PROPAGATION OF SOLAR RADIATION THROUGH AN ARTIFICIAL CLOUD OF BARIUM VAPOR

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The processes of ionization and of luminescence of a thick spherically symmetric barium cloud irradiated by sunlight are numerically simulated to study the dynamics of such luminescence in the atomic line of Ba *at* λ = 5535 Đ *and its radial distribution across an observable disk. Computations indicate resonantly scattered sunlight to be strongly anisotropic, the temporal dependence of that line intensity agreeing quite well with experimental data.*

The present publication is a follow–up on studies by its authors[1,2] and is dedicated to numerical simulation of the processes of ionization, excitation, and luminescence of a barium cloud illuminated by sunlight. It mainly aims to obtain a spatiotemporal picture to describe ionization and excitation of the atoms and ions of Ba, and also the frequency–angular dependence for radiation scattered by the cloud, the latter being the experimentally observed characteristic.[3,4] The principal difference from the problem set in Ref. 1 is that a spherically symmetric cloud with a homogeneous atom number density distribution is now envisaged. The resulting solution is pertinent for most experiments on injecting barium into the upper atmosphere since these are staged so that the dynamic gas dispersal results in cloud shapes of similar geometry. That is why we believe modelling the process of radiation transfer and of the induced atom and ion ionization and excitation in the cloud is so important for interpreting experimental spectroscopic data and for adequate description of the processes developing in the cloud.

Statement of the problem. Mathematically the problem is similar to that set in Ref. 1, except that:

1) the cloud is spherical (see Fig. 1);

2) except for the metastable and basic levels, the excited states of both atoms and ions are assumed to meet the condition of quasistationary: $dN_p/dt = 0$, where N_p is the number density of the excited particles, i.e., the population levels adiabatically follow changes in the populations of both the basic and the metastable states.

The last condition is necessarily met due to short lifetimes of the excited states as compared to the characteristic time of ionization.

Numerical solution technique. Demanding that the population in the excited states remains quasistationary, one necessarily has to seek for a spatial distribution of atoms in both the excited and basic states, which may then be used as an initial value to solve the problem of the dynamics of ionization of barium by sunlight. Since there exists a selected direction, related to propagation of sunlight, the problem in general is cylindrically symmetric, despite the overall spherical symmetry of the cloud. That is why the task arises of constructing a spatial grid to adequately describe a curvilinear boundary (a hemisphere). The grid we choose for the cross section through the centre of the cloud is shown in Fig. 1. The equation of transfer of radiation along the selected direction $\mu = \cos(\varphi)$ for every target plane is solved by the technique of short characteristics.[5,6] Otherwise substituting the integrals over angle and frequency by the respective cubature formulas makes results in a system of differential equations to describe populations at every spatial point, the dimension of such a system considerably reduced because of the symmetry of the problem. The resulting Cauchit problem is numerically solved.

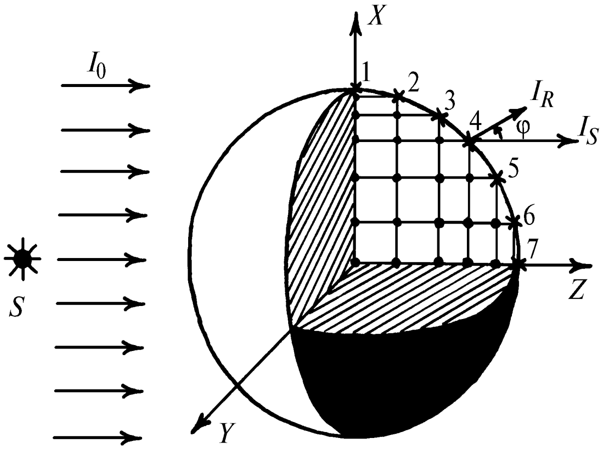

FIG. 1. Problem geometry and computational grid. I_0, I_s, and I_r are incident, passing and scattered radiation intensities, respectively, φ is the angle of scattering. Figures and crosses show boundary gridpoints across the central cross section of the cloud.

Discussion of results. In what follows we discuss numerical results for only the atomic component of the cloud, although the ionic component has also been treated. Computations covered various initial optical densities of the cloud, τ_0, found for the atomic transition of Ba at λ = 5535 Å, chosen from the interval between 1 and 100. Besides the model and the algorithm suggested make it possible to account for radiation transfer in an arbitrary set of atomic and/or ionic lines of Ba. Results presented in the figures correspond to the case when radiation transfer is described within the atomic resonance transition at λ = 5535 Å only, and the initial optical density of the cloud is set at $\tau_0 = 30$.

Figure 2*a* shows the dynamics of change in ion density at the shaded cloud boundary, indicated by crosses in Fig. 1, which essentially corresponds to different optical densities for passing solar radiation. One can see that ionization is delayed as the layer deepens optically. However, this inhomogeneity in the distribution of ions is not too large, as compared, e.g., to that for excited atoms

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(Fig. 2*b*). Point–to–point populations ratio for the excited level may become as high as 10 or more (compare curves *1* and *7* in Fig. 2*b*). One should also note that the temporal trend of population of the excited state is not always monotonous, as is the case for the ions. It may reach a maximum which is shifted to later times as the optical depth increases, its amplitude simultaneously diminishing (see curves *3*–*7* in Fig. 2*b*). Starting from a certain moment (around 50 s in our case) all the curves practically merge.

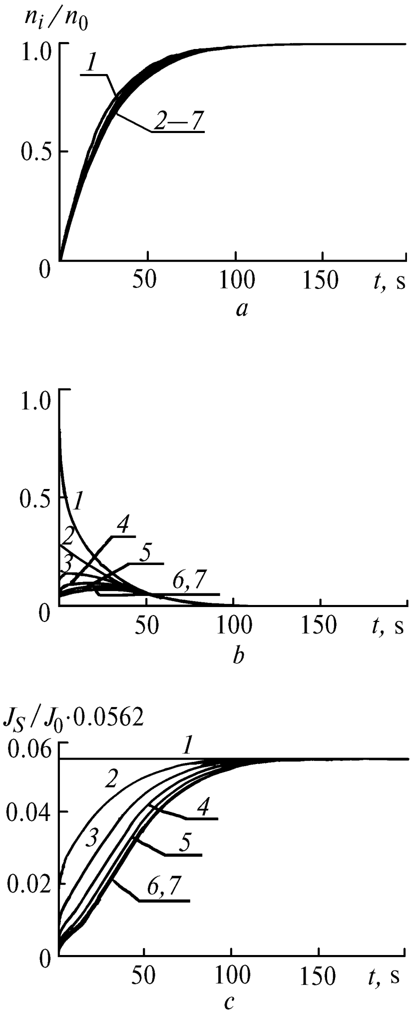

FIG. 2. Temporal trends of number densities for ions (a) and for excited atoms of Ba *in the* $^1P_1$ *state (b); passing solar intensities at boundary points of the cloud (c). Figures at curves correspond to those for gridpoints in Fig. 1.*

The population of the excited state behaves as it does because the cloud remains optically thick within the first 50 s, while the absorption processes result in weaker intensities of radiation at given points of the medium. Therefore the excited state becomes less densely populated.

Figure 2*c* illustrates the dynamics of lightening of a spherical cloud at various exit points. It may be seen that such lightening occurs later for paths with large optical thicknesses.

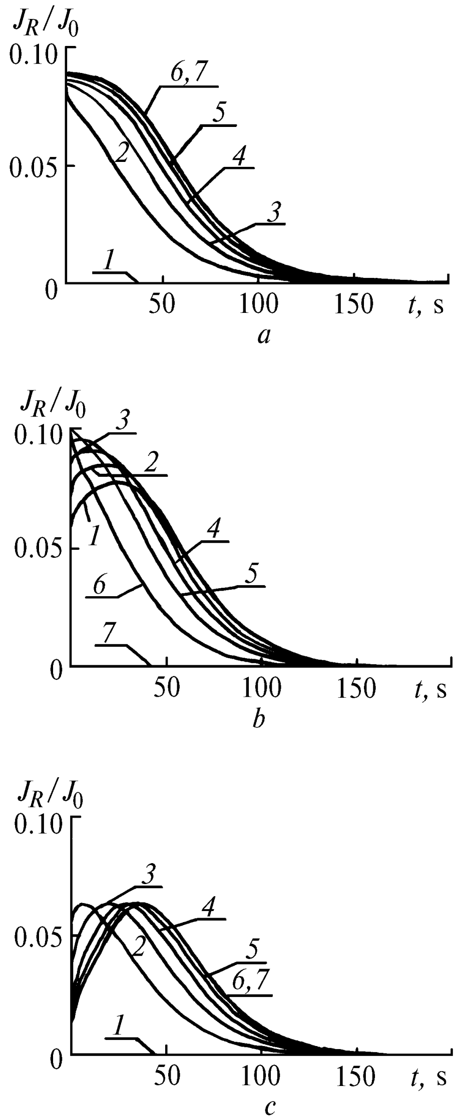

FIG. 3. Dynamics of intensity for radiation outgoing from the cloud at various gridpoints and angles. a) 180°, *b)* 90°, *illuminated side; c)* 0°, *and d)* 90°, *shaded side. Cloud brightness (e) at: 1)* 0°, *2)* 45°, *3)* 90°, *4)* 135°, *and 5)* 180°. *Spectral line wavelength* $\lambda = 5535$ Å.

Data on radiation scattered by the cloud in the process of fluorescence are of the highest practical value. Figures 3*a*, *b*, *c*, and *d* show the dynamics of luminescence in the atomic line of Ba at $\lambda = 5535$ Å for different boundary points of the central cross section of the hemisphere at various angles off the initial beam of solar radiation. Figure 3*a* presents the brightness of the cloud in the same spectral line vs. time at different angles of observation (that angle is counted off the direction of propagation of the solar radiation). The dependences shown indicate that the dynamics of line intensity strongly depends on the angle of scattering. Note that it is only at the scattering angle of 180° that the intensity falls off to zero monotonously as the ionization develops (see Fig. 3*a*). In every other case the dynamics of intensity is such that its temporal profile is bell–shaped. A sharp maximum appears, its position depending on the coordinate of the entry point and on the direction (angle) of propagation. For example, maxima appear in the intensities described by curves *1*, *2*, and *3* (Fig. 3*b*), which describe the behavior of radiation scattered by 90° off the illuminated side of the cloud. The position of the maximum shifts to later times as the sighting line approaches the centre of the cloud. As for the shaped side of the cloud, the intensity in the line of Ba is nonmonotonous with time. Moreover, for radiation scattered by the cloud at an angle of 0° (Fig. 3*c*), a shift is clearly visible of the intensity maximum as the optical depth of the path grows to peak, while the sighting line approaches the cloud centre.

Curves in Fig. 3*c* show that, independent of exit points, the maxima of intensity of scattered radiation remain the same, equalling 0.064. The position of the maximum of intensity scattered by 90° off the shaded side of the cloud is not as time sensitive in dependence of the position of exit point (see Fig. 3*d*). A characteristic more sensitive to the coordinate of exit point is its amplitude, which peaks as the sighting line approaches the centre of the cloud. All the curves in Fig. 3*a* merge to become practically indistinguishable from some moment within 130–150 s. By that time the cloud becomes optically thin to solar radiation. Computational results indicate that, as far as optically thick clouds are concerned, the dynamics of intensity of radiation scattered in the resonance line is extremely sensitive to the angle of observation and to the coordinate of exit point. That is why both the angular and spatial dependences specific for the field of scattered radiation have to be accounted for while interpreting spectroscopic observations of optically thick barium clouds.

The characteristic recorded most often during experiments with Ba injections is cloud brightness. Figure 3*d* shows its changes at 0, 45, 90, 135, and 180° angles of scattering. This brightness drops off monotonously for radiation scattered to 135 and 180°, at the same time having a strong maximum for every other direction. The position of maximum is delayed to longer times as the angle of scattering decreases. All the curves merge from approximately 60 s, thus they agree quite well with the dynamics of change in the population of excited atoms (see Fig. 2*b*), for which such a situation takes place from 45 s on. Thus brightness appears to better describe the change of population of excited atoms than that in the line intensity. Meanwhile the amplitude of the brightness maximum grows at larger scattering angles.

Inhomogeneity in cloud luminescence within the line at various scattering angles and stages of ionization is illustrated by Fig. 4. By analysing the curves one can see that curve *1*, corresponding to the scattering angles of 0°, has a dip at the centre of the disk, deepening as the ionization develops, so that finally there appears a luminescence maximum at the centre of the disk (Fig. 4*d* and *e*). The radial dependence then reminds one the profile of curve *3* (the scattering angle of 180°, Fig. 4*d* and *e*). It is strictly concave with a maximum in the centre. Its maximum value drops off with time. Starting from approximately 50 s, curves *1* and *3* are similar in shape, further to practically coincide (see Fig. 4*d* and *e*). As for the radial distribution of spectral intensity at 90° angle of scattering, it appears to be asymmetric to center. The intensity is at maximum at a certain point, close to the illuminated edge of the disk. Gradually, the maximum shifts towards the center of the disk and passes through it during the final stage of ionization of the atomized cloud. However, the degree of such inhomogeneity is high during the initial stage of ionization, and the profile of that distribution approaches the respective curves for 0° and 180°, as that ionization develops (see Fig. 4*e*). It follows from the above that a radial inhomogeneity of its spectral line luminescence is typical of a spectral cloud, provided the observation (scattering) angle is fixed. The shape of radial distribution of intensity may then radically change in dependence of such an angle (Figs. 4*a*, *b*, and *c*).

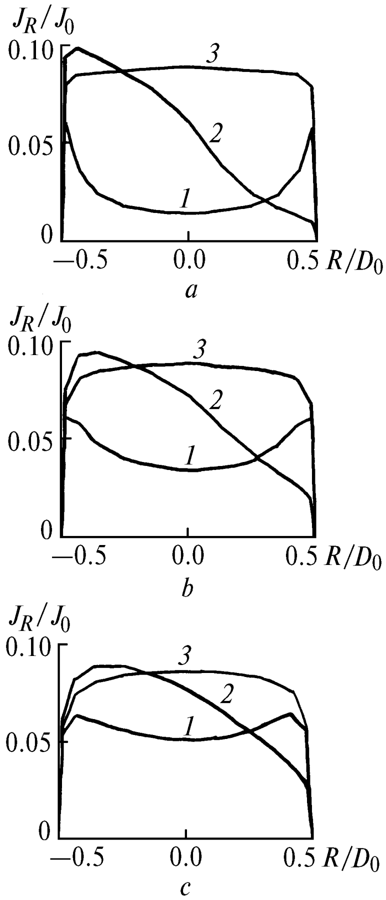

FIG. 4. Radial distributions of intensity for radiation outgoing from the cloud a) 1 s*, b)* 10 s*, c)* 20 s*, d)* 50 s*, and e)* 100 s *after injection. Curve 1 is for observations at* 0°*, 2 –* 90°*, and 3 –* 180°*. Spectral line wavelength* λ = 5535 Å.

The anisotropy of intensity of scattered radiation may be easy followed from stage to stage of cloud ionization (see the intensity of cloud luminescence in the spectral line vs. scattering angle as presented in Fig. 5). These data show a strong anizotropy of scattering down to approximately 50 s of cloud lifetime (curves *1* through 4), while by 100 s of that lifetime scattering becomes practically isotropic (curve *5*, Fig. 5).

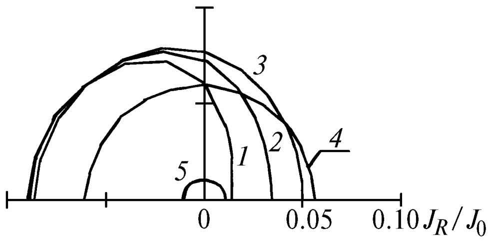

FIG. 5. Intensity of cloud luminescence, J, vs. angle of scattering at various stages of ionization: 1) 1 s*, 2)* 10 s*, 3)* 20 s*, 4)* 50 s*, and 5)* 100 s *after injection. Spectral line wavelength* λ = 5535 Å.

Numerical simulation also yields changes in the frequency profile of spectral line from the luminescing cloud at various scattering angles. The phenomenon of spectral line self–inversion (that is a dip in the centre of line contour) is found within quite long cloud lifetimes, up to 20 s for a cloud of initial optical depth of 30. Its presence indicates that the cloud is optically deep then, and radiation capture by the medium plays the main role in forming the line profile. This dip appears for radiation scattered to angles below 90°. It is found that the smaller the angle of scattering, the deeper is that dip. For radiation exiting the cloud on its illuminated side the intensity falls off with time at every frequency within the line contour. The dip flattens as ionization develops, testifying to lower optical depths of the cloud, while the intensity amplitude grows at every frequency within the line contour, approaching its value at 180° of scattering. The dip vanishes then, and the intensity decreases at every frequency, and at long lifetimes, starting from 50 s, so that the line profiles merge for practically every angle of scattering. At its final stage of ionization the cloud becomes transparent to radiation, and processes of radiation transfer do not affect the formation of line contour.

A specific point lies with comparing the results described above with the available observational data. For example, one notes a qualitative agreement between the simulated dynamics of cloud brightness (Fig. 4) with data cited in Refs. 7 and 8. Experimental curves for cloud intensity in the atomic line of Ba at λ = 5535 Đ feature a clear–cut maximum, after which the intensity falls off to zero. Computational curves (curves *1–3*, Fig. 3*e*) follow the same profile.

To quantitatively compare our model of ionization of Ba clouds by solar radiation one has to account for:

a) the inhomogeneous spatial distribution of atoms, resulting from gas dynamical scatter of the injected substance, and the diffusion stage of blooming,

b) the field of atom velocities, resulting in point–to–point inhomogeneous Doppler shift of the absorption frequency throughout the cloud.

With exception of diffusion blooming, the above factors are accounted for in Ref. 9, in which radiation transfer is considered according to the model suggested in Ref. 10. The authors of Ref. 9 are right in commenting that their model describes the initial stage of ionization of barium cloud. However, most of the available experimental data on luminosity of the atomic and ionized components of barium clouds refer to those times when gas dynamical processes of scatter are already terminated, and slowest diffusion blooming of the cloud takes place. It is planned further to account for these factors, so as to simulate the field of radiation scattered by a sun–illuminated barium cloud.

To conclude we formulate the principal results of this study:

1. A model is suggested to describe the process of propagation of solar radiation through an optically dense spherical barium cloud and an algorithm to solve it.

2. Spatial inhomogeneity of substance in such a cloud is studied, which is most strongly manifested in the distribution of excited atoms and (or) ions.

3. It is demonstrated that the maximum of line intensity and of cloud brightness in the atomic transition λ = 5535 Đ is shifted towards later lifetimes as the initial optical depth of the cloud increases.

4. The dynamics is traced of change of the line frequency shape.

5. Numerical data indicate a strong anisotropy of line emission, dynamically changing as the ionization develops, and show the dynamics of line intensity to qualitatively agree with the available experimental data.

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