S \to 1S$), calculated per scattering event, will obviously depend on the electronic (proton) density of the medium $n_e (= n_p)$. It is given by the following formula ([3]):

$$p_1 = \frac{3.765 \cdot 10^{-13} n_e}{1 + 8.58 \cdot 10^{-5} n_e}. \tag{1}$$

The value p_1, determined by this formula, is of the order of 10^{-9}–10^{-10} for planetary nebulae, 10^{-11}–10^{-12} for diffuse nebulae and H I regions around planetary nebulae, and 10^{-17} for the interstellar medium.

The second mechanism of splitting of L_α-quanta, indicated by A. J. Kipper and V. M. Tyt ([4]), is as follows. The transition $2P \to 1S$ for hydrogen is allowed with the emission of one L_α-quantum. But this transition can also occur with the emission of two quanta, only with a much smaller probability ($\sim 2 \cdot 10^{-5}$ sec^{-1}). In this case (cycle $1S \to 2P \to 1S$) the probability of

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splitting of an L_α-quantum, calculated per scattering event, does not depend on the physical conditions of the medium and is of the order

$$p_2 \approx 0.5 \cdot 10^{-13}. \tag{2}$$

The probabilities of splitting of an L_α-quantum in both mechanisms are extremely small, and a very large number (of the order of 10^9–10^{13}) of scattering events is required for it to be inevitably destroyed, being converted into two quanta. For ordinary gaseous nebulae this condition is not fulfilled.

Along with this, one can indicate still another mechanism for the splitting of L_α-quanta under the conditions of nebulae and the interstellar medium—a third, more effective one. It is connected with the fact that the energy difference between the levels $2P$ and $2S$ of hydrogen is small and lies within the dispersion of the kinetic energy of the atoms caused by their thermal motions. In frequency units this difference is $1.092 \cdot 10^{10}$ sec^{-1}, which is equivalent to a difference between the velocities of two hydrogen atoms of 1.32 km/sec. Therefore, if the atom absorbing the L_α-quantum has a negative component of the "radial" velocity of motion relative to the atom emitting the given L_α-quantum of 1.32 km/sec, then the absorbing atom will be raised immediately to the metastable level $2S$, carrying out the transition $1S \to 2S$. An atom which has found itself at the $2S$ level under nebular conditions ultimately has only one path for returning to the normal level—the transition $2S \to 1S$ by emission of two quanta, irrespective of the magnitude of the probability of this transition with emission of only one quantum. This is the essence of the proposed mechanism for the splitting of L_α-quanta (the cycle $1S \to 2S \to 1S$).

The effectiveness of the mechanism described obviously depends above all on the probability of the transition $1S \to 2S$ for hydrogen. This transition is forbidden by the selection rules, and an exact calculation gives, for the lifetime of the $2S$-state in the case of magnetic dipole radiation, a value of the order of 10^5 sec ([5]). Recently, however, data have appeared, connected with the behavior of the positron in an external electric field ([6]), indicating that the positron and the electron must possess a small electric dipole moment. Feinberg ([7]) and Salpeter ([8]), considering the influence of this moment on the energy levels of the atom, pointed out, in particular, the possibility of mixing the metastable $2S$ level of hydrogen with the $2P$ level, as a result of which a substantial shortening of the lifetime of the atom in the $2S$ state may take place. A special experiment carried out by Fite et al. ([9]) confirmed this assumption: the lifetime of the $2S$-state of hydrogen proved to be of the order of $2.4 \cdot 10^{-3}$ sec. Hence we obtain the Einstein coefficient for spontaneous transition with emission of only one quantum, $A_{2S\to 1S} \simeq 0.4 \cdot 10^3$ sec^{-1}, i.e., about ~ 50 times greater than the Einstein probability coefficient for the transition $2S \to 1S$ with emission of two quanta ($A_{2q} = 8.227$ sec^{-1}).

A velocity difference equal to 1.32 km/sec corresponds to a kinetic temperature of the medium equal to 100°K. Therefore the indicated mechanism for

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splitting L_α-quanta can operate in all cases where the electron temperature of the medium is greater than 100°K, i.e. not only in ordinary gaseous nebulae, but also in clouds of interstellar neutral hydrogen. The question is what the probability of splitting of L_α-quanta is in this case.

The numbers of transitions $1S \to 2S$ and $1S \to 2P$ carried out by hydrogen atoms per unit time and per unit volume under the influence of L_α-radiation will obviously be $N_{1S,2S} = n_1 B_{1S,2S}\rho_\alpha$ and $N_{1S,2P} = n_1 B_{1S,2P}\rho_\alpha$, respectively, where n_1 is the concentration of neutral hydrogen atoms in the ground state; $B_{1S,2S}$ and $B_{1S,2P}$ are the Einstein coefficients for the probabilities of induced transitions; ρ_α is the density of L_α-radiation. Hence we can write for the probability of splitting of an L_α-quantum p_3 in the cycle $1S \to 2S \to 1S$:

$$p_3 = \frac{N_{1S,2S}}{N_{1S,2P}} \frac{A_{2q}}{A_{2q} + A_{2S,1S}} = \frac{g_{2S}}{g_{2P}} \frac{A_{2S,1S}}{A_{2P,1S}} \frac{A_{2q}}{A_{2q} + A_{2S,1S}} \simeq \frac{g_{2S}}{g_{2P}} \frac{A_{2q}}{A_{2P,1S}}, \quad (3)$$

where $A_{2S,1S} \gg A_{2q}$, and g_{2S} and g_{2P} are the statistical weights of the corresponding levels; $A_{2P,1S}$ is the Einstein coefficient of spontaneous transition $2P \to 1S$ with emission of one quantum.

Substituting in (3) $g_{2S}/g_{2P} = 1/3$, $A_{2q} = 8.227$ sec^{-1}, $A_{2P,1S} = 6.24 \cdot 10^8$ sec^{-1}, we find for p_3, calculated per one act of scattering,

$$p_3 = 0.44 \cdot 10^{-8}, \quad (4)$$

that is at least 1-2 orders of magnitude greater than in the case of the Spitzer-Greenstein mechanism, and 5 orders of magnitude greater than in the case of the Kipper-Tyt mechanism. Only for very dense planetary nebulae ($n_e \gg 10^5$ cm^{-3}) do the fragmentation probabilities in the case considered here and in the case of the Spitzer-Greenstein mechanism become equal in order of magnitude.

A result analogous to (4) was obtained in a somewhat different way by A. Sapar and I. Kuusik*.

In a more rigorous formulation of the problem one should take into account the influence of electron and proton collisions on the population of the $2S$ level (the deactivation effect ([10])); then, instead of (4), we shall have

$$p_3 = \frac{0.44 \cdot 10^{-8}}{1 + 6 \cdot 11^{-5} n_e}. \quad (5)$$

The dependence of p_3 on n_e is appreciable only at large values of the electron concentration ($n_e > 10^4$ cm^{-3}). At comparatively small values of n_e ($< 10^4$ cm^{-3}) the probability of fragmentation of an L_α-quantum is practically independent of the physical conditions of the medium. Therefore, other conditions being equal,

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this fragmentation mechanism may prove more effective than the other mechanisms in planetary nebulae of medium and low density, in diffuse nebulae, in zones of neutral hydrogen around gaseous nebulae, and in clouds of interstellar hydrogen. In all the enumerated cases, for the fragmentation of an L_α-quantum into two quanta it is necessary that it undergo on the average 10^8 scattering events.

The question of what the real probability is of fragmentation of an L_α-quantum during its stay within a nebula, or in a given volume of an interstellar-hydrogen cloud, depends on the total number of scattering and absorption events which, on the average, a single L_α-quantum undergoes. This question reduces, in turn, to the problem of diffusion of L_α-radiation with allowance for the real conditions in the medium. The most complete analysis of this problem was carried out by V. V. Sobolev, who showed, in particular, that both effects influencing the character of the L_α-radiation field—the velocity gradient of expansion of the medium and the redistribution of radiation over frequencies—play an equal role. Therefore, in order to calculate the number of scatterings $N(t)$ undergone by an L_α-quantum, we may use the results of a theory developed, for example, with allowance only for complete redistribution of radiation over frequencies. The corresponding formulae determining the parameters of the radiation field are given by V. V. Sobolev in ([11]). From these formulae one can derive for $N(t)$, where t is the optical thickness of the medium at the frequency of L_α-radiation:

$$N(t) = 2t\sqrt{\pi \ln t}. \tag{6}$$

This formula is valid for a Doppler profile of the absorption coefficient and for large values of t. In planetary nebulae t is of the order of 10^5, if one assumes that the optical thickness of the nebula τ_c at frequencies beyond the Lyman-series limit is of order unity. This gives $N \sim 10^6$, i.e., only about 1% of the L_α-quanta present in the nebula can be split into two quanta.

For complete fragmentation of all L_α-quanta present in the medium into two quanta, it is necessary that its optical thickness in the L_α-line be of the order of 10^7. One may indicate a number of cases when this condition can nevertheless be satisfied.

1. The zone of neutral hydrogen (the H I zone) surrounding a planetary nebula. A layer of neutral hydrogen with a thickness of the order of a thousand astronomical units will have an optical thickness in the L_α-line of the order of 10^7, if its temperature is 1000° K, and the concentration of neutral hydrogen in it is 10^3-10^4 cm^{-3}.

* Oral communication.

For many diffuse nebulae, τ_c is, in all probability, greater than unity. This means that they must be surrounded by an H I zone. Such a zone, with a thickness of the order of one parsec, must have an optical depth t of the order of 10^7, if in this zone one takes $T_e = 100$°K and $n_1 = 10 \div 100$ cm^{-3}. However, in order for this mechanism of fragmentation of L_α quanta to operate, the indicated zone must be "clean," i.e., free of dust; otherwise the L_α quanta, during multiple scatterings, may be absorbed by the dust.

3. Individual clouds, and even individual regions of interstellar hydrogen that are more or less "clean," can likewise be a suitable medium for the fragmentation of L_α quanta. At a temperature of these clouds of the order of 100°K, the radius of the zone where $t \sim 10^7$ is found to be 5.6, 18.7, and 56 parsecs for neutral-hydrogen concentrations, respectively, of 10, 3, and 1 per 1 cm^3.

Thus, although the probability of fragmentation of an L_α quantum in a single act of scattering, p_3, does not depend on the physical conditions of the medium, the actual probability that the L_α quanta will in general be split into two quanta depends substantially on the physical conditions of the medium. Since these conditions may differ greatly in going from one nebula to another, the relative intensities (with respect to the emission lines) of their continuous spectra must also differ from one another. Incidentally, such a scatter in the relative intensities of continuous spectra is observed both in planetary and in diffuse nebulae, and it cannot be explained within the framework of existing theories. It is possible that, in these and other cases, the phenomenon of fragmentation of L_α quanta plays some role.

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