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Abstract

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On the Question of the Polarization of Light in the Emission Lines of Nonstationary Stars Excited by the Synchrotron Radiation of Relativistic Electrons

(Presented by Academician V. A. Ambartsumian, 6 II 1958)

In recent years, variable nonthermal radiation in the spectra of nonstationary stars of various types has been discovered. V. A. Ambartsumian ([1]) and one of the authors ([2]) showed that the radiation with which the brightness variations of stars of the T Tauri and UV Ceti types are associated is nonthermal in nature. There are a number of grounds for assuming that the source of the nonthermal radiation of nonstationary stars is the synchrotron radiation of relativistic electrons. One of the authors developed a theory of the excitation of the emission spectra of nonstationary stars by synchrotron radiation ([3]). In these works it was shown that, if an emission spectrum is excited by linearly polarized radiation in the continuous spectrum, then the emission lines, under certain conditions, can also exhibit a considerable polarization of light. An analogous effect may also be produced by absorption lines.

The aim of the present work is to calculate the depolarization of the emission lines of hydrogen arising under various conditions of scattering of linearly polarized synchrotron radiation by excited hydrogen atoms. This calculation proves applicable also to other hydrogen-like atoms.

1. The polarization properties of light scattered by excited atoms were considered by V. L. German in ([4]). There a formula is also given for the probability of scattering of light.

Let us consider the case in which the excited state of a hydrogen atom arises as a result of the absorption of linearly polarized light. Since for hydrogen atoms there is degeneracy not only with respect to the magnetic but also with respect to the azimuthal quantum numbers, the formula for the probability of scattering takes the form

$$W_{N_4}^{N_1} \sim \sum \frac{1}{2I_1+1} \sum_{N_1 L_1 M_1} (f_{iklm})_{N_4 L_4 M_4}^{N_1 L_1 M_1} (f^*_{prst})_{N_4 L_4 M_4}^{N_1 L_1 M_1} l_j^{(1)} l_k^{(2)} l_l^{(3)} l_m^{(4)} l_p^{(1)} l_r^{(2)} l_s^{(3)} l_t^{(4)} \tag{1}$$

(the notation is the same as in ([4])). Averaging over the direction n_4 and l_4 (see ([4])) and introducing a coordinate system such that l_1 and l_2 are directed along the OX axis, and also taking into account that the ground state of hydrogen is $1S$ ($N_1 = N_4 = 1$; $L_1 = L_4 = 0$; $M_1 = M_4 = 0$), we obtain

$$W_{N_4}^{N_1} \sim (F_{1111s})_{N_l l}^{N_1 l^{(3)}} l_s^{(3)} \qquad (l, s = 1, 2, 3), \tag{2}$$

where F_{1111s} are components of a tensor of rank 6,

$$(F_{iklprs})_{N_4 L_4 M_4}^{N_1 L_1 M_1} = \sum_{L_2 M_2 L_3 M_3} (P_{iP} p^*)_{N_2 L_2 M_2}^{N_1 L_1 M_1} (C_{kl} C^*_{rs})_{N_3 L_3 M_3}^{N_2 L_2 M_2} (P_{mP} t^*)_{N_4 L_4 M_4}^{N_3 L_3 M_3}, \tag{3}$$

If the scattering of light occurs on gas atoms, then (2) must be averaged over space ([5,6]). Averaging by the method indicated in ([5]), we obtain:

$$W_{N_4}^{N_1} \sim \overline{F}_{111111} \left(l_1^{(3)}\right)^2 + \overline{F}_{112112} \left(l_2^{(3)}\right)^2 + \overline{F}_{113113} \left(l_3^{(3)}\right)^2, \tag{4}$$

where

$$\overline{F}_{111111} = \frac{1}{105} S_1, \quad \overline{F}_{112112} = \overline{F}_{113113} = \frac{1}{30} S_2 - \frac{1}{210} S_1.$$

The sums S_1 and S_2 depend on 15 invariants of the type F_{iklilk}, obtained from the tensor F_{iklprs} by contraction over three pairs of indices. Taking into account that, in the scattering of the H_α line, the excited states before and after scattering are $2S$ or $2P$, and that the tensor C_{kl} in the case of resonance scattering of the H_α line is equal to

$$C_{kl} = \sum_{L'M'} (P_k)_{3L'M'}^{21M_2} (P_l)_{21M_s}^{3L'M'}, \tag{5}$$

and calculating the matrix elements of the dipole moment by the formulas given in ([7]), we obtain for S_1' and S_2', in units of C, where C is a certain constant: $S_1' = 62.5$; $S_2' = 11$.

Let the propagation direction of the scattered light $n_1^{(3)}$ lie in the plane XY and form an angle α with the X axis. Then the depolarization coefficient will be equal to the ratio of the probability of scattering of a photon with polarization parallel to the Z axis to the probability of scattering with polarization parallel to the plane XOY:

$$\rho = \frac{W\left(l_3^{(3)} = 1;\ l_1^{(3)} = l_2^{(3)} = 0\right)}{W\left(l_1^{(3)} = -\sin\alpha;\ l_2^{(3)} = \cos\alpha;\ l_3^{(3)} = 0\right)}. \tag{6}$$

The minimum depolarization coefficient at $\alpha = \pi/2$ is 7%.

2. Let us consider the case when the excited state arises upon the transition of an electron to the second level from the continuous spectrum. Averaging (1) over $n^{(1)}$, $l^{(1)}$ and $n^{(4)}$, $l^{(4)}$, and introducing the same coordinate system as in the preceding case, we obtain

$$W_{N_4}^{v} \sim \sum \frac{1}{2L+1} \sum (F_{111s})_{N_4 L_4 M_4}^{vLM} l_1^{(3)} l_s^{(3)}; \tag{7}$$

here v is the electron velocity. Taking into account the selection rules for dipole moments leads to the result that the tensor components different from zero will occur only for two values of L—for 0 and 2.

Averaging (7) over space, we obtain

$$W_{N_4}^{v} \sim \sum \frac{1}{2L+1} \sum_{M_2 L_4 M_4} (F_{111s})_{N_4 L_4 M_4}^{vLM} l_1^{(3)} l_s^{(3)}. \tag{8}$$

We find the mean values of the tensor components analogously to the preceding case. The depolarization coefficient turns out to be 17.5%.

3. Let us now consider the case when excitation is produced by unpolarized light, while polarized radiation is scattered in the H_α line. In this case, averaging (1) also over $n^{(1)}$, $l^{(1)}$, we obtain, instead of (2),

$$W_{N_4}^{N_1} \sim (F_{111s})_{N_4}^{N_1} l_1^{(3)} l_s^{(3)}, \tag{9}$$

where F_{111s} are the components of a tensor of rank 4,

$$F_{klrs} = \sum_{L_2 M_2} \sum_{L_3 M_3} (P_{iP} i^*)_{N_2 L_2 M_2}^{N_1 L_1 M_1} (C_{kl} C_{rs}^*)_{N_3 L_3 M_3}^{N_2 L_2 M_2} (P_{mP} m^*)_{N_4 L_4 M_4}^{N_3 L_3 M_3}. \tag{10}$$

Averaging over space by the same method, we obtain

$$W_{N_4}^{N_1} \sim \overline{F}_{1111} (l_1^{(3)})^2 + \overline{F}_{1212} (l_2^{(3)})^2 + \overline{F}_{1313} (l_3^{(3)})^2, \tag{11}$$

where $\overline{F}_{1111} = \dfrac{1}{15} S_1$, $\quad \overline{F}_{1212} = \overline{F}_{1313} = -\dfrac{1}{6} S_2 + \dfrac{1}{30} S_1$.

S_1 and S_2 depend on three invariants $(F_{iikk}, F_{ikih}, F_{ikki})$ and have the following values (in units of C): $S_1 = 22.5$; $S_2 = 6$.
In this case the minimum depolarization coefficient will be equal to

$$\rho_{\min} = \frac{W(l_3^{(3)} = 1;\ l_1^{(3)} = l_2^{(3)} = 0)}{W(l_1^{(3)} = 1;\ l_2^{(3)} = l_3^{(3)} = 0)} = \frac{7.5}{45} = 17.5\%, \tag{12}$$

as in the preceding case.

4. Of some interest for the theory of spectra of nonstationary stars may be the case when excitation occurs under the action of linearly polarized light, while unpolarized light is scattered. Averaging formula (1) over $n^{(2)}$, $l^{(2)}$ –the directions of propagation and polarization of the scattered photon –introducing the coordinate system so that $l_1^{(1)} = 1,\ l_2^{(1)} = l_3^{(1)} = 0$, and averaging over space, we obtain the formula

$$W_{N_2}^{N_1} \sim \overline{F}_{1111}(l_1^{(3)})^2 + \overline{F}_{1212}(l_2^{(3)})^2 + \overline{F}_{1313}(l_2^{(3)})^2, \tag{13}$$

where $\overline{F}_{1111}, \overline{F}_{1212}, \overline{F}_{1313}$ are the mean values of the components of the fourth-rank tensor

$$F_{ilpr} = \sum_{N_1 N_3} (P_i)_{N_2}^{N_1} (C_{kl})_{N_3}^{N_2} (P_m)_{N_4}^{N_3} (P_p^*)_{N_2}^{N_1} (C_{kl}^*)_{N_3}^{N_2} (P_m^*)_{N_4}^{N_3}.$$

Computing the invariants, we find that the minimum depolarization coefficient is 75%. Thus, the maximum polarization in the H_α line, formed by the scattering of natural light by hydrogen atoms excited by linearly polarized light, is 25%.

5. Up to now we have considered the polarization properties of the H_α line. At the same time, the question of the degree of polarization of other lines of the Balmer series, as well as of the Balmer continuum, is of considerable interest. Calculation shows that the formulas obtained for the depolarization coefficient of the H_α line retain their form also for the corresponding cases of emission of other lines of the Balmer series, with only the difference that other radial integrals enter into the expression for the scattering matrix (R_{21}^{k2} instead of R_{21}^{32}). However, the radial integrals do not in any way affect the values of the depolarization coefficients. Therefore, the results obtained for the H_α line are valid for all higher members of the Balmer series, and also for the Balmer continuum. Let us note that in the case of the continuum the radial integrals R_{21}^{k2} are replaced by the radial integrals R_{21}^{v2}, where v is the velocity of the electron in the continuous energy spectrum.

The physical meaning of such a result is obvious. It is a consequence of the fact that the depolarization of the scattered light depends only on the symmetry of the state of the scattering atom, and not on the frequency of the scattered light. In the case of scattering of the Balmer series or the Balmer continuum, the depolarization under similar excitation conditions is determined only by the symmetry of the hydrogen atom in the second state.

6. Direct observations of the Lyman lines and the Lyman continuum in the spectra of nonstationary stars are at present still impossible, since for this it is necessary to carry out observations beyond the limits of the Earth' s atmosphere. At the same time, it is of some interest to estimate

depolarization in the Lyman lines and in the Lyman continuum. A calculation analogous to that given above shows that, in the scattering of linearly polarized light by hydrogen atoms in the ground state, the depolarization coefficient is equal to zero. This conclusion follows from the spherical symmetry of the ground state of the hydrogen atom.

Thus, we see that emission lines formed in the scattering of polarized light by excited hydrogen atoms must exhibit polarization of the light. Polarization under another mechanism of emission-line radiation, when the upper level of the Balmer line is populated through induced recombinations, and emission of the Balmer quantum occurs through induced radiation under the action of linearly polarized light, will be considered separately.

It follows from considerations connected with the correspondence principle that in this case as well polarization must occur ([3]).

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Note added in proof. We have additionally considered the question of the polarization of light in the lines of the Balmer series, studied in spontaneous transitions from levels $n \geqslant 3$, which were populated through induced recombinations under the action of linearly polarized radiation.

1. In the transition to the metastable level $2S$, the polarization of the corresponding line is negligibly small.
2. In the transition to the level $2P$ (with subsequent transition to the stationary state $1S$), the polarization does not exceed 25%.

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REFERENCES

[1] V. A. Ambartsumian, *Communications of the Byurakan Observatory*, **13**, 1 (1954).
[2] I. M. Gordon, *Dokl. Akad. Nauk*, **97**, 621 (1954).
[3] I. M. Gordon, *Dokl. Akad. Nauk USSR*, No. 6, 551 (1956); *Astron. Zh.*, **34**, 739 (1957); *Uch. Zap. Astron. Observ. Kharkov State Univ.*, **12**, 15 (1957).

[4] V. German, *Dokl. Akad. Nauk*, **42**, 168 (1944).
[5] V. L. Ginzburg, *ZhETF*, **9**, 1215 (1939).
[6] G. Placzek, *Rayleigh Scattering and the Raman Effect*, Kharkov–Kiev, 1935.
[7] K. Bethe, *Quantum Mechanics of the Simplest Systems*, 1935.

Note: Figure translations are in progress. See original paper for figures.