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

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SUMMARY: In this paper we analyse the influence of gravitational redshift on the spectral line profiles of homogeneous, static and optically thin region near massive AGN (Seyfert galaxies and quasars). The correction function (Φ) that determines the degree of spectral line profile distorsion produced by gravitational field has been investigated.

1. INTRODUCTION

The emission line spectrum is one of the characteristics of the Active Galactic Nuclei – AGN. These emission lines are very broadened, shifted and asymmetrical. For example, the full width at half maximum (FWHM) of the Balmer lines in spectrum of Seyfert galaxies and quasars is usually greater than 1000 km/s (see, e.g., Anderson 1971, Osterbrock & Shuder 1982, Gorbackiy 1986). The shape of spectral lines is determined by conditions in the emission region. The dynamical effect is widely accepted as the main cause of shift, broadening and asymmetry of spectral line profiles (De Robertis & Show 1990).

In this paper we study the influence of gravitational field on the spectral line shapes from AGN. Based on preliminary examination (Popović *et al.* 1994a) by the use of a very simple model of Active Galactic Nuclei (see, e.g., Gorbackiy 1986) it was shown that the influence of gravitational field of the massive nuclei on spectral lines is not negligible. This can be explained by the following: (1) one part of emission region is in a strong gravitational field of the massive AGN and (2) this region is large enough, so that the emitters are in different gravitational fields along the line of sight. For example, masses of Seyfert galaxies are about $10^7 - 10^9$ $M_\odot$ (see, e.g., Padovani *et al.* 1990), and the size of the emission region is about $10^{14} - 10^{17}$ m (see e. g. Bonatto & Pastoriza (1990) for the case of NGC 7469).

To focus our attention to the gravitational field effects, in this paper we consider homogeneous, static and optically thin region near massive nuclei. In the analysis we use the Lorentz profile function because the expression for the Φ function, that determines the degree of spectral line profile distorsion caused by gravitational field has a very simple analytical form in this case. The analysis of more realistic case comprising Voigt profile function as well as an optically thick medium is performed in the paper by Popović *et al.* (1994b).

2. THEORY

The Lorentzian profile can be given by (see, e.g., Gray 1980)

$$S(\lambda) = \frac{w_L}{(\lambda-\lambda_0)^2 + w_L^2}, \qquad (1)$$

where $S(\lambda)d\lambda$ is the probability of finding the emitted photon in an interval $(\lambda, \lambda+d\lambda)$, λ_0 is the unperturbed transition wavelength, w_L is the broadening parameter.

For emitters in a gravitational field the transition wavelength will be shifted by (see, e.g., Weinberg 1972)

$$\lambda_0' - \lambda_0 = \lambda_0 \frac{\Delta U}{c^2}, \qquad (2)$$

where λ_0' is the shifted wavelength, c is the speed of light, and ΔU is the difference of the gravitational potential between the birth place of photons and the position of the observer.

If we consider the emitter in the gravitational field of a mass M at a distance r from the central body, and assume the gravitational potential at the position of the observer negligibly small, then the relation (2) yields (Weinberg 1972)

$$\lambda_0'(r, M) = \lambda_0 + \lambda_0 \cdot \frac{GM}{rc^2},$$

where G is the gravitational constant.

If we take into account the gravitational shift, than the relation (1) may be rewritten as

$$S(\lambda, r, M) = \frac{w_L}{[\lambda - \lambda_0'(r, M)]^2 + w_L^2}. \qquad (3)$$

For optically thin region of thickness $D = R - R_0$ the intrinsic line profile is given as a sum of radiation of all emitters along the line of sight

$$S'(\lambda, R, R_0, M) = \frac{1}{D} \int_{R_0}^{R} S(\lambda, r, M) dr. \qquad (4)$$

The solution of (4) yields (Popović *et al.* 1994a)

$$S'(\lambda, R, R_0, M) = S(\lambda)\Phi(\lambda, R_0, R, M), \qquad (5)$$

where Φ is the correction function that determines the degree of spectral line distortion produced by the gravitation field. In the case of Lorentzian profile for Φ – function we obtain

$$\Phi(\lambda, R_0, R, M) = 1 + \frac{k_1^2 - k_2^2}{k_2} \cdot \frac{(\mathrm{arctg}\alpha - \mathrm{arctg}\alpha_0)}{D} + \frac{k_1 \log b}{D}, \qquad (6)$$

where

$$k_1 = \frac{\lambda_0(\lambda-\lambda_0)A}{(\lambda-\lambda_0)^2 + w_L^2}, \qquad (7)$$

$$k_2 = \frac{\lambda_0 A w_L}{(\lambda-\lambda_0)^2 + w_L^2}, \qquad (8)$$

$$\alpha = \frac{R - k_1}{k_2}, \quad \alpha_0 = \frac{R_0 - k_1}{k_2}, \qquad (9)$$

$$b = \frac{(R-k_1)^2 + k_2^2}{(R_0 - k_1)^2 + k_2^2}. \qquad (10)$$

In Eqs. 7 and 8 $A = R_{Sc}/2 = GM/c^2$, where R_{Sc} is Schwarzschild's radius of a massive nucleus.

3. ILLUSTRATIVE RESULTS AND DISCUSSION

As an illustration of the influence of gravitational field on spectral line shape we calculated the Φ–function for different masses and the intensity variation with wavelength ($I(\lambda)$) normalyzed to its maximal value (I_{max}):

$$\frac{I(\lambda)}{I_{\max}} = S'(\lambda, R_0, R, M), \qquad (11)$$

with the following parameters: $R_0 = 10^{14}$ m, $R = 10^{16}$ m. The calculation was performed for the H_α transition wavelength range.

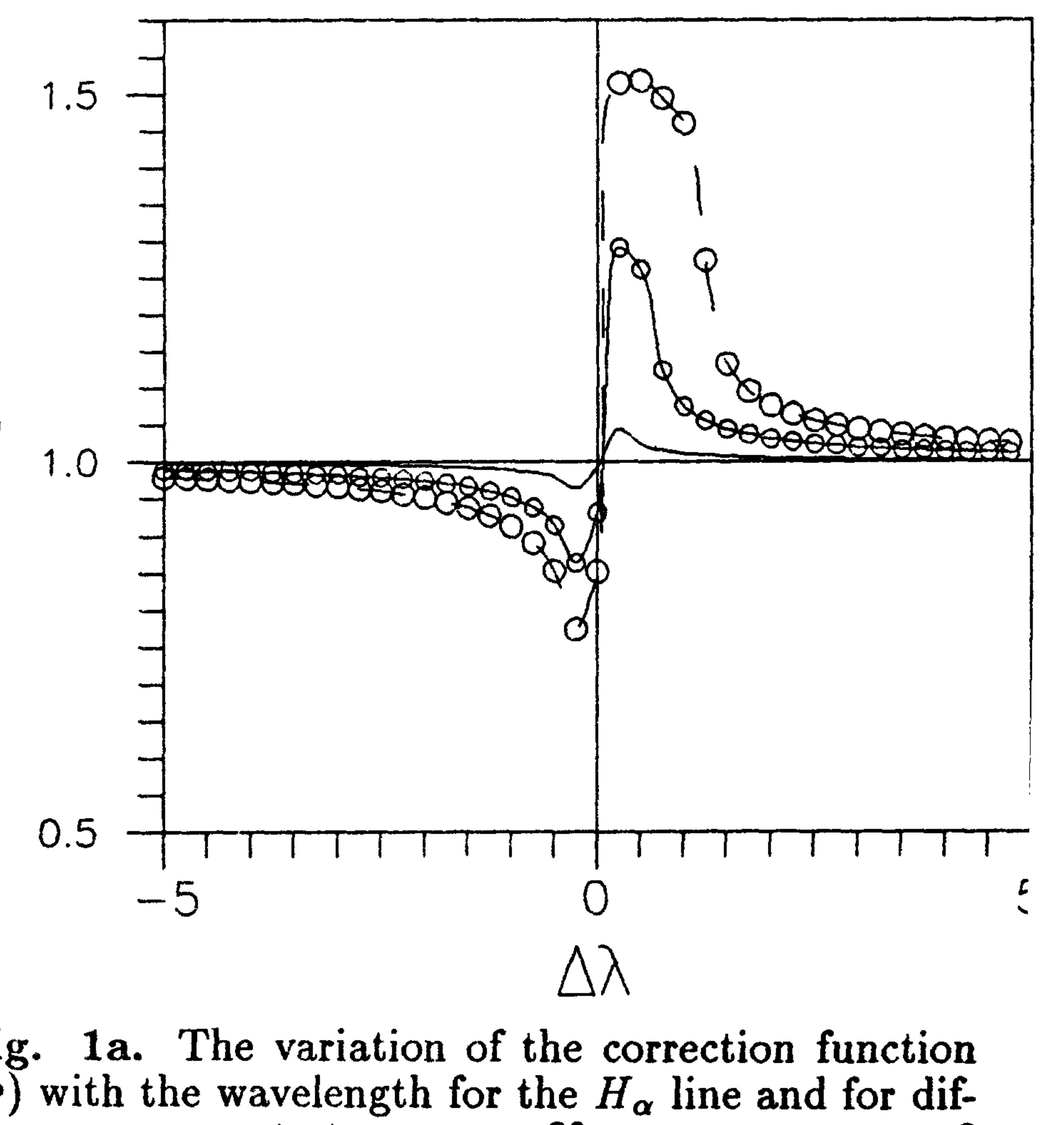

Fig. 1a. The variation of the correction function (Φ) with the wavelength for the H_α line and for different masses : (—) - $M = 10^{36}$ kg ($A = 7.42 \times 10^8$ m), (– ∘ –) - $M = 5 \times 10^{36}$ kg ($A = 3.71 \times 10^9$ m) and (– ∘ –) - $M = 10^{37}$ kg ($A = 7.42 \times 10^9$ m). $\Delta\lambda$ is expressed in w_L.

The variation of the Φ–function with wavelength for different masses is shown in Figures 1a. and 1b. The Φ–function is asymmetric with respect to both the transition wavelength (λ_0) and to the $\Phi = 1$. As one can see from Figures 1a. and 1b. the asymmetry of Φ – function depends on the mass of AGN.

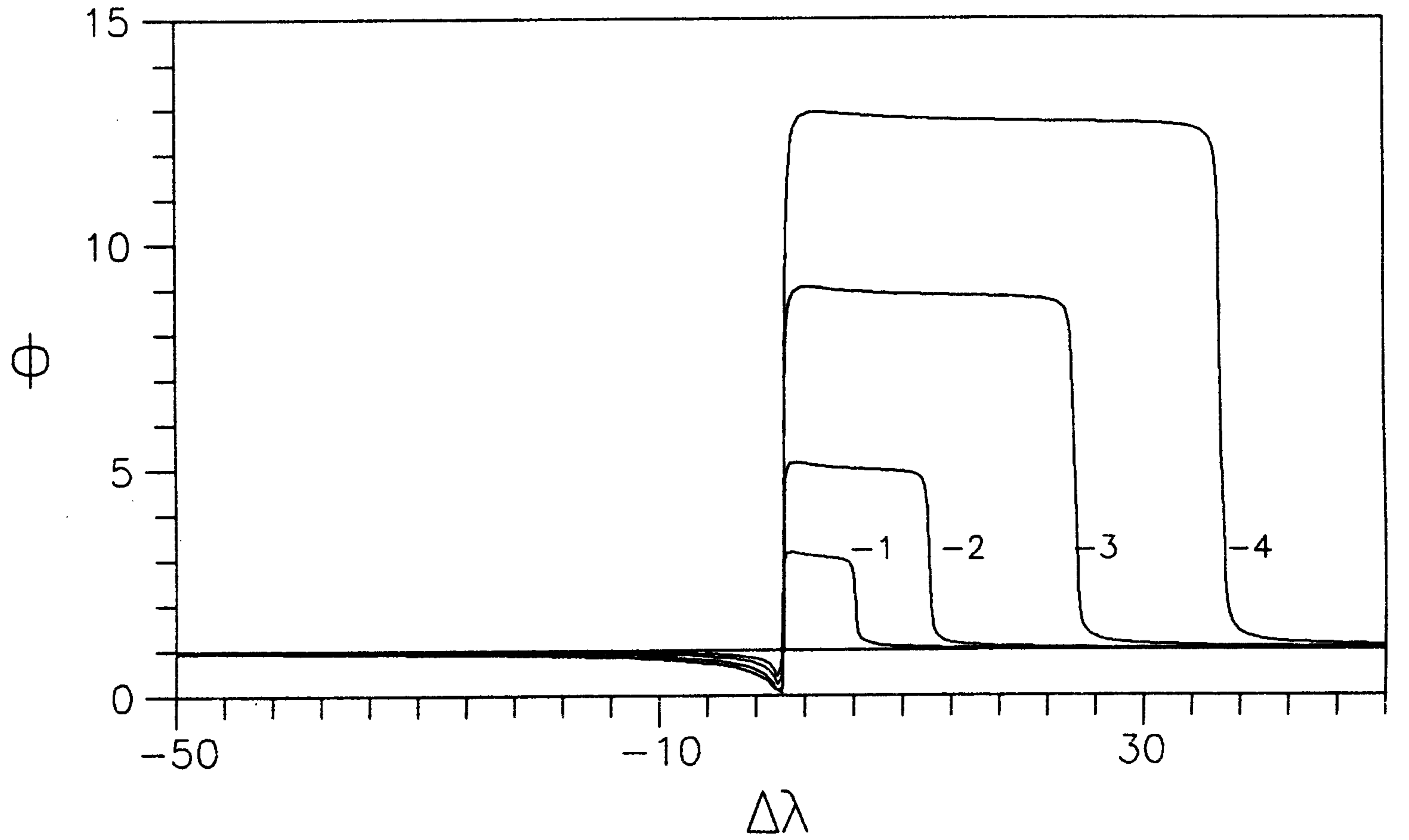

Fig. 1b. Same as in Fig. 1a, but for: (1) - $M = 5 \times 10^{37}$ kg ($A = 3.71 \times 10^{10}$ m), (2) - $M = 1 \times 10^{38}$ kg ($A = 7.42 \times 10^{10}$ m), (3) - $M = 2 \times 10^{38}$ kg ($A = 1.48 \times 10^{11}$ m), and (4) - $M = 3 \times 10^{38}$ kg ($A = 2.23 \times 10^{11}$ m).

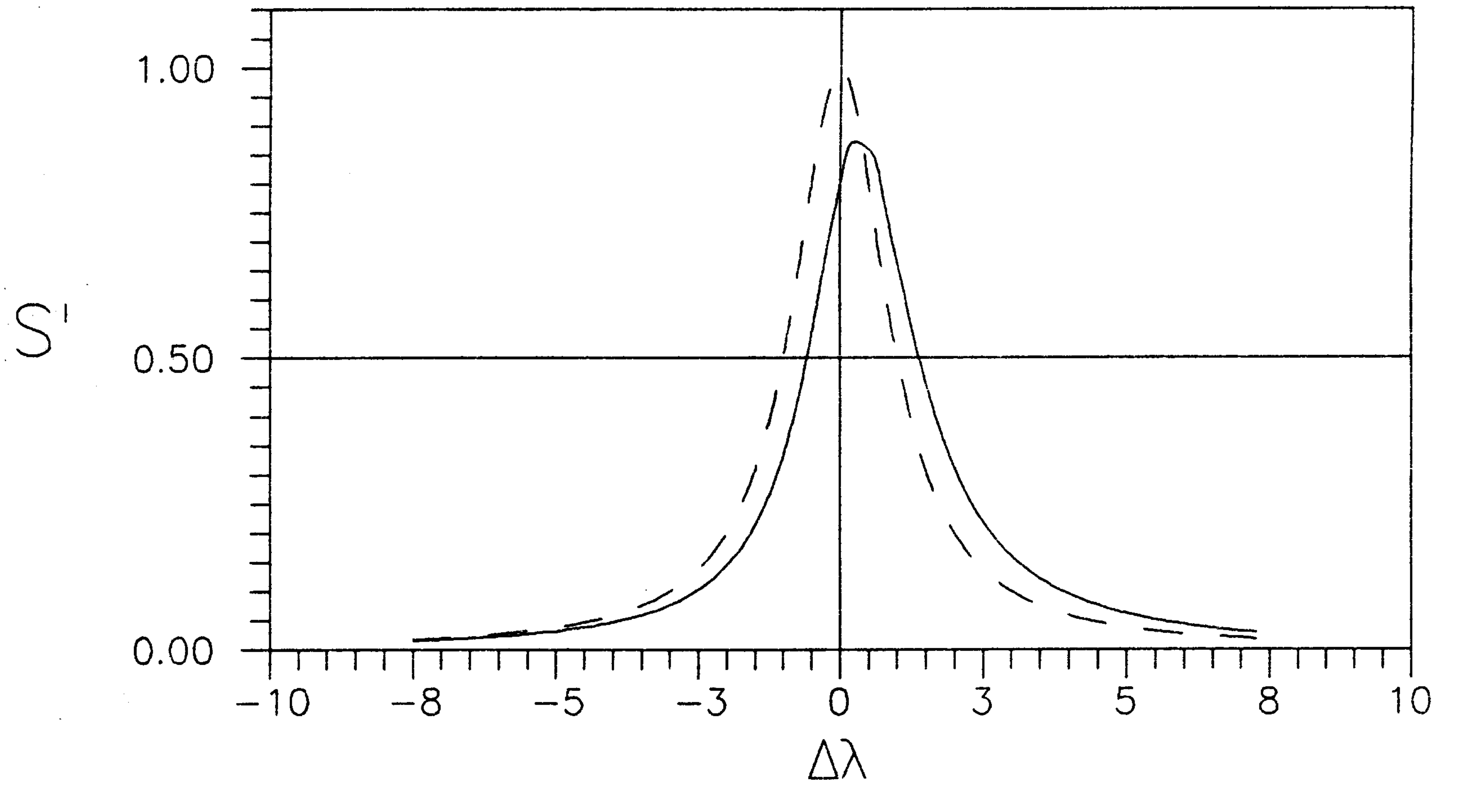

Fig. 2. The gravitationally deformed H_α line profile (full line) in comparison with the nondeformed Lorentzian profile (dashed line). The used parameters are the same as in Figure 1a, but for the mass of $5 \times 10^7 M_\odot$. $\Delta\lambda$ is expressed in w_L.

These asymmetries yielded shifted, broadened and asymmetric intrinsic spectral line profile. In Figure 2. the gravitationally deformed spectral line profile (full line) is compared with the nondeformed Lorentzian one (dashed line). The spectral line is shifted by about $w_L/3$ towards the red and is broadened for 18%. The blue wing of the deformed spectral line is lower, while the red one is higher than in the undisturbed line profile.

To examine the influence of Φ – function on spectral lines with different transition wavelengths we calculated the full width of several fictive spectral lines using the same atomic parameter w_L as that used for the H_α line. In Figure 3. we show a change of w (where w is the full width in the case when influence of gravitational field is taken into account) in function of wavelength. For longer transition wavelength the FWHM is larger than for the shorter one.

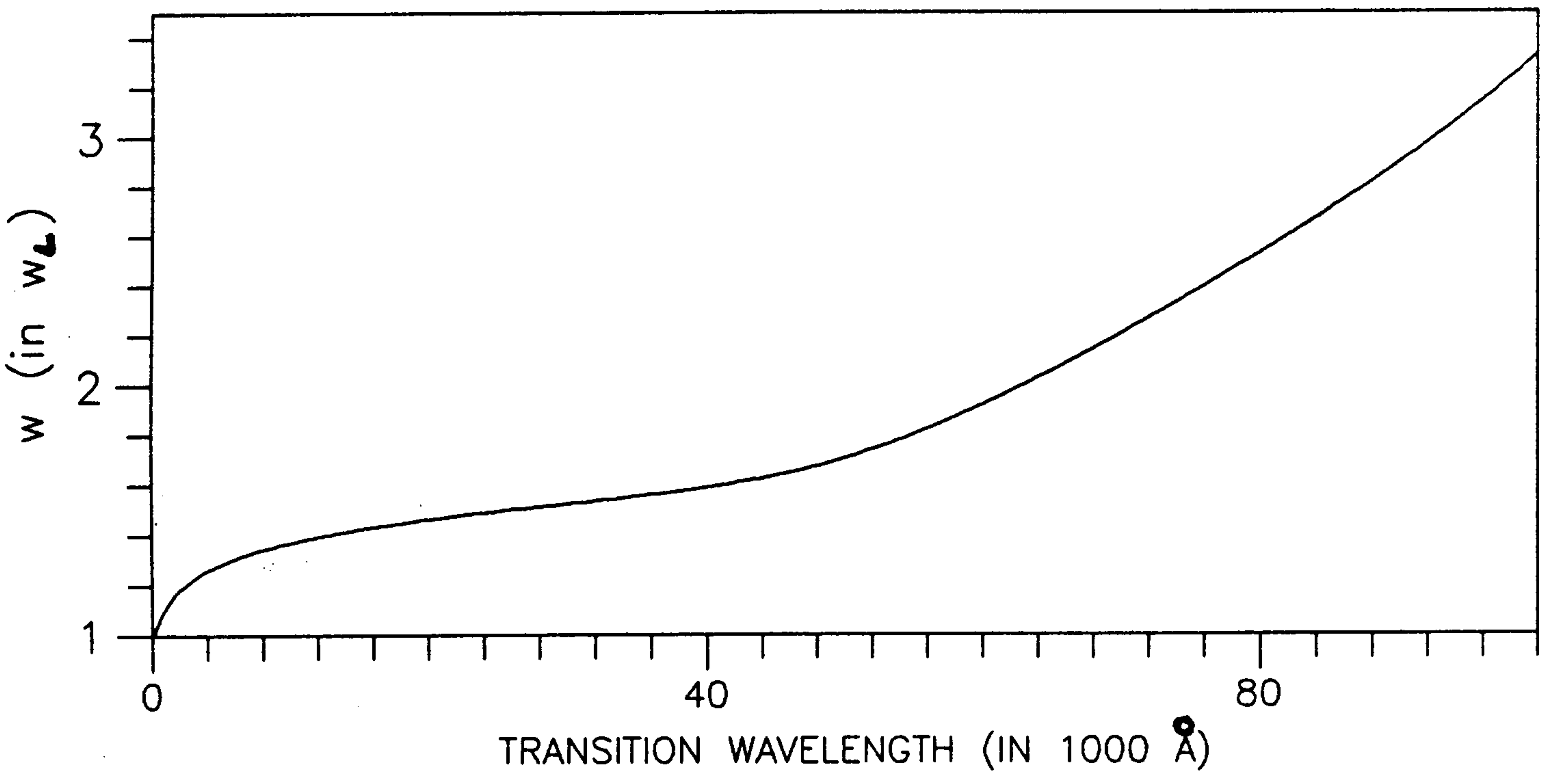

Fig. 3. The variation of w with transition wavelength. ($M = 5 \cdot 10^7 M_\odot$, $R = 10^{14} - 10^{16}$ m).

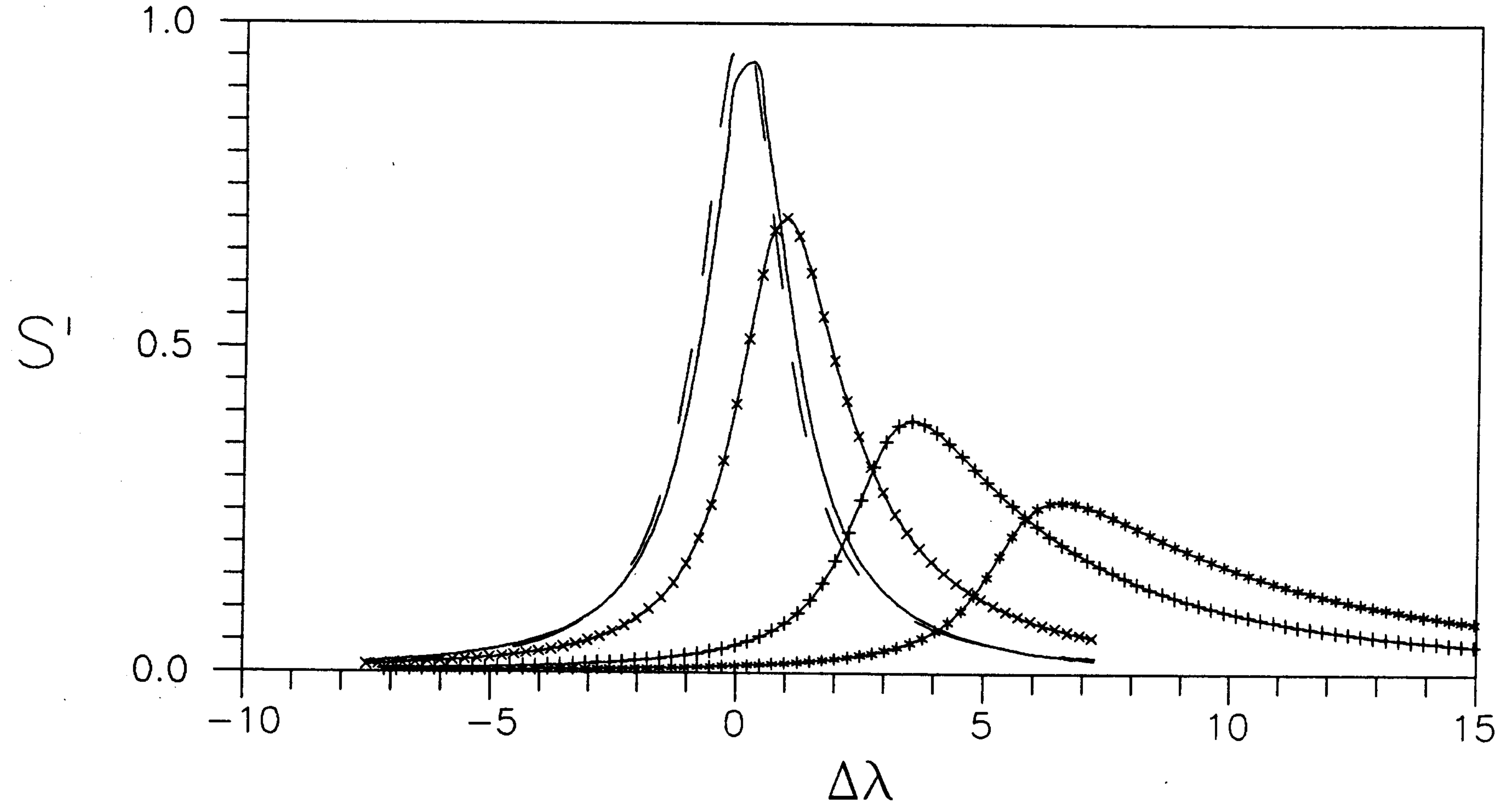

Fig. 4. The shape of spectral line for different transition wavelength (λ_0) range in comparison with the nondeformed Lorentzian profile (dashed line). Full line presents the line profile with transition wavelength λ_0 = 1000 Å, (-x-x) with λ_0 = 10000 Å, (+-+-) with λ_0 = 50000 Å, and (* *) with λ_0 = 100000 Å. ($M = 5 \cdot 10^7 M_\odot$, $R = 10^{14} - 10^{16}$ m). $\Delta\lambda$ is expressed in w_L.

Figure 4. presents influence of the gravitation field for different wavelength ranges. As one can see this influence is more important for spectral lines in infrared and radio than in ultraviolet range of wavelengths.

4. CONCLUSION

Using a simple model of the emission region (static, optically thin) near massive AGN we showed that the contribution of gravitational redshift is not negligible. The gravitational field gradient gave rise to the shifted, broadened and asymmetrical line profiles of AGN.

The observed profiles of H_α line of Seyfert galaxies showed both the red and the blue asymmetry (see, e.g., Osterbrock and Shuder 1982).

In a more elaborate analysis of such a behaviour of H_α line, besides the dynamics of the emission (Krolik & Vrtilek 1984) the gravitational redshift should be taken into account. The other effects (e.g., inhomogenity of the cloud, departures from the spherical symmetry of galactic gravitational field, radiative transfer and different broadening effects (e.g., Stark, Doppler, Wan der Waals) not considered here might also have certain influence on the spectral line shapes from AGN.

Some of these (influence of Voigt profile function and radiative transfer effects) are alredy under the study (Popović *et al.*, 1994b).

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

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Оригинални научни рад

У овом раду је анализиран утицај гравитационог црвеног помака на профил спектралне линије за хомоген, статичан и оптички танак регион у близини активних галактичких језгара (Сејфертових галаксија и квазара). Испитана је Φ – функција која одређује степен утицаја гравитационог поља на облик линије.