NON-LTE EFFECTS ON THE STRENGTH OF THE LYMAN EDGE IN QUASAR ACCRETION DISKS

H. STÖRZER
I. Physikalisches Institut der Universität zu Köln, Zülpicher Straße 77, D-50937 Köln, Germany.
E-mail: stoezer@host.ph1.uni-koeln.de

P. H. HAUSCHILDT
Department of Physics and Astronomy, Arizona State University, Box 871504, Tempe, AZ 85287-1504.
E-mail: yeti@sara.la.asu.edu

AND

F. ALLARD
Department of Geophysics and Astronomy, University of British Columbia, 129-2219 Main Mall, Vancouver, B.C., Canada, V6T 1Z4.
E-mail: allard@astro.ubc.ca

Received 1994 April 15; accepted 1994 October 5

ABSTRACT

We have calculated UV/EUV (300 Å ≤ λ ≤ 1500 Å) continuous energy distributions of accretion disks in the centers of active galactic nuclei (AGNs) for disk luminosities in the range 0.1L_{edd} ≤ L_{acc} < 1.0L_{edd} and central masses ranging from 10^8 M_{⊙} to 10^9 M_{⊙}. The vertical gas pressure structure of the disk and the disk height are obtained analytically; the temperature stratification and the resulting continuum radiation fields are calculated numerically. We have included non-LTE effects of both the ionization equilibrium and the level populations of hydrogen and helium. We show that these non-LTE effects reduce the strength of the Lyman edge when compared to the LTE case. In non-LTE we find that the edge can be weakly in emission or absorption for disks seen face-on, depending on the disk parameters.

Subject headings: accretion, accretion disks — galaxies: active — methods: numerical — radiative transfer

1. INTRODUCTION

Observations of a large number of quasars indicate that the H I Lyman edge is weak or there is no observable Lyman edge at all (Antonucci, Kinney, & Ford 1989; Koratkar, Kinney, & Bohlin 1992). This fact has been considered as an argument against the presence of a geometrically thin, optically thick accretion disk around a massive black hole in the center of active galaxies (AGNs) as the main source of the radiation in the optical and UV spectral ranges. However, the current theoretical models of the physical structure and the radiation emitted by such disks are far from being complete. More accurate models are necessary to settle the question if the thin disk approximation can be ruled out solely due to the lack of strong Lyman edges. In this Letter, we present results of model calculations in which the physical structure of the disk is described using a simplified, semianalytical approach (see Störzer & Hauschildt 1994, hereafter Paper I, for details). These model calculations result in a disk atmosphere (τ ≲ 10) in which the gas pressures are low (P_g < 100 dy cm^{-2}) and in which the temperatures are relatively high. For such configurations, non-LTE effects are expected to be important both for the ionization equilibrium and the level populations of hydrogen and helium and other important species. Therefore, we solve in a second step for a fixed gas pressure structure the non-LTE rate and radiative energy equations in the vertical direction for each ring of the disk.

After a brief discussion of the model assumptions in the next section, we present the energy distributions in the UV/EUV range (300 Å ≤ λ ≤ 1500 Å) for disks with luminosities in the range 0.1L_{edd} ≤ L_{acc} < 1.0L_{edd} (L_{edd} is the Eddington luminosity) and discuss the influence of non-LTE effects on the strength of the Lyman edge.

2. MODEL CONSTRUCTION

2.1. Analytic Solution of the Vertical Disk Structure

The continuous energy distributions are calculated in two steps. In the first step, we compute the gas pressure distribution, the vertical flux distribution, and the disk height analytically under the following assumptions:

1. The disk is stationary and in local hydrostatic and thermal equilibrium.
2. The disk is geometrically thin and optically thick, implying that the radial temperature and gas pressure gradients are much smaller than the corresponding gradients in the vertical direction.
3. The orbital motion is given by Kepler's law.
4. The shear stress τ_{σθ} is proportional to the gas pressure τ_{σθ} = αP_g.
5. The temperature in the disk atmosphere is given by the local effective temperature.
6. That the plasma inside the disk consists only of hydrogen and helium.
7. That electron scattering is the most important opacity source in the disk atmosphere.

This results in the following analytical expression for the gas pressure P_g(z) and the flux in vertical direction F_z as function of the distance to the central black hole r and the height above
the disk's symmetry plane $z$ (see Paper I for details):

$$P_d(z) = P_d(z_0) \exp \left[ \frac{c_1}{2} (z_0^2 - z^2) - c_2 z_0 - z \right]$$

for $z_0 \geq z > z_m$,

$$P_d(z) = P_d(z_0) \exp \left[ \frac{c_1}{2} z_0^2 - c_2 z_0 + \frac{c_2^2}{2c_1} \right]$$

for $z_m \geq z \geq 0$ .

(1)

Here $z_0$ is the disk height at the radius $r$, $P_d(z_0)$ is the gas pressure at the disk surface, and $z_m$ is the height where the gas pressure gets maximal $z_m = c_2/c_1$. The constant $c_1$ is given by $c_1 = (\mu m_u/kT_d)(GM_*/r^2)c_1$, $\mu$ is the mean molecular weight (we use $\mu = 0.524$), $M_*$ is the mass of the central black hole, and $c_1$ is a general relativistic correction factor given by $c_1 = \mathcal{B}/\mathcal{E}$ in terms of the factors $\mathcal{A}$, $\mathcal{B}$, $\mathcal{E}$, $\mathcal{G}$, and $\mathcal{L}$ defined in Novikov & Thorne (1972) and Page & Thorne (1974). These correction factors are functions of the radius $r$ (in terms of the Schwarzschild radius $r_s = 2GM_*/c^2$) and of the specific angular momentum $a_*$ of the central black hole. The effective temperature is

$$T_{\text{eff}} = \left( \frac{3GM_*/M}{8\pi^2\sigma_R \mathcal{B}/\mathcal{E}} \right)^{1/4} .$$

(2)

$M$ is the accretion rate, and $\sigma_R$ is the Stefan-Boltzmann constant. The factor $c_2$ is given by $c_2 = (\pi m_u/kT_d)(X + 2Y)/(1 + X + 2Y)$, where $\sigma_d = 6.65 \times 10^{-25} \text{ cm}^2$ is the Thomson cross section, $X$ and $Y$ are the fractional abundances (by number) of hydrogen and helium. The analytic expression for the vertical flux $F_z$ is

$$F_z = F_0 = \sigma_R T_{\text{eff}}^4 z \geq z_1$$

$$F_z = F_0 - (z_1 - z)xP_{\text{gas}}^\alpha C_2 (\frac{d\Omega}{dr}) z < z_1 .$$

(3)

Here, $z_1 = \sigma_R T_{\text{eff}}^4/[xP_{\text{gas}}(r\Omega/dr)]$, and $z_0 \geq z \geq z_m$. The maximal gas pressure is given by $P_{\text{gas}} = P_d(z_0) \exp [(c_1/2)z_0^2 - c_2 z_0 + c_2^2/2c_1]$, $x$ is the viscosity parameter, $\Omega = (GM_*/r^2)^{1/2}$, and $C_2 = \mathcal{B}/\mathcal{E}$. The disk height $z_0$ can be calculated by solving

$$z_0^2 - 2z_0 c_2 + \frac{c_2^2}{c_1} - 2c_2^2/c_1 + 2\ln [P_d(z_0)] + 2\ln (z_0) = 0 .$$

(4)

Here $c_1 = \ln (M\Omega/c_4/4\pi\alpha)$ and $C_2 = \mathcal{B}/\mathcal{E}$. The roots of equation (4) can be found numerically. The above analytical solution typically results in an optically thick accretion disk where the disk atmosphere ($r \leq 10$) is a thin layer at the disk surface. The gas pressure inside the atmosphere is small ($P_d \leq 100 \text{ dyn cm}^{-2}$); the temperatures are relatively large ($15,000 \text{ K} \leq T \leq 100,000 \text{ K}$). Non-LTE effects are, therefore, important both for the ionization equilibrium and the level populations of hydrogen and helium.

2.2. Solution of the Non-LTE Radiative Transfer and Rate Equations

In the second step we solve the one-dimensional, plane-parallel, nongray radiative transfer and energy equations simultaneously with the non-LTE rate equations for H I and He I in the vertical direction at a number of fixed (typically 30) radial rings for a given disk height and gas pressure and vertical flux stratification. We use the generalized NLTE model atmosphere code PHOENIX, version 4.7, to compute the vertical temperature structure and the departures from LTE for each ring. PHOENIX is described in some detail in Hauschildt et al. (1994a), Baron, Hauschildt, & Branch (1993), and Allard & Hauschildt (1994), so we describe here only the features most relevant for this work.

We use an accelerated A-iteration (ALI) method to solve the plane-parallel equation of radiative transfer at each point of a prescribed grid with about 1200 wavelength points. We use a short characteristic method (Olson & Kunasz 1987; Hauschildt 1992) for the formal solution of the transfer equation required by the ALI method. The approximate A-operator is constructed using a band-matrix representation of the discrete A-operator (or A-matrix). This ensures fast convergence and results in a very high accuracy and performance of the rate transfer (Hauschildt, Störzer, & Baron 1994b). The multi-level radiative transfer and rate equations are solved using the rate operator formalism of Hauschildt (1993), which is an extension of the ALI method developed by Rybicki & Hummer (1991) to overlapping lines and continua. It uses an "approximate rate operator" computed using a tridiagonal representation of the discrete rate operator to accelerate the convergence. We solve the radiative energy equation using a modified Unsöld-Lucy method (Allard 1990), which has the advantage of rapid convergence and a negligible impact on the total computing time.

The atomic data for the H I model atom were taken from Johnson (1972). For He I we take the level energies from Wiese, Smith, & Glennon (1966) and the radiative and collisional cross sections from Berrington & Kingston (1987, lines), Mathiesen (1984, photoionization), and Mihalas & Stone (1968, collisional ionization). In the calculations we include the NLTE $b-b$ transitions but neglect, for simplicity, other $b-b$ transitions. These will be included in subsequent calculations.

After we have calculated the structure of the disk, we compute the UV/EUV continua for an inclination angle of $i = 0^\circ$ directly by using PHOENIX. The effects of the inclination on the strength of the Lyman edge cannot be studied by this approach because the radiative transfer problem is only solved for a plane-parallel geometry. LTE calculations in which the inclination is treated more consistently (Störzer & Hauschildt 1994) show that the behavior of the Lyman edge is not very sensitive to the inclination angle $i$ as long as $i$ is not too large ($0^\circ \leq i \leq 60^\circ$). The results of the non-LTE calculations for $i = 0^\circ$ should therefore also be representative for the above angle range.

The calculations are not fully self-consistent because the Doppler shifts in the lines, due to the orbital motions inside the disk, are not included in the radiative transfer code. We present, therefore, only the continuous energy distributions. We find that the LTE energy distributions are in good agreement with the results obtained in Paper I. This demonstrates both the accuracy of the three-dimensional radiative transfer used in Paper I and that our approach here is appropriate for the continuous energy distribution.

The computing time requirements of the calculations presented here are very large; we can, therefore, only present a limited number of model continua. The purpose of this Letter is not to make a large parameter study, but we want to study the principal effects of non-LTE on the strength of the Lyman edge for a number of selected models.
3. RESULTS

The luminosity $L_{\text{rad}}$ of the disks we consider is in the range $0.1L_{\text{Edd}} \leq L_{\text{rad}} < 1.0L_{\text{Edd}}$, ($L_{\text{Edd}} \approx 1.3 \times 10^{38} M_*/M_\odot$ ergs s$^{-1}$) the mass of the central object varies from $M_* = 10^9 M_\odot$ to $M_* = 10^9 M_\odot$. We consider disks with $a_* = 0$ (nonrotating black hole) and $a_* = 0.9981$ (maximal rotating black hole). The outer edge of the disk $r_{\text{out}}$ is at the radius where $T_{\text{eff}} = 15,000$ K; however, we choose $r_{\text{out}} = 100r_*$ ($r_* = 2GM_*/c^2$ is the Schwarzschild radius) when the corresponding radius is larger than $100r_*$. The inner edge of the disk in the radiative transfer calculations is set for $a_* = 0$ always at $r_{\text{in}} = 4r_*$, whereas for $a_* = 0.9981$ we set the inner edge at $r_{\text{in}} = 2r_*$. The $\alpha$ parameter is chosen as 1.0, and we use solar abundances (Anders & Grevesse 1989).

In Figure 1 we show the continua for non-LTE and LTE (curves marked with crosses) models with $M_* = 10^9 M_\odot$, $a_* = 0$, $\alpha = 1$, an inclination angle of $i = 0^\circ$ (i.e., a disk seen face-on), an accretion rate of $M = 0.5 M_\odot$ yr$^{-1}$, $M = 1.0 M_\odot$ yr$^{-1}$, and $\dot{M} = 3.0 M_\odot$ yr$^{-1}$ (lower to upper pairs of curves).

The overall shape of the LTE and non-LTE continua is very similar. However, the Lyman edge, which is always in absorption in the LTE models, is weaker in the non-LTE case when compared to the LTE models. In addition, the Lyman edge can be in emission for large accretion rates. The reasons for this behavior can be understood as follows. In regions with small surface gravity and high effective temperatures, hydrogen is mostly ionized. The non-LTE/absorption coefficients of the H I ground state are larger than unity (cf. Fig. 2). Therefore, the absorption coefficient $\chi$ just blueward of the Lyman edge is larger than its LTE value. However, the extinction coefficient $\chi = \sigma + \kappa$ (where $\sigma$ is the scattering coefficient, dominated by electron scattering) and the optical depth $\delta \tau = -\chi \delta x$ remain practically constant when compared to the LTE case because of $\chi \approx \sigma \gg \kappa$ on both sides of the Lyman jump. The larger value of the thermal coupling coefficient $\epsilon = \kappa/\chi$, when compared to its LTE value and to its value just longward of the Lyman jump, results in a larger thermal source function $S_\kappa = \kappa B/\chi$, therefore, in larger outgoing flux just shortward of the Lyman edge when compared to the LTE value. This will reduce the Lyman jump and eventually reverse it to emission at some disk radii.

In models for which the maximum effective temperature is smaller and, in addition, the surface gravity is larger when compared to the models discussed previously, the situation is different. The degree of ionization is now smaller and the LTE absorption coefficient just shortward of the Lyman edge is comparable to or even larger than the scattering coefficient. Therefore, the increase of the thermal source function shortward of the Lyman edge is overcompensated for by the larger optical depth, i.e., the radiation emerges from layers with smaller temperatures. This results in a LTE Lyman edge in absorption. In the non-LTE models, the departure coefficients for the larger radii are typically less than unity (cf. Fig. 2). This results in an overionization of hydrogen when compared to LTE. Although this reduces the thermal part of the source function, it increases the importance of electron scattering and, additionally, reduces the total absorption optical depth of the region shortward of the Lyman jump. This results in a weaker Lyman jump when compared to the LTE case; however, it does not reverse the jump into emission in the models we consider here.

Disks with higher accretion rate and fixed mass of the central black hole have, at a point with fixed effective temperature, a smaller surface gravity than disks with smaller accretion rate (see Paper I). Because fixed $\Teff$ and smaller surface gravity implies a stronger degree of ionization, non-LTE effects tend to reverse the Lyman edge into emission for the high accretion rate models. Such disks have also larger maximum effective temperatures which, in addition, can shift the Lyman edge into emission. For smaller accretion rates, the spectrum is formed in regions with larger surface gravity, i.e., regions where the degree of ionization of hydrogen is smaller, thus only reducing the strength of the Lyman jump.

In the case of fixed luminosity (in terms of the Eddington luminosity) and varying mass of the central black hole, the situation is similar. In Figure 3 we show the continua for non-LTE and LTE (curves marked with crosses) models with $M_* = 10^9 M_\odot$, $M = 3.52 M_\odot$ yr$^{-1}$ (this corresponds to
We have performed a study in which we investigated the influence of non-LTE effects on the strength of the Lyman edge in quasar accretion disks. The strength of the Lyman edge of geometrically thin and optically thick accretion disks around black holes is a strong function of the model parameters. For disks seen nearly face-on, we find that the non-LTE effects are very important and reduce the Lyman edge or can even reverse it from absorption to very weak emission, depending on the disk parameters. This shows that weak Lyman edges in quasar spectra can be consistent with the presence of a central, geometrically thin, and optically thick accretion disk. In most of the models a nonvanishing Lyman discontinuity is still present, either in absorption or emission. However, in order to predict the strength of the Lyman jump quantitatively for disks seen not face-on and in order to investigate the parameter space which is consistent with current observations, more detailed models are required. A comparison of these models with observational data will provide a possibility to test the validity of the thin disk assumption applied to quasars.

We thank the referee for very helpful comments on an earlier draft of this Letter. This research was supported by the Deutsche Forschungsgemeinschaft through grant SFB 301, by a NASA LTSA grant to Arizona State University, as well by grants to G. F. Fahlman and H. B. Richer from NSERC (Canada). Some of the calculations presented in this Letter were performed on the Cray C90 of the San Diego Supercomputer Center (SDSC), we thank them for a generous allocation of computer time.

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