SOME PECULIARITIES OF RADIATION PROPAGATION THROUGH A SCATTERING VOLUME WITH ABSORPTION

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Received July 15, 1996

Transfer of a collimated radiation flux in a given wavelength range through a spatially limited scattering disperse medium is considered. It is shown that the optical dimensions of the medium and the scattering phase function deform a spectral line profile.

The problem of selectivity in radiation transfer theory is very urgent, especially in connection with the widespread use of optical quantum generators in systems operating through the atmosphere and ocean.

It is well known[1] that the absorption line profile is broadened with the increase of the thickness of a layer of the medium through which the radiation is transferred. The problem of the influence of the transverse optical dimensions of the medium on the absorption line profile is less well understood, so in this paper we analyze the dependence of the absorption line profile broadening on the transverse dimensions of the medium. The intensity of radiation transferred through the disperse medium was calculated by the technique described in Ref. 2 taking into account the dependence of the radiation intensity on the transverse dimensions of the medium.

Let us express the absorption coefficient of the disperse medium $\varkappa(\upsilon)$ in terms of the single scattering albedo Λ and the scattering coefficient σ, whose dependence on frequency can be neglected in the first approximation

$$\varkappa(\upsilon) = \sigma\,(1/\Lambda - 1). \tag{1}$$

Let us set the value of the single scattering albedo Λ_0 at the maximum of the spectral line, then the maximum absorption coefficient is

$$\varkappa_0 = \sigma\,(1/\Lambda_0 - 1). \tag{2}$$

Let the medium absorb radiation in the spectral line with the Lorentz profile

$$\varkappa(\upsilon) = \varkappa_0/(1 + x^2), \tag{3}$$

where $x = (\upsilon - \upsilon_0)/\gamma_L$ is the dimensionless frequency expressed in units of the line half-width[3] γ_L. The relation between the radiation frequency in the line and the single scattering albedo at this frequency can be obtained from Eqs. (1), (2), and (3)

$$x = \sqrt{\left(\frac{1}{\Lambda_0} - 1\right) / \left(\frac{1}{\Lambda} - 1\right) - 1}. \tag{4}$$

We consider the medium with the optical dimensions τ_x and $\tau_y = \tau_z$, on which the radiation flux $I_0(\upsilon) = 1$ is incident in the x-axis direction. The absorption line profile $r(x)$ is defined as a ratio of the intensity I coming from the medium at the frequency υ lying in the spectral line to the intensity of radiation coming from the medium at the frequency lying off the line $I(\Lambda = 1)$ or (at logarithmic scale) as $\log(I/I(\Lambda = 1))$. The calculated profiles of the absorption lines $r(x) = \log(I/I(\Lambda = 1))$ for different optical dimensions of the medium are shown in Figs. 1 and 2. The single scattering albedo at the center of the considered absorption line was 0.94. It is seen from Figs. 1 and 2 that the absorption line intensity sharply increases as τ_x increases, because a larger optical thickness absorbs a greater part of flux of the transferred radiation. The increase of the transverse dimensions of the medium for the constant optical thickness τ_x also results in the increase of the absorption line intensity. One can explain this increase of intensity by greater role of multiple scattering with the increase of transverse dimensions of the medium. Then a photon passes, on average, a longer path than at smaller transverse dimensions, so the probability of absorption of this photon by the medium increases.

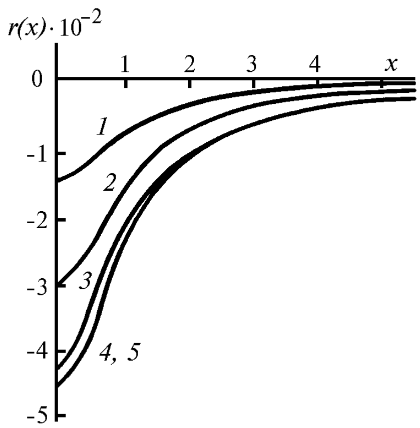

FIG. 1. Absorption line profiles. Optical dimensions of the medium are $\tau_x = 1$ and $\tau_y = 1$ (1), 10 (2), 10^2 (3), 10^3 (4), and 10^4 (5).

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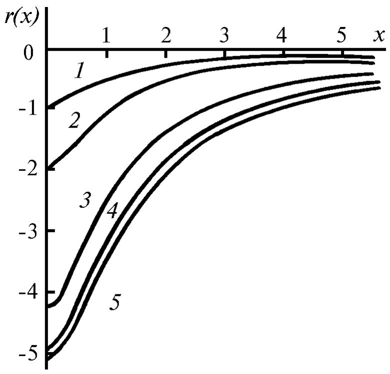

FIG. 2. Absorption line profiles. Optical dimensions of the medium are $\tau_x = 50$ and $\tau_y = 1$ (1), 10 (2), 10^2 (3), 10^3 (4), and 10^4 (5).

Thus, in the case under consideration the efficient absorption coefficient increases due to the multiple scattering. Let us consider how the line profile is deformed with the increase of the transverse dimensions of the medium $\tau_y = \tau_z$.

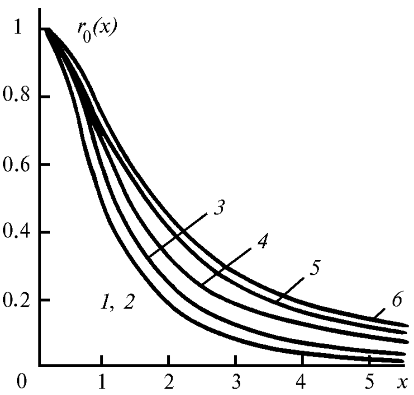

FIG. 3. Absorption line profiles normalized to unity. Optical dimensions of the medium are $\tau_x = 10^2$ and $\tau_y = 1$ (2), 10 (3), 10^2 (4), 10^3 (5), and 10^4 (6). Curve 1 is for the absorption coefficient profile.

Figure 3 shows the absorption line profiles $r_0(x)$ normalized to unity, from which one can judge about the relative increase of the intensity at different points of the profile with the increase of the dimensions of the medium. Our calculations show that the absorption line profile is broadened not only with the increase of the optical thickness of the medium, but also with the increase of its transverse dimensions. However, the increase of the transverse dimensions at small optical thickness of the medium ($\tau_x \approx 1$) almost does not lead to the increase of the absorption intensity in the line and to broadening of its profile. One can explain this by the fact that the increase of the transverse dimensions of the medium at small optical thickness cannot significantly increase the portion of multiple scattering and increase the average path of the photon in the medium. Correspondingly, the increase of the medium thickness τ_x at small transverse dimensions of the medium ($\tau_y = \tau_z \approx 1$) leads to insignificant intensification of absorption in the line and to insignificant broadening of the absorption line profile.

Thus, our calculations show that the transverse dimensions of the medium essentially affect the absorption line profile for $\tau_{x,y,z} > 1$. Neglect of this dependence may introduce errors when solving the problems of radiative transfer in the spectral line.

Let us consider the deformation of the spectral line profile caused by the wavelength dependence of the scattering phase function of particles when radiation is transferred through the scattering medium. Let the radiation in the spectral line of the intensity $I_0(\upsilon)=I_0(\upsilon_0)\alpha(\upsilon)$ be transferred through the disperse medium. Here, $I_0(\upsilon_0)$ is the radiation intensity at the line maximum, υ_0 is the frequency of the line maximum, and $\alpha(\upsilon)$ is the Lorentz line profile normalized to unity. The relative intensity of radiation at the frequency υ transferred through the medium does not depend on the incident radiation intensity. If the particles had equally scattered the radiation of different frequencies, the profile of the line coming from the medium should have had lower intensity, but its shape should have coincided with the incident line profile. However, the form of the scattering phase function of particles depends on the radiation frequency. The scattering coefficient of the disperse medium also depends in a complex way on the wavelength, but we do not consider it in this paper, because we think that the optical dimensions of the medium are the same for all frequencies within the line.

The scattering properties of particles are determined by their scattering parameters $\rho = 2\pi a/\lambda$, where a is the particle size and λ is the wavelength of radiation incident on the particle. The parameter ρ for the given particle size distribution increases with the decrease of the radiation wavelength. So the intensity of radiation transferred through the medium should increase as the wavelength decreases for the constant optical dimensions of the medium. In this case, the profile of the spectral line transferred through the medium is deformed. The profile deformation is better pronounced for the transfer of wide lines through the disperse medium.

Our calculations show that the relative change of the intensity of radiation transferred through the medium, $\Delta I/I_0$, per unit wavelength (here, I_0 is the intensity of radiation transferred through the medium at the line maximum) increases as the optical thickness τ_x increases and the optical transverse dimensions τ_y and τ_z decrease. The atomic oxygen line with the half-width $\upsilon_0 \approx 0.1$ cm^{-1} and the maximum at λ = 5577 Å was chosen for calculations. Optical dimensions of the medium were as follows: $\tau_y = \tau_z = 1$ and $\tau_x = 100$. The scattering parameter of the particles ρ in the medium at the line center was equal to 3.7. The intensity of radiation transferred through the medium increases due to the "scattering phase function effect" with the frequency increase. The change of the relative intensity per unit frequency range $\Delta I / I_0 \Delta\upsilon$ for these optical dimensions was approximately equal to 472 cm^{-1}. The intensity of radiation transferred through the medium increased by $\Delta I' \approx \Delta I(\upsilon - \upsilon_0)/\Delta\upsilon = \Delta I \Delta\upsilon_0 \, x/\Delta\upsilon$ for the frequency separation $\Delta\upsilon = \upsilon - \upsilon_0$ from the line center toward higher frequencies, and decreased by the same value for separation toward lower frequencies from the line center. Here, I_0 is the intensity of radiation transferred at the line center and $\Delta\upsilon_0$ is the line half-width. The profile of the spectral line transferred through the medium is $I = (I_0 + \Delta I \; \Delta\upsilon_0 \, x/\Delta\upsilon)\alpha$, where α is the profile of the spectral line of radiation incident on the medium normalized to unity. Let us write the normalized profile of the line transferred through the medium as

$$r = \frac{I}{I_0} = \left(1 + \frac{\Delta I \; \Delta\upsilon_0}{I_0 \; \Delta\upsilon} \, x\right)\alpha. \quad (5)$$

Table I presents the profile of the spectral line transferred through the dispersed medium. It is seen from the Table that the line profile deformation due to the scattering phase function effect results in its asymmetry.

TABLE I. Deformation of the line profile transferred through the medium due to the scattering phase function effect for $\tau_x = 100$, $\tau_y = 1$, $\lambda_0 = 5577$Å, $\upsilon_0 = 0.1$ cm^{-1}, *and* $\Delta I/I_0 \Delta\upsilon = 472$ cm^{-1}.

x	r	x	r
0.46	0.82574	−0.46	0.82526
0.73	0.65330	−0.73	0.65270
1.46	0.32030	−1.46	0.31970
2.3	0.15823	−2.3	0.15777
3.42	0.07887	−3.42	0.07853
5.55	0.03151	−5.55	0.03129
7.92	0.01576	−7.92	0.01560

Deformation of the wide Raman scattering line profile of carbon tetrachloride[4] with the half-width $\Delta\upsilon_0 = 12$ cm^{-1}, transferred through the disperse medium with the optical dimensions $\tau_x = 50$ and $\tau_y = \tau_z = 1$, is shown in Fig. 4 for more vivid presentation. The half width of the line *2* is 3 times less than that of the line *3*. The profiles are normalized to unity.

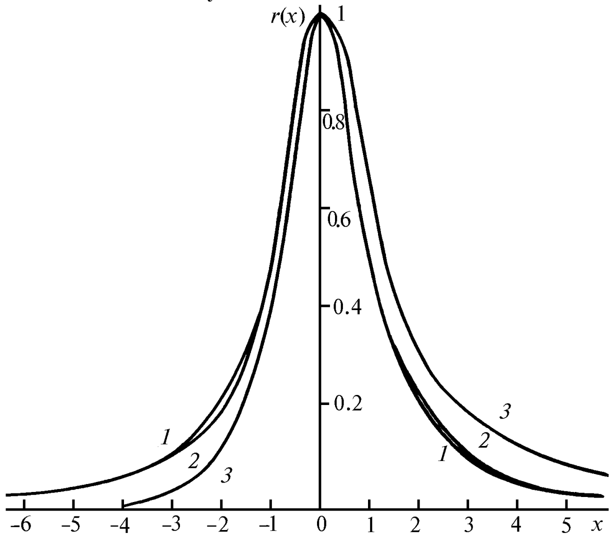

FIG. 4. Effect of the scattering phase function on the line profile deformation. Optical dimensions of the medium are $\tau_x = 50$ *and* $\tau_y = 1$: *1) line profile of the radiation transferred through the medium* ($\alpha(\upsilon)$); *2) line maximum is at* $\upsilon_0 = 3062$ cm^{-1} *and the line half-width is* $\Delta\upsilon_0 \cong 3.5$ cm^{-1}; *3) line maximum is at* $\upsilon_0 = 790$ cm^{-1} *and the line half-width is* $\Delta\upsilon_0 \cong 12$ cm^{-1}.

It is seen from Fig. 4 that during propagation through the scattering medium, the center of gravity of the line is displaced toward higher frequencies. The intensity in the line wing shifted from the line center toward higher frequencies increases, and the intensity in another wing decreases.

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