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Original scientific paper

CONTRIBUTION OF GRAVITATIONAL REDSHIFT TO SPECTRAL LINE PROFILES OF AGN: THE CASE OF VOIGT PROFILE

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SUMMARY: In a previous work (Paper I of this series) we analysed the influence of gravitational redshift on the line profiles formed in a homogeneous, static and optically thin region near massive AGN, assuming Lorentz profile function. In this paper we analyze the influence when the radiative transfer effects are taken into account. Assuming Voigt profile function for $H\beta$ line the importance of this effect is illustrated through several examples of different optical thickness of the emission region situated at various distances from the massive nucleus.

1. INTRODUCTION

The effect of gravitational redshift on the spectral line profiles of AGN has been investigated in the papers (Popović *et al.* 1994abc). It was found that the gravitational field of the massive nuclei gives rise to the line shift and asymmetry.

In the previously published paper (Popović *et al.* 1994b), henceforth referred to as Paper I, in order to derive the first conclusions about the importance of this effect we considered an oversimplified case of an optically thin emission region. Since the optical thickness in most observed lines formed in the broad line region (BLR) is much larger than unity (e.g., for H_β is of the order of $10^3 - 10^4$ (Kwan & Krolik 1979, Collin-Souffrin *et al.* 1981)), in this paper we shall consider a more realistic case when the radiative transfer effects are taken into account.

In order to demonstrate the conditions under which this effect can be important we consider the emission regions of different thickness, at various distances from the massive nuclei.

2. THEORY

Here we shall analyze the behaviour of spectral lines formed in a strong gravitational field of a static and optically thick region near massive galactic nuclei. A simple model of a line formed by two-level atoms in a finite slab of prescribed and constant temperature and density is assumed.

Under these assumptions the specific intensity $I(x, \mu, \tau)$ of the line radiation field is described by the time independent radiative transfer equation for a planar and static medium with no background opacity (Mihalas 1978):

$$\mu \frac{dI(x, \mu, \tau)}{d\tau} = \varphi(x, \tau)[I(x, \mu, \tau) - S(\tau)] \quad . \qquad (1)$$

Assuming complete redistribution the line source function is given by the well-known expression:

$$S(\tau) = \varepsilon B + (1-\varepsilon)\frac{1}{2}\int_{-\infty}^{\infty} dx \varphi(x,\tau) \int_{-1}^{1} d\mu I(x,\mu,\tau) \ . \quad (2)$$

In the above equations, μ ($= cos\theta$) is the cosine of the angle θ from the outward normal, $x = (\lambda - \lambda_0)/w_D$ is the wavelength displacement from the line center expressed in Doppler width (w_D) units, τ - optical depth, ε – the destruction probability per scattering for the photons and B - the Planck function. $\varphi(x,\tau)$ is the Voigt normalized profile function, given by:

$$\varphi(x,\tau) = \frac{a}{\pi^{3/2}} \int_{-\infty}^{+\infty} \frac{e^{-y^2}}{a^2 + (x'(\tau) - y)^2} dy, \quad (3)$$

where $a = w_L/w_D$, w_L is the Lorentzian half-width. Integration is performed over $y = \frac{\Delta\lambda}{w_D}$.

Here, depth dependence of the profile function $\varphi(x,\tau)$ means a depth variation of x:

$$x'(\tau) = x - \xi(\tau),$$

due to the gravitational redshift introduced via parameter $\xi(\tau)$.

As already given in Paper I (Eq. (2)), the gravitational redshift of the transition wavelength is expressed by:

$$\lambda_0' - \lambda_0 = \frac{\lambda_0 GM}{c^2 r} \ ,$$

where G is the gravitational constant, c is the speed of light and r is the radial distance from the nucleus of mass M.

Parameter $\xi(r)$ as a dimensionless form of the above expression is given by:

$$\xi(r) = \frac{\lambda_0}{w_D}\frac{GM}{c^2 r} \ .$$

As the optical depth τ in radial direction from the outer boundary R to r is given by

$$\tau = -\int_R^r k dr \ .$$

and the mean line absorption coefficient per unit length k is taken as given and constant in a constant property medium, parameter $\xi(\tau)$ in the optical depth scale has the following form:

$$\xi(\tau) = \frac{\lambda_0}{w_D}\frac{GM}{c^2}\frac{k}{kR - \tau} \ . \quad (4)$$

3. RESULTS AND DISSCUSION

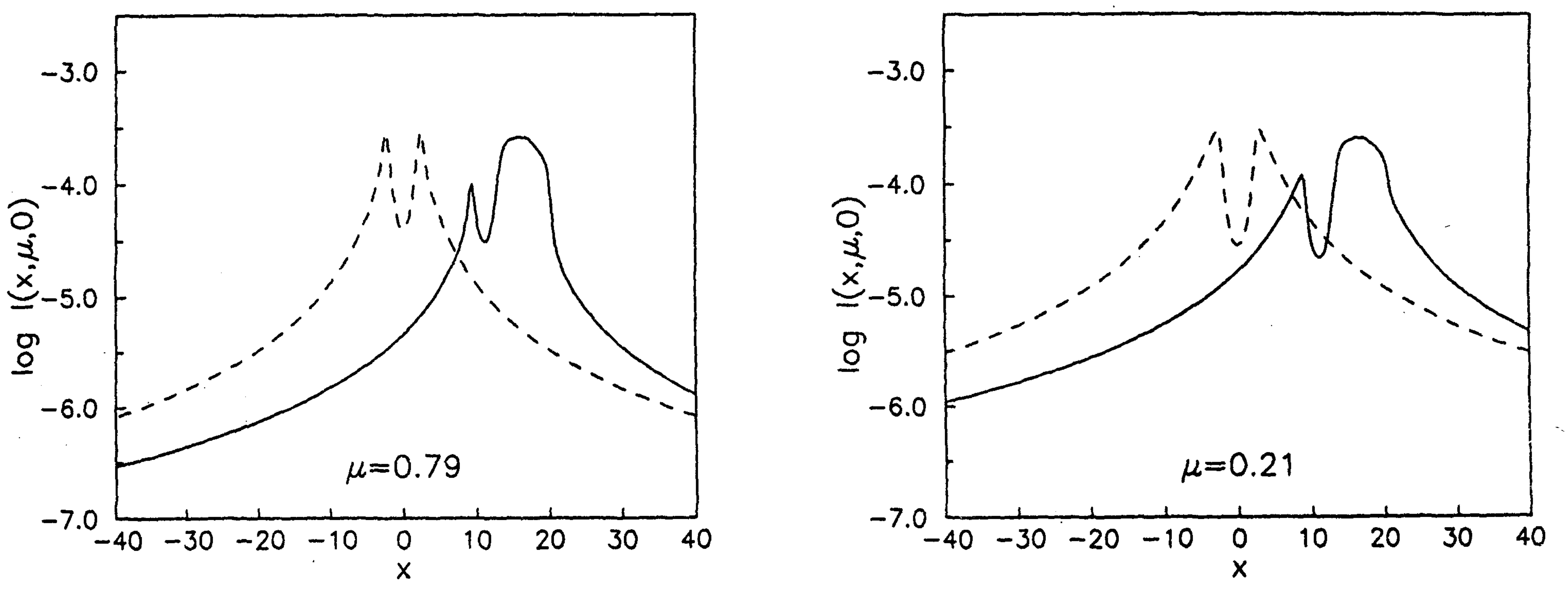
Eqs. (1)-(4) are solved for the H_β line and the region of total optical thickness $T = k(R - R_0)$ (R_0 and R are the inner and outer boundaries, respectively) with no radiation incident on the boundaries using new Implicit Integral Method of Simonneau and Crivellari (1993).

Computations are performed for the emission region of constant temperature (10^4 K) and density $n_e = n_H = 10^9$ cm^{-3} surrounding the central mass $M = 10^8 M_\odot$. We suppose that the absorber's density is also constant throughout the region and equal to $3 \cdot 10^4$ cm $^{-3}$. The computations are carried out with the Voigt parameter $a = 10^{-2}$ and the non-LTE parameter $\varepsilon = 10^{-6}$.

In Figure 1 we present the emergent intensities as a function of x for two directions μ. In Figs. 1(a)-(c) the outer boundary of the emission region is placed at $R = 5, 10, 50$ Schwarzschild radii (R_{Sch}), respectively, whereas the inner boundary is taken to be the same ($R_0 = 3R_{Sch}$) for the three cases. Hence, the total optical thickness of the regions is $T = 10^3, 3.4 \cdot 10^3$ and $2.2 \cdot 10^4$, respectively. Figure 1(d) represents the case where the boundary nearest the observer is at the same distance as in the case 1(c) but the region is optically thinner.

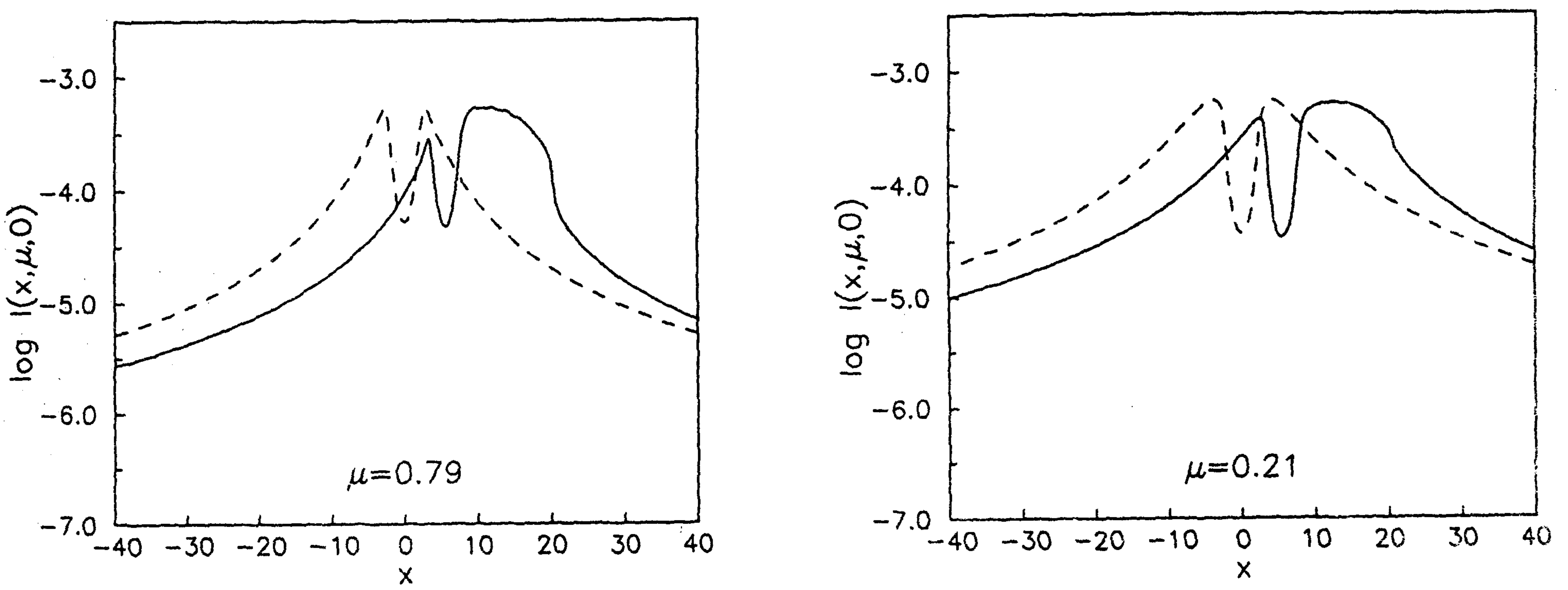
Comparing the cases of no gravitational field influence (dashed lines) with those where the influence is taken into account (solid lines) one can see that the redshift and the asymmetry decrease with receding from the nucleus. Although the outer boundary of the layer in Fig 1(c) is far from the nucleus, due to the emergent photons strongly influenced by the gravitational field deep in the extended region with large g-gradient, the asymmetry is still present. If the thickness of the region is smaller and the whole region is situated far from the nucleus only small redshift and no asymmetry is visible (Figure 1(d)). At the same time the last figure illustrates the limits of the visibility of the considered effect.

The line source function as a function of optical depth (τ) is given for the four cases in Figure 2. The effect of total optical thickness of the region on the source function is the most pronounced one: source function increases with increase in the total optical depth. The discrepancy between the source functions obtained when the gravitational field influence is taken into account (solid curves) or when it is not (dashed ones) becomes smaller as the emission region is farther from the nucleus. In case (d) the two curves completely overlap.



log I(x,μ,0)
-3.0
-4.0
-5.0
-6.0
-7.0
μ=0.79
μ=0.21
-40 -30 -20 -10 0 10 20 30 40
x

Fig. 1a



log I(x,μ,0)
-3.0
-4.0
-5.0
-6.0
-7.0
μ=0.79
μ=0.21
-40 -30 -20 -10 0 10 20 30 40
x

Fig. 1b

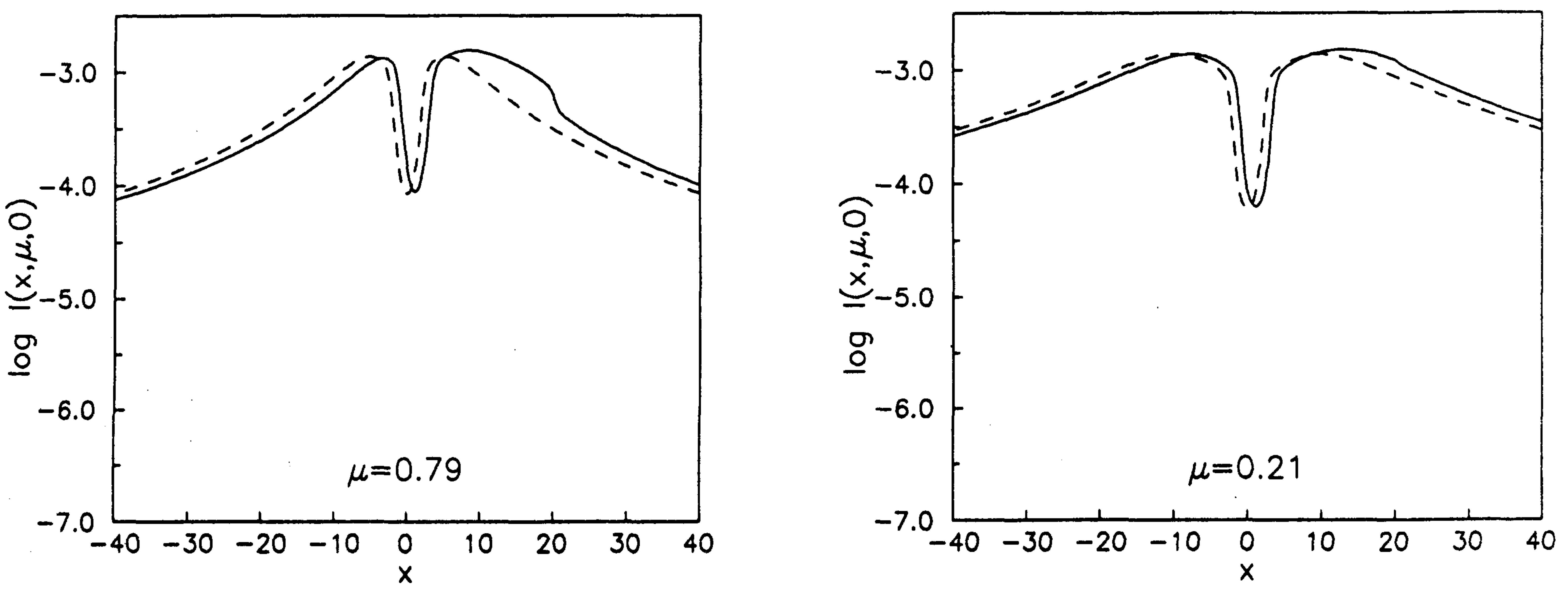


Fig. 1c

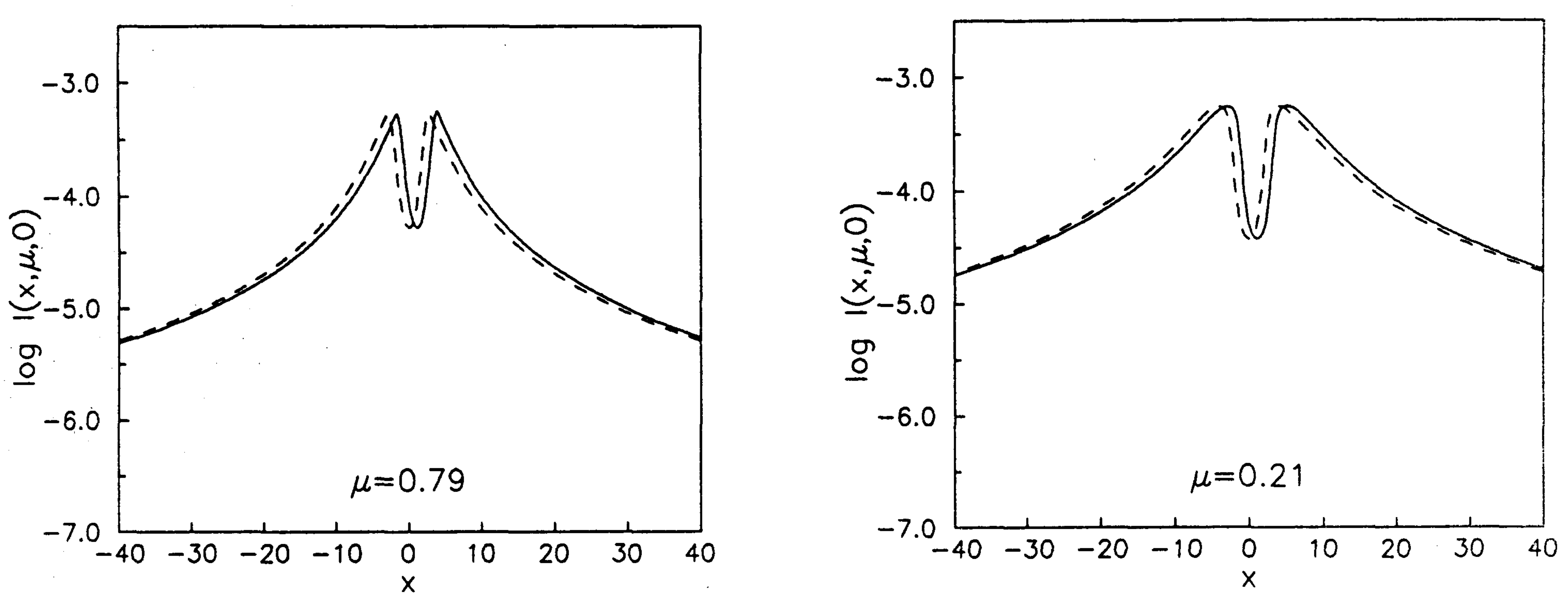


Fig. 1d

Fig. 1. The emergent intensities from the regions of different optical thicknesses placed at various distances: (1a) $R_0 = 3R_{Sch}$, $R = 5R_{Sch}$; (1b) $R_0 = 3R_{Sch}$, $R = 10R_{Sch}$; (1c) $R_0 = 3R_{Sch}$, $R = 50R_{Sch}$; (1d) $R_0 = 43R_{Sch}$, $R = 50R_{Sch}$, for $\varepsilon = 10^{-6}$, $a = 10^{-2}$, $B = 1$ and for two directions μ.

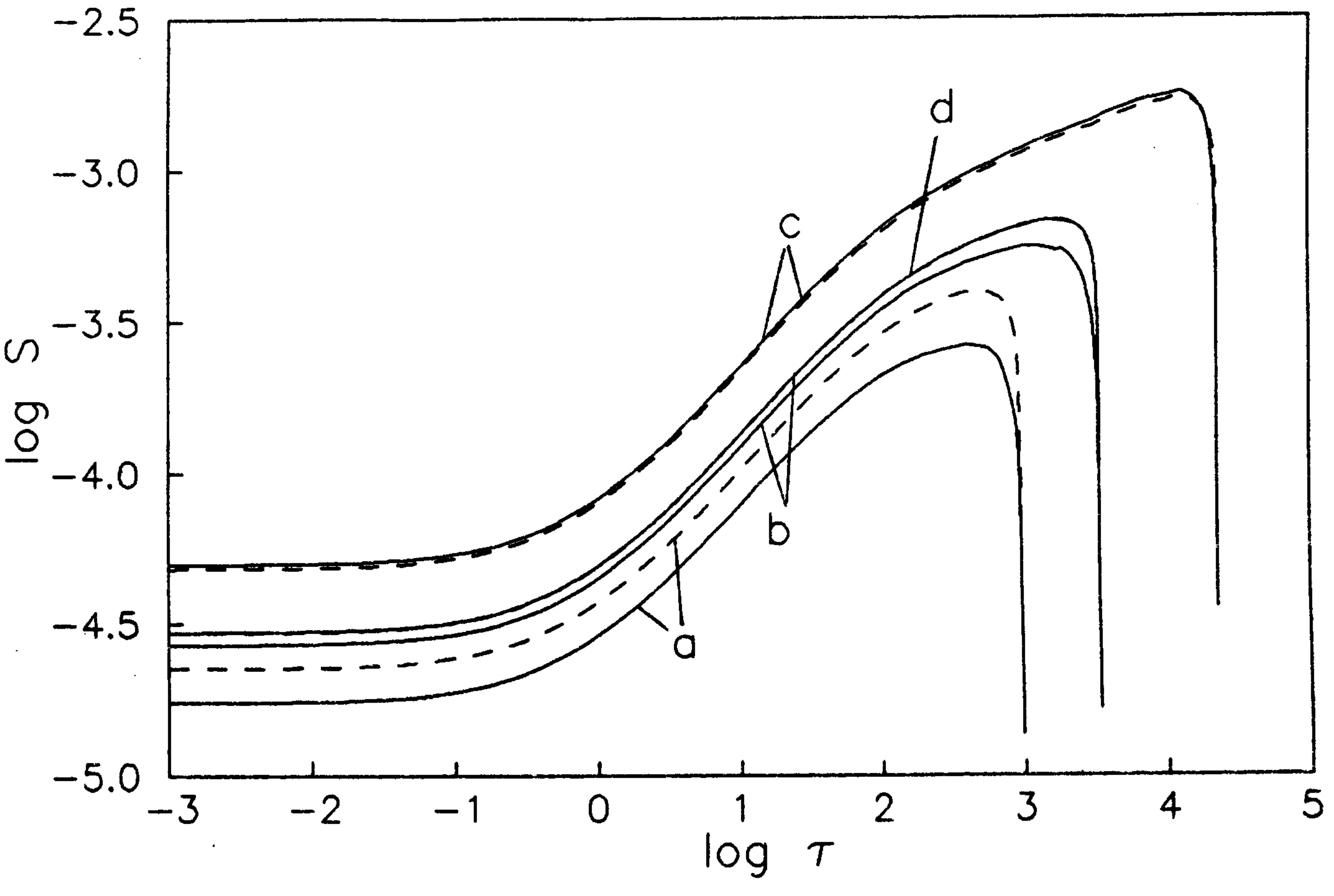


Fig. 2. Source functions corresponding to the four cases in Figure 1.

Briefly, the effect of the gravitational redshift is visible on the radiation emerging from an optically thick slab only if the region of line formation is very close to the massive nuclei where the gravitational field as well as its gradient are very strong.

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ДОПРИНОС ГРАВИТАЦИОНОГ ЦРВЕНОГ ПОМАКА ОБЛИКУ СПЕКТРАЛНИХ ЛИНИЈА AGN: СЛУЧАЈ ФОЈТОВОГ ПРОФИЛА

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Оригинални научни рад

У предходном раду (Paper I) анализиран је утицај гравитационог црвеног помака на профиле спектралних линија формираних у хомогеном, статичном и оптички танком региону близу масивног AGN под претпоставком да је профил Лоренцов. У овом раду је испитиван овај утицај при чему су укључени ефекти преноса зрачења. Претпостављајући да је Фојтов профил H_β линије значај овог ефекта је илустрован на неколико примера за различите оптичке дубине емисионог региона на различитим растојањима од масивног језгра.