THE HYDROGEN ATOM KINETICS IN FLARE STAR CHROMOSPHERES

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ABSTRACT. The solution of steady-state equations for hydrogen is carried out. The diffuse radiation field was taken into account in these equations the value β≡NRB - the escape probability of photons from the medium. This value is calculated for a layer of motionless plasma with finite optical depth. Our results are compared with analogical ones using Sobolev's method.

1. INTRODUCTION

The spectra of red dwarf stars with high temporal resolution were recently obtained. These data show very peculiar behaviour of the Balmer decrement during the flares and out-of-flare for several stars. The theoretical analysis of this problem was possible if one uses calculations by Gershberg and Schnoll, 1974 (further GS). However, these authors employed Sobolev's method for consideration of the radiative transfer problems. In our case, the large gradients of velocity in red dwarf atmospheres are absent and increase of transparence of medium at the Lyman and Balmer lines is not connected with motions. We have carried out the consideration of hydrogen atom kinetics for the case of motionless medium.

2. THE BASIS OF METHOD FOR OPTICALLY THICK STATIONARY MEDIUM

Here, as in GS, we have been examined the statistical equilibrium equations for hydrogen plasma without account of the outer radiation field:

$$n_i\Big[\sum_{k=1}^{i-1}(A_{ik}+B_{ik}J_{ki})+\sum_{l=i+1}^{\infty}B_{il}J_{il}+n_e\Big(\sum_{k=1}^{i-1}q_{ik}+\sum_{l=i+1}^{\infty}q_{il}+q_{ic}\Big)\Big]=$$
$$=\sum_{l=i+1}^{\infty}n_l(A_{li}+B_{li}J_{il})+\sum_{k=1}^{i-1}n_k B_{ki}J_{ki}+n_e\Big(\sum_{l=i+1}^{\infty}n_l q_{li}+\sum_{k=1}^{i-1}n_k q_{ki}\Big)+ \qquad (1)$$
$$+n_e n_p C_i+n_e^2 n_p Q_{ci}$$

where n_i, n_k, n_l are populations of relevant quantum levels of neutral

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hydrogen atoms, n_e, n_p are electron and proton densities, A and B are the Einstein probabilities, J is mean intensity $\int I_\nu d\omega/4\pi$ at the frequences of lines, q is the rate of excitation by electron collisions, C_i is the coefficient of recombination, Q_{ci} is the coefficient of triple recombination to the level i.

We transform system (1), as GS by introducing the Mensel's parameter b_i

$$\frac{n_i}{n_e n_p} = b_i \frac{i^2 h^3}{(2\pi m k T_e)^{3/2}} \exp \chi_i \qquad (2)$$

where $\chi_i = h\nu/kT_e$ is the ionization potential of relevant quantum state in units kT_e, n_i is the population of the same level. Taking into account the previous results, in particular, the conclusion about the equilibrium populations of the upper level, i.e. $b_i=1$ for $i \geqslant 9$ in all the range of physical conditions discussed, we are confined to consideration of the hydrogen atom model "8 levels plus continuum" only.

The influence of radiative transfer in lines on the hydrogen atom kinetics will take into account by introduction in (1) of the escape probability of a photon from a layer β_{ik}=NRB for each of the lines. Otherwise, the diffuse radiation field J_{ki} for each of $i \to k$ transitions is excluded from (1) as follows

$$n_i(A_{ik} + B_{ik}J_{ki}) - n_k B_{ki} J_{ki} = n_i A_{ik} \beta_{ik} \qquad (3)$$

In our case the value β_{ik} is determined by escape of photons at frequencies of the line wings. Taking into account a weak dependence of solution of system (1) on β_{ik}, i.e. the solutions of radiative transfer equations, we shall use in (3) the value β_{ik} averaged over the layer.

We compute the value β_{ik} for layer with fixed optical depth at $L\alpha$ line. Assume for simplicity that primary sources of photons are distributed uniformly over a layer: S^*=const. Then using an expression for the mean number of scatterings $\bar{N}_o$ (Ivanov, 1973) and Ivanov's, 1972 approximation for the function $X(\infty,\tau)$, we can obtain

$$\bar{N}_0 = \frac{1}{\tau_0}\int_0^{\tau_0} X^2(\infty,\tau)\,d\tau = \frac{1}{\tau_0}\int_0^{\tau_0} \frac{d\tau}{1-\lambda+\lambda L(\tau)}$$

or

$$\bar{\beta}_{ik} = \beta = 1 - (1-\lambda)\bar{N}_0 = 1 - \frac{1-\lambda}{\tau_0}\int_0^{\tau_0} \frac{d\tau}{1-\lambda+\lambda L(\tau)} \qquad (4)$$

Here λ is the probability of photon surviving by single scattireng for each line, $L(\tau)$ is the function, which determines the escape probability of a photon from a medium without any scattering:

$$L(\tau) = 2\int_0^\infty \alpha(x)\,Ei_2\left(\frac{\alpha(x)}{\alpha(0)}\tau\right) dx$$

where $\alpha(x)$ is absorption coefficient from Vidal et al.,1973, x is the distance from the line centre. This function for $n_e=10^{13}$ and 10^{14} cm^{-3} and $T=10^4$ K was given earlier (Bruevich et al.,1989).

3. RESULTS AND DISCUSSION

We have calculated $L(\tau)$ and β for each set of physical parameters ne, T, $\tau(L\alpha)$ and all the lines. For solution of steady-state equations (1), the method NONLINEAR was used, which leads (1) to the system of weak nonlinear equations.

First of all, we repeated the GS'computation of n_i for $n_e=10^{12}-10^{14}$ cm^{-3} with calculation of β after the formulae given there. Taking these n_i values as a first approximation, we find the optical depths τ_{ki} for all the lines as

$$\frac{\tau_{ki}}{\tau_{12}} = \frac{\alpha_{ki}(0)}{\alpha_{12}(0)} \cdot \frac{n_k}{n_1}$$

Then we calculate β after (4) and carry out the solution of system (1). Then, finding once again the relative scale of optical depths, we determined once more τ_{ki} and repeated the solution of system (1) with recalculated value of β. This is enough to obtain the final result, given in Table for $T=10^4$ K.

Thus, our consideration supports the GS's results and shows that reference to velocity field is not necessary. If we put GS's parameter β_{21}equal to $1/\tau(L\alpha)$, their solution is described well by b_i, n_i-values, especially in the case of $n_e=10^{14}$ cm^{-3}; also the general conclusions of GS's consideration hold true. For $n<10^{14}$ cm^{-3} some numerical discrepancies appear, see Table.

The solution of steady-state equations depends on the value β_{ik} weakly. The precision in computation of β from (4) is enough to determine of values n_i with sufficient accuracy.

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TABLE

T=1E4	$\tau(L\alpha)$=1E8	ne=1E14			ne=1E13 $\tau(L\alpha)$=1E8		Method GS β_{21}=1E-8 ne=1E13	
i	β_{i1}	β_{i2}	b_i	n_i	b_i	n_i	b_i	n_i
1	-	-	4.96	1.5E14	231.8	6.9E13	27.52	8.2E12
2	1.0E-3	-	1.51	1.3E9	7.44	6.4E7	4.87	4.2E7
3	4.0E-3	4.32E-3	1.12	2.4E8	2.31	5.0E6	1.6	3.5E6
4	1.5E-2	2.48E-2	1.02	1.8E8	1.19	2.1E6	1.13	2.0E6
5	3.4E-2	5.18E-2	1.00	2.0E8	1.04	2.0E6	1.04	2.0E6
6	7.8E-2	8.55E-2	1.00	2.3E8	1.01	2.3E6	1.01	2.3E6
7	0.126	0.123	1.00	2.8E8	1.00	2.8E6	1.00	2.8E6
8	0.226	0.175	1.00	3.4E8	1.00	3.4E6	1.00	3.4E6
9	0.3	0.225	1.00	-	1.00	-	1.00	-

4.32E-3 means 4.32 10^{-3}

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