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Line Shifts in the Two-Phase Broad-Line Region with Radial Kinematics[1]

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Abstract. We consider in detail the two-phase BLR model with radial infall kinematics. Numerical calculations show that Lyα and C IV λ1549 profiles are blueshifted from their systemic rest-frame velocity, and their profiles are in qualitative agreement with the observations. It seems that the observed velocity differences between the high and low-ionization lines in the spectra of quasars can be understood in such a simple, physical, self-consistent model.

1. Introduction

A series of published papers (Gaskell 1982; Wilkes 1984; Espey et al. 1989; Corbin 1990; Carswell et al. 1991) have revealed that there are systematic profile and velocity differences between many broad emission lines in the spectra of high-redshift quasars. Generally speaking, the high-ionization lines and Lyα are blueshifted with respect to the source systemic velocity, which is likely to be determined by the low-ionization lines or forbidden lines since they are expected to arise in the extended emission regions.

A number of possible explanations for these velocity differences have been suggested. They generally involve bulk mass flows and internal obscuration in the quasar. For example, Kallman & Krolik (1986, hereafter KK) considered the effects of electron-scattering opacity on line profiles in the standard two-phase BLR model. Under the assumption of radial kinematics, they demonstrated for their wind outflow model that scattering can cause the Lyα profile to be very nearly symmetric, while the peaks of both Lyα and C IV λ1549 are offset from the source rest-frame velocity by a certain amounts of the line width (FWHM). Unfortunately, the direction of line offsets in this case is towards the red, in contradiction to the observations. It is thus expected that an infall model will shift these lines towards the blue, but in this case electron scattering is not as effective as it is in the outflow model; in the infall model, the electron-scattering opacity rises steeply inward, while the photons at the line peak come from clouds at large radii (therefore with small velocities) in the BLR, where the scatter-

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ing is weak. Therefore, one can hardly say that scattering effects in the BLR are capable of pushing some relevant lines to the blue in agreement with the observations.

In order to find if any other factors govern line-shift properties, we consider in more detail the two-phase BLR model with radial infall kinematics. We wish to know to what extent this simple, physical, self-consistent BLR model can explain the observed line properties.

2. The Model and Numerical Calculations

2.1. Line-Profile Expressions

Following the standard scenario for the BLR, we assume that it is a thick spherical shell, with a number of line-emitting clouds immersed in an hot intercloud medium; the two-phase material shares the nearly same radial dynamics in approximately pressure equilibrium. The line shapes are determined by adding the contributions from those individual clouds, each with its own line luminosity which is dependent on the local physical conditions and contributing at a frequency determined by its line-of-sight velocity. An expression for the line profile is thus

$$L_\nu \propto \int_{r_{in}}^{r_{out}} r^2 dr \int_{-1}^{+1} d\mu \, n_{cl}(r) \Phi_l(r,\mu) \delta \left\{ \nu - \nu_l \left[1 + \mu \frac{v(r)}{c} \right] \right\} \exp[-\tau(r,\mu)]. \quad (1)$$

To determine the line luminosity Φ_l produced by an individual cloud at $\mathbf{r}(r,\theta)$ in the BLR, following KK, we take into account the effects of electron scattering, i.e., the scattered ionizing radiation hits the back, neutral side of the cloud, producing additional ionization and line emission. A schematic model of such an emission cloud is shown in Fig. 1.

For high-ionization lines, the intensities must depend sensitively on the cloud surface ionization, whether it is directly illuminated by central continuum or by scattering diffuse continuum (therefore an effective ionization parameter Ξ^i_{eff} is introduced). The total luminosity of a specific line can be regarded as the integral of the flux comes from the cloud hemisphere facing the observer,

$$\Phi_l(r,\theta) = a^2(r) \int\int_{azb} \sin\theta' d\theta' d\varphi' \; S_l(n_c, \Xi^i_{eff}) H(\cos\Theta) \cos\Theta, \qquad (2)$$

where a is the radius of a cloud and H is the limb-darkening law expressed as a function of the cosine of the angle Θ between the surface normal and the inverse line of sight.

For Lyα and C IV λ1549, the surface brightness S_l can be obtained through calculations of a grid of photoionization models (Kallman & Krolik 1986).

The emerging line photons are likely to suffer some extinction in the hot medium because of the optical depth to scattering as they diffuse out of the BLR from their point of origin $\mathbf{r}(r,\theta)$ (Xue, Cheng, & Kwan 1996),

$$\tau_l(r,\theta) = \int_{r\cos\theta}^{\infty} 1.2\, \sigma_T n_h \left[(z^2 + r^2 \sin^2\theta)^{1/2} \right] \left| \frac{dr'}{dz} \right| dz, \qquad (3)$$

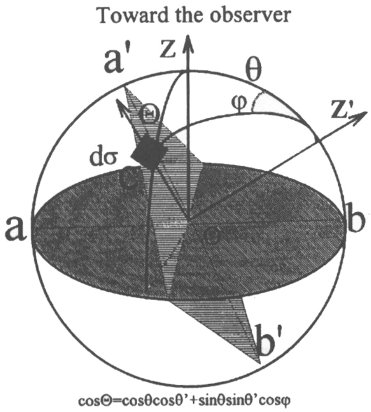

Figure 1. A schematic model of an emission-cloud in the BLR. The hemisphere *azb* is facing the observer. The hemisphere *a'zb'* faces away from the continuum source and is ionized by the scattering diffuse continuum.

where $r'^2 = z^2 + r^2 \sin^2\theta$. If a radial velocity field $v \propto r^\alpha$ is employed, and further a steady mass flow is assumed in the BLR, then all the unknowns in the eqs. (1)–(3), including the density of the hot medium n_h and cloud distribution n_{cl}, normalized to a set of 'standard' BLR characteristic quantities such as the characteristic scale R and velocity $v(R)$, the cloud temperature $T_c(R)$, and particle density $n_c(R)$, can be fully determined. Combining eqs. (1)–(3), line profiles can be worked out self-consistently.

2.2. Numerical Calculations

For the case $\alpha = -0.5$, which corresponds the radial infall or decelerating outflow dynamics, we establish radii r_{in} and r_{out} (normalized to R) defined so that, in the absence of electron scattering, a logarithmic profile can be achieved over a reasonable frequency or velocity range, e.g., 0.05–$2.0\,v(R)$. It is then required that $r_{in} = 0.25$ and $r_{out} = 400$. In such a BLR, the self-consistency of the two-phase balance for the standard emission cloud ($\Xi = 0.16$, $n_c = 2 \times 10^9\,\mathrm{cm}^{-3}$, $T_c = 10^4\,\mathrm{K}$; Kwan & Krolik 1981) requires the hot medium to have $n_h = 2 \times 10^5\,\mathrm{cm}^{-3}$ and $T_h = 10^8\,\mathrm{K}$ at R, indicating a characteristic electron-scattering depth $\tau_0(R) = 1.2\sigma_T n_h R \approx 0.32$, and the resulting line profiles are shown in Fig. 2a. The profiles are very similar to the results given by KK (in their Figs. 5 and 8), i.e., line asymmetries, especially that of Lyα, are significantly improved compared to the model without electron scattering, but the position of the peak is nearly unaltered, as explained in §1.

Without violating the self-consistency of the radial-infall, two-phase BLR model, we have tried to identify the most sensitive quantity that affects the line shifts. We find that the cutoff of the BLR outer radius r_{out} almost definitely determines the blueward line offsets. Figure 2b shows the resulting profiles produced in a BLR with $r_{in} = 0.1$, $r_{out} = 10$, and the standard physical conditions. Here both the Lyα and C IV profiles are shifted to the blue at a substantial level,

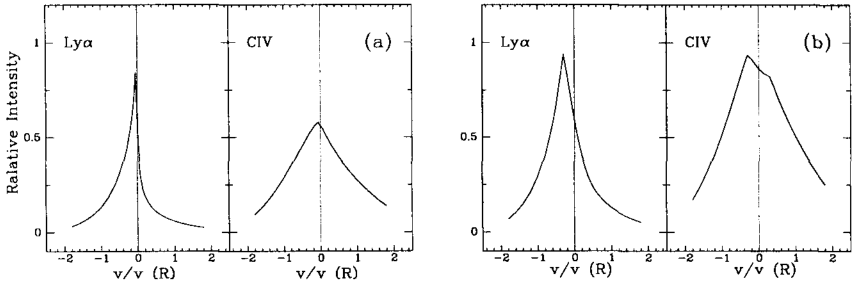

Figure 2. Line profiles in the two-phase BLR model with infall kinematics. a) The BLR with $r_{in} = 0.25$, $r_{out} = 400$; b) The BLR with $r_{in} = 0.1$, $r_{out} = 10$. Note line shapes and their blue offsets from the zero velocity.

$\sim 0.3v(R)$, Lyα is nearly symmetric, and C IV is slightly asymmetric, which is qualitatively consistent with the observations.

3. Conclusions

In the context of the two-phase BLR model with radial-infall kinematics, we find that the outer radius of the BLR largely determines the line-profile properties. With a properly chosen BLR outer radius, the model can produce blueshifted Lyα and C IV profiles, while their profiles, e.g., the nearly symmetric Lyα and slightly asymmetric C IV, are qualitatively in agreement with the observations. The cut-off of the BLR outer radius physically means that the emission regions of Lyα, C IV, and perhaps other high-ionization lines are not very extended. Therefore it seems that the observed redshift differences between the emission lines in the spectra of quasars can be understood: because the low-ionization lines arise in more extended emission regions compared to the high-ionization lines, their profiles tend to peak at the systemic rest-frame velocity. But high-ionization lines are produced in more compact regions, and therefore their 'BLR' must be cut off at some outer radius in the calculations, which results in their profiles being blueshifted with respect to the source rest-frame velocity.

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