PROPAGATION OF BROAD–BAND RADIATION THROUGH A BARIUM LAYER

N.I. Kosarev and I.M. Shkedov

Computer Center, Siberian Branch of the Academy of Sciences of the USSR, Krasnoyarsk
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The results of numerical simulation of the process of propagation of a broad–band radiation in an optically thick plane–parallel barium layer are presented. The dynamics of photoionization of atomic photoexcitation of ion layers and the glow due to resonance transitions in the atoms and ions of barium under the action of solar radiation are described.

At present a lot of experiments are being carried out on creating artificial formations (AF) in the upper atmosphere to make the studies of its properties easier. For this purpose, the vapors of alkali and alkaliearth elements (most commonly barium[1]) are injected. The processes of ionization and excitation developed in the AF under the action of solar radiation result in a resonance–fluorescent glow of barium atoms and ions. The emission from the AF is recorded by means of remote optical methods for extracting information about movement and variations of thus formed clouds. From this information it is possible to obtain the data on high–latitude winds, electromagnetic fields, and mass–transfer phenomena.[2] Therefore, the study of the effect of radiation on ionization, excitation, and glow of the AF is of paramount importance in developing the methods of their remote sounding, interpreting the experimental data, and planning the experiments.

Formulation of the problem. Ionization, excitation, and glow of a barium cloud under the action of a broad–band radiation depends on the dynamics of populating of the atomic and ion energy levels. Therefore, it is necessary to construct the atom and ion models of barium which would take into account a sufficient number of their states required for adequate description of the processes under study. It was shown[3] that the model of a barium atom should include twelve levels. The number of states is a function of the absorption cross section of the transitions studied and of the shape of spectral distribution of the sunlight strength since they determine the rates of stimulated photoprocesses. The use of a similar approach to the barium ion has shown that its model must consist of five levels. Variations in populations of all atomic and ionic states are described by a system of balance equations with an account of the following radiative processes: photoionization, photoexcitation, photodissosiation, and spontaneous quenching. Photoionization of ions is neglected since the sunlight strength in the far–ultraviolet region is extremely low.

The system of kinetic equations describing the dynamics of variations in populations of atomic and ionic levels in a plane–parallel layer has the form

$$\frac{dN_j(z,\,t)}{dt} = -\left[R_j^f + \sum_{i=1}^{j-1} R_{ji}\,N_j(z,\,t)\right] + \sum_{k=j+1}^{n_a} R_{kj}\,N_k(z,\,t)\ ,$$

$$j = 1,\,2,\,\ldots,\,n_a, \qquad (1)$$

$$\frac{dN_i(z,\,t)}{dt} = -\sum_{i=n_a+1}^{l-1} R_{li}\,N_l\,(z,\,t)) + \sum_{k=l+1}^{n_a+n_i} R_{kl}\,N_k(z,\,t)\ , \qquad (2)$$

$$l = n_a + 2,\ n_a + 3,\ \ldots\ n_a + n_i\ ;$$

$$\sum_{k=1}^{n_a+n_i} N_k(z,\,t) = N_0\ ; \qquad (3)$$

$$N_1(z,\,t) = N_0;\quad N_m(z,\,0) = 0,\quad m = 2,\,3,\,\ldots,\,n_a + n_i\ , \qquad (4)$$

where $N_m(z,\,t)$ is the population of the mth level, z is the space variable, t is time, N_0 is the total number of particles per unit volume, n_a and n_i are the numbers of the atomic and ionic levels of barium, R_j^f is the rate of barium atoms photoionization from the jth state. Relation (3) describes the law of particles number conservation. The initial conditions (4) are written assuming that prior to the irradiation all atoms are in the ground (first) state and that there are no ions which appear only during ionization. We have for the rates of the radiative excitation R_{kj} and decay R_{jk}

$$R_{kj} = B_{kj}\tilde{J}_{kj}(z)\ , \qquad (5)$$

$$R_{jk} = B_{jk}\tilde{J}_{kj}(z) + A_{jk}, \qquad (6)$$

respectively.

Here B_{kj}, B_{jk}, and A_{jk} are the rates of stimulated excitation, deexcitation, and spontaneous decay for the transition $j \to k$ and $\tilde{J}_{jk}$ is the intensity of radiation $I^{jk}(z,\,\pm\,\mu,\,\nu)$ averaged over the frequency ν and the angular $\mu = \cos(\theta)$ variables (θ is the angle determining the direction of photon propagation)

$$\tilde{J}_{jk}(z) = \frac{1}{2I_0^{jk}} \int_{-\infty}^{\infty} F^{jk}(\nu) \int_{-1}^{+1} I^{ik}(z,\,\pm\,\mu,\,\nu)\,d\mu d\nu\ , \qquad (7)$$

where $\Phi^{jk}(\nu)$ is the function describing the absorption line contour, I_0^{jk} is the strength of solar radiation at the frequency of the transition $j \to k$.

Then it follows that the rates of radiative processes depend in general on the spatial variable z since the radiation intensity $I^{jk}(z,\,\pm\,\mu,\,\nu)$, (see Eqs. (5)–(7)) is related to it. If an absorbing layer is optically thin, then $I^{jk}(z,\,\pm\,\mu,\,\nu)$ is independent of z and is equal to I_0^{jk}. In this case the right side of Eq. (7) is identically equal to unity and the values R_{kj} and R_{jk} are the constants.

In examining the optically thick media when the processes of radiation propagation are important the radiation transfer equations for resonance transitions of barium atoms and barium ions must be added to the system of balance equations (1)–(4). The specific view of these equations is determined from the following physical assumptions[4]: a) the photon reemission is described within the frameworks of the model of a complete frequency redistribution, b) the spectral line contours have the Doppler shape, and c) atoms (ions) emit isotropically

$$\pm \mu \frac{\partial I^{lm}(z, \pm \mu, \nu)}{\partial z} =$$

$$= \Phi^{lm}(\nu)\, \kappa_0^{lm}(N_l, N_m) \left[S^{lm}(N_l, N_m) - I^{lm}(z, \pm \mu, \nu) \right]. \quad (8)$$

The boundary conditions

$$I^{lm}(0, \mu, \nu) = 0, \qquad I^{lm}(L, -\mu, \nu) = \begin{cases} 0, & \mu \neq 1 \\ I_0^{lm}, & \mu = 1 \end{cases} \quad (9)$$

are determined based on the geometry of the problem. The function of the sources $S^{lm}(N_l, N_m)$ and the absorption coefficient $\kappa_0^{lm}(N_l, N_m)$ depends on population

$$S^{lm}(N_l, N_m) = \frac{2h\nu_{lm}^3}{c^2} \frac{N_l(z, t)}{N_m(z, t) - \dfrac{g_m}{g_l} N_l(z, t)}; \quad (10)$$

$$k_0^{lm}(N_l, N_m) = \frac{c^2 A_{lm}}{8\pi \nu_{lm}^2} \frac{g_l}{g_m} \left[N_m(z, t) - \frac{g_m}{g_l} N_l(z, t) \right], \quad (11)$$

where g_m and g_l are the statistical weights of the mth and lth levels, ν_{lm} is the frequency of the transition $l \to m$, and L is the thickness of the absorbing layer. For the line profile $\Phi^{lm}(\nu)$ we have

$$\Phi^{lm}(\nu) = \frac{1}{\pi^{1/2} \Delta\nu_D^{lm}} \exp\left\{ - \left[\frac{\nu - \nu_{lm}}{\Delta\nu_D^{lm}} \right]^2 \right\}, \quad (12)$$

where $\Delta\nu_D^{lm}$ is the Doppler width of the transition.

Thus the system of equations (1)–(4) and (8)–(9) fully describes the dynamics of ionization, excitation, and glow of a plane–parallel layer of barium vapor under the effect of solar radiation.

The procedure of problem solution. First a grid of z values was introduced for each node of which, according to Eqs. (1)–(4), the system of kinetic equations was written relative to the populations $N_i(z_n, t)$, where z_n is the coordinate of the nth node. Integral (7) over the angular μ and frequency ν variables was replaced by a sum using the Laguerre and Hermite quadrature formulas.[5] To obtain a set of frequencies and angles the transfer equations (5)–(7) for every moment of time were solved using the Rybik method.[6] As a result, we reduced our problem to the Cauchy problem for a system of ordinary differential equations with respect to populations of the atomic levels at a discrete set of nodes over the spatial variable z the solution of which was found by the numerical methods of Adams and Girz.[7]

Calculational results. Below we present the results of numerical simulations of photoionization and glow of the barium vapor layer the initial optical depth of which $\tau_0 = 10$ for the atomic transition at $\lambda = 5535.48$ Å. The analysis of the data showed that at the initial stage of atomic photoionization it was possible to observe essential gradients in the spatial distribution of the intensity of transmitted solar radiation at the frequency of the aforementioned atomic transition (see Fig. 1).

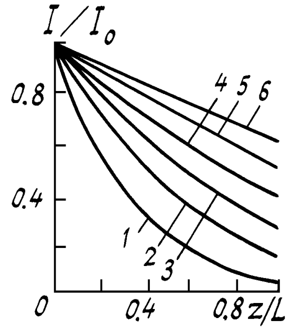

FIG. 1. Spatial distribution of solar radiation intensity at central frequency of the atomic line contour at $\lambda = 5535.48$ Å at t: 1) 1s, 2) 4s, 3) 8s, 4) 12s, 5) 16s, and 6) 20s.

Their occurrence was caused by the fact that the optical depth τ_0 which determines the extinction of light along the spatial variable (see Eq. (8)) was maximum at t the beginning of the process and then, as the ionization developed it decreased due to the atomic transitions to the continuum. Therefore, following the dynamics of τ_0 variation, one obtains for intensity of transmitted radiation as a function of the z coordinate for different instants of time t the curves shown in Fig. 1. These curves show strong dependence of the rates of the stimulated radiative processes on the spatial variable which, in turn, results in nonuniform distribution of the scattered radiation intensity and atoms (ions) in the excited states over the layer. Specific shapes of such dependences are determined by two competitive processes: the emission (i.e., by the number of emitters which contribute to the radiation intensity at a given point of the medium) and absorption of light propagated along a path of certain length. As a result, their joint action should influence on the dynamics of ionization of atoms and excitation of ions which will develop differently with the change of the z coordinate (see Fig. 2, where the temporal behavior of ion concentration is shown at different points of the medium).

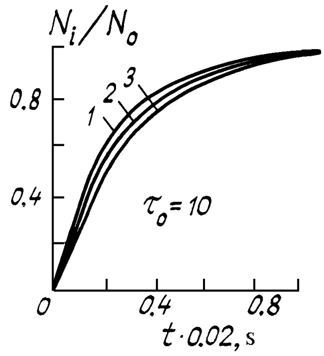

FIG. 2. The dynamics of photoion density at different points of the layer (z/L): 1) 0.0; 2) 0.6; and 3) 1.0.

From the practical point of view it is important to know the behavior of the intensities of atomic and ionic resonance lines which are used in the experiments for recording the AF glow. Shown in Fig. 3 is the dynamics of the intensities of atomic (a) and ionic (b) lines for the radiation outgoing from the shadow face of the layer at different angles. As can be seen from comparison of the curves *1*, *2*, *3*, and *4* in Fig. 3*a*, the intensity maximum is displacing to the region of longer times with increasing angle. Larger scattering angles are related to the larger optical depths. Hence it follows that the maximum of the atomic resonance line glow occurs at later times of the barium photoionization for the layers with larger optical depths. Thus it was shown with the aid of a numerical simulation that during the ionization of the dense barium clouds by solar radiation one must observe a time delay of the glow maximum at the atomic line with increase of the initial optical depth of the layer τ_0. Therefore in measuring and analyzing the delays for different AF it is possible to compare their optical depths. The intensity of the ion line at $\lambda = 4554$ Å monotonically increases with respect to the atomic one (see Fig. 3, *b*). Such a behavior is explained by the fact that the optical depth of the ion layer equals zero at the beginning of the process (there are no ions). The effects associated with radiation propagation in the dense media for the ion layer become noticeable to the end of the ionization of atoms when optical depth of the layer is maximum while being yet smaller than τ_0. Moreover, it should be noted that the function of the sources for the ion transition weakly depends on the spatial variable. This fact is confirmed by numerical computations and its qualitative explanation is as follows. Since at the initial stage of ionization the ion layer is optically thin, the intensity of radiation propagated through it does not virtually decrease. However, the rate of photoexcitation of the ion levels is much larger than that of photoionization. This circumstance allows us to make use of the condition of quasistationarity $dN_l/dt \cong 0$ for estimating the populations of the excited states of ions. Hence it is possible to show that their values are much less than the populations of the ground and metastable states of the ions, since the rate of photoexcitation is several orders of magnitude less than the probability of spontaneous decay for the transition under study. By reducing Eq. (10) to the form

$$S^{lm}(N_l, N_m) = \frac{2h\nu_{lm}^3}{c^2}\frac{g_l}{g_m}\left[\frac{N_m(z, t)}{N_m(z, t) - \dfrac{g_m}{g_l}N_l(z, t)} - 1\right] \qquad (13)$$

and taking into account the above said it is not difficult to verify that the first term in the parentheses is a slowly varying function of z.

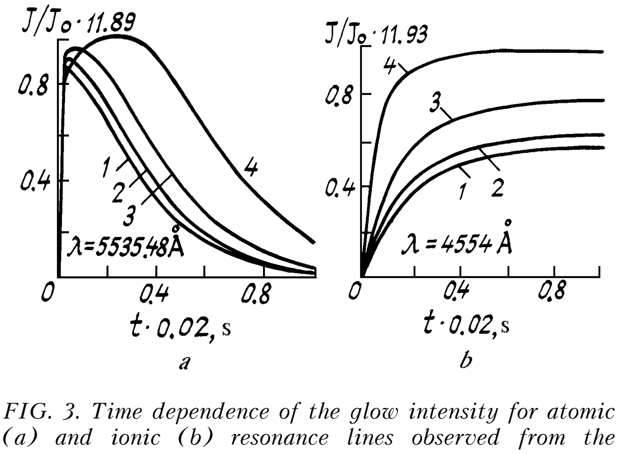

FIG. 3. Time dependence of the glow intensity for atomic (a) and ionic (b) resonance lines observed from the shadow face of the layer at angles θ*: 1)* 6.2°, *2)* 30.8°, *3)* 55.4°, *and 4) 80.0°.*

It should be emphasized that there always occurs a time interval for the ion layer in the beginning of the atomic ionization during which the $S^{lm}(N_l, N_m)$ value is independent of the spatial variable. This result can be employed for a qualitative evaluation of the glow intensity for ion lines through the solution of the transfer equation in an integral form by removing the source function from the integrand. We then obtain an explicit form for the dependence of radiation intensity on the optical depth of the ion layer at the transition under study. Using it one can determine the density of ions in the AF.

The behavior of the intensity of solar radiation outgoing from the shadow face of the layer as a function of frequency is shown in Fig. 4. The analysis of the curves related to different times of the development of the barium vapor photoionization is indicative of the effects of ''brightening'' (the intensity growth) of the atomic layer (Fig. 4, *a*) and ''darkening'' of the ion layer (Fig. 4, *b*). In the frequency dependence of the glow intensity for the atomic line there occurs a gap at the central frequencies (reabsorption) caused by the effects of radiation capture. The amplitude of the gap is maximum at the beginning of the process and as the ionization develops it vanishes.

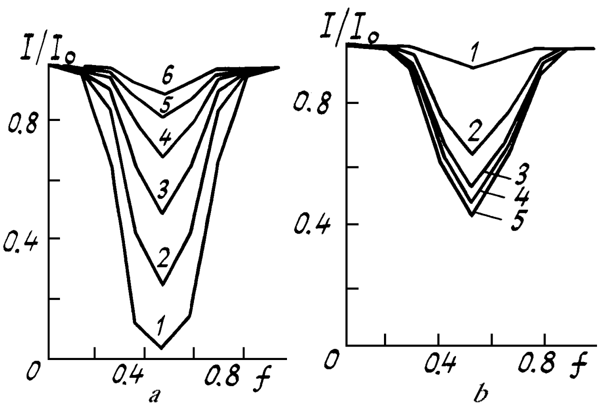

FIG. 4. Frequency dependence of intensity of the solar radiation outgoing from the layer at atomic (a) and ionic (b) barium transitions at different time: 1) 1 s, *2)* 8 s, *3)* 16 s, *4)* 24 s, *5)* 32 s, *and 6)* 40 s; *(*$f = (\nu - \nu_{lm})/6.38 \cdot \Delta\nu_D^{lm} + 0.5$*).*

Thus the numerical simulation of solar radiation propagation through a barium layer reveals the following:

1. The sun light absorption and reemission results in inhomogeneous distribution of the source function over the layer for resonance transitions of atoms and ions.
2. At the initial stage of barium photoionization we observe significant gradients in spatial distribution of solar radiation intensity in the vicinity of central frequency of an atomic line at $\lambda = 5535.48$ Å.
3. The dynamics of ''brightening'' of the atomic layer and ''darkening'' of the ion layer on the transitions at the wavelengths 5535.48 Å and 4554 Å, respectively, is caused by the photoionization of atoms.
4. The profile of the atomic line glow has a gap at central frequencies which is formed due to the radiation capture by a medium.
5. Ionization of an optically dense barium layer is more slow as compared to that of an optically thin medium.

It should be noted that the radiation transfer in multilevel systems has not been yet studied[8] though its consideration is of practical importance for analyzing the spectroscopic information obtained from such glowing objects as plasma, artificial formations, gas, and others.

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