2012

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Digital Object Identifier (DOI)
http://dx.doi.org/10.1111/j.1365-2966.2012.21389.x

Notes/Citation Information

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Intervening broad-line region clouds’ effects on the optical/ultraviolet spectrum

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ABSTRACT
Recent X-ray observations of Mrk 766 suggest that broad emission-line region clouds cross our line of sight and produce variable X-ray absorption. Here we investigate what optical/ultraviolet (UV) spectroscopic features would be produced by such ‘intervening broad-line region (BLR) clouds’ (IBC) crossing our line of sight to the accretion disc, the source of the optical/UV continuum. Although the emission spectrum produced by intervening clouds is identical to the standard BLR model, they may produce absorption features on the optical or UV continuum. Single clouds will have little effect on the optical/UV spectrum because BLR clouds are likely to be much smaller than the accretion disc. This is unlike the X-ray case, where the radiation source is considerably smaller. However, an ensemble of intervening clouds will produce spectroscopic features in the far-ultraviolet including a strong depression between the Lyman limit and Lyα. The amount of the depression will indicate the line-of-sight covering factor of clouds, an unknown quantity that is important for the ionization of the intergalactic medium and the energy budget of active galactic nuclei (AGNs). Comparison with observations suggests that the Spectral Energy Distribution (SED) of Mrk 766 may be affected by IBC that may exist in most of AGNs.

Key words: accretion, accretion discs – quasars: emission lines – quasars: general – galaxies: seyfert.

1 INTRODUCTION

The nature of the broad-line region (BLR) of active galactic nuclei (AGNs) is an area of vigorous debate (see the summary by Osterbrock & Mathews 1986; Korista 1999; Ferland 2004; Wang et al. 2011, 2012). The BLR is used to measure black hole masses and may be the avenue coupling feedback between the central black hole and the surrounding galaxy. The picture that has emerged is the one where a large number of clouds orbit the central black hole (Arav et al. 1997, 1998). Some recent work on the structure of an AGN suggests that the clouds, which emit the broad lines in the ultraviolet (UV) and optical, constitute a flattened, self-shielding and physically thick system (Gaskell, Goosmann & Klimek 2008), as Fig. 1 shows. Indeed, it may provide the coupling between the outer regions of the accretion disc and the inner parts of the obscuring dusty torus (Wang et al. 2010). The accretion disc, BLR and torus may have a continuous geometry with matter flowing from the torus through the BLR on to the disc and eventually the black hole (Hu et al. 2008a,b). The geometry of individual BLR clouds, where the strong emission lines form, is also uncertain. Some models that invoke winds off the accretion disc (Wang et al. 2012), or a fine ‘mist’ of small clouds (Arav et al. 1998), have been proposed.

Some recent works (Elvis et al. 2004; Risaliti et al. 2005, 2007, 2009; Puccetti et al. 2007; Bianchi et al. 2009; Bianchi, Maiolino & Risaliti 2012) suggest that BLR clouds may produce X-ray absorption, which is very common in AGNs. In this work, X-ray absorbers are described as clouds with linear dimensions of the order of 10^{13}–10^{14} cm, velocities in excess of 10^{3} km s^{-1} and densities n ≈ 10^{10}–10^{11} cm^{-3}. The distance from the X-ray source to the absorbers would be of the order of thousands of gravitational radii, assuming that the clouds orbit the black hole with Keplerian velocities. The similarity of these physical parameters to those of the BLR clouds suggests that they are the same.

Observations of Mrk 766 (Risaliti et al. 2011, hereafter R11) and NGC 4395 (Nardini & Risaliti 2011) suggest that variations in the observed properties of the X-ray absorption are due to the motion of X-ray absorbers across the line of sight (LOS) between the observer and the X-ray source. R11 also argued that the absorbing clouds have denser neutral core, which absorbs the X-rays, and an extensive ‘comet tail’ of high-ionization gas.

The BLR global covering factor should be, on average, 40 per cent (Dunn et al. 2007; Gaskell, Klimek & Nazarova 2007; Gaskell et al. 2008). Because of the large vertical thickness of the torus, we usually view most type 1 AGNs within ~45° of the polar axis (Smith et al. 2004). Considering these specifics of the BLR geometry, we may view the central regions of most AGNs through the BLR. The
The purpose of this paper is to examine the observational consequences of such a geometry.

There have been a large number of studies of the emission properties of BLR clouds. The most sophisticated ones are the ‘locally optimally emitting cloud (LOC)’ models that allow the properties of clouds to change within the BLR (Baldwin et al. 1995). These models largely reproduce observed emission properties. This spectrum is not changed by the geometry proposed in the Risaliti et al. (2011) work. Rather, the novel aspect of this work is to consider the absorption produced by emitting clouds. Some clouds lie along the LOS to the central accretion disc and black hole, and produce certain characteristic absorption features on the accretion disc’s continuum. We show what effects clouds have on the optical and UV continuum, and identify a broad feature below $L_{\alpha}$ that appears to be present. This has implications for the true SED of the accretion disc.

2 PARAMETERS AND GEOMETRY OF CLOUDS

2.1 Parameters of clouds and continuum source

To know what effect the clouds will have on the observed spectrum, we need to compare the size scales of a cloud with the size of the continuum source. For instance, if the cloud is larger than the continuum source, which is likely to be true at X-ray energies, a single cloud can nearly fully block our view of the X-ray source. However, if the cloud is much smaller than the continuum source, as we show seems likely for the optical or UV, a single cloud may have little effect upon the spectrum and we would mainly observe the effects of an ensemble of clouds.

We assume that the parameters derived by R11 and mentioned in Section 1 are reasonable enough for a typical BLR cloud. Therefore, we assume a cloud density of $n(H) = 10^{10}$ cm$^{-3}$ and the cloud column density of $N(H) = 10^{23}$ cm$^{-2}$. The corresponding linear scale of the cloud is $10^{13}$ cm.

R11 used XMM–Newton observations of Mrk 766 to derive the size of the X-ray source. They did this by combining the transverse velocity of the clouds with their occultation times derived from observed variability. They estimated that the X-ray source has a size $r_{xr}$ between $20R_g$ and $100R_g$, based on the highest physically acceptable cloud velocity. They further argued that the source is likely to have a size closer to the lower end of the range. The range corresponds to between $r_{sr} \sim 10^{13}$ cm and a maximum of $r_{sr} \sim 10^{14}$ cm for Mrk 766.

This physical size of the X-ray source is close to the cloud length scale derived above (R11). As a result, a single cloud can easily block the X-ray source and strongly absorb the X-ray spectrum, allowing very little light to pass to the observer if the cloud column density is large enough. This is the essence of the R11 model.

In this paper, we ask what these intervening clouds will do to the UV/optical spectrum. The radiation field in this spectral region is predominantly emitted by the accretion disc surrounding the central black hole. For AGN Mrk 766, the parameters are black hole mass $M_6 = 10^6 M_\odot$ (Bentz et al. 2009) and a luminosity in the range $L = 10^{44.0} - 10^{44.4}$ erg s$^{-1}$ (Vasudevan et al. 2010, we assume $L = 10^{44.2}$ erg s$^{-1}$). These correspond to an accretion rate of $\dot{M} = 0.03 M_\odot$ yr$^{-1}$ (equation 3.7 in Peterson 1997). The corresponding Eddington ratio is 0.7.

We next estimate the size of the UV/optical continuum source with these parameters. There are different analytical forms of the temperature-radius relation for discs around black holes. Bregman...
(1990) gives an expression for the temperature of gas near the last stable orbit. This will be at far smaller radii than the parts of the disc which emit in the far-ultraviolet (FUV) and optical. Wang & Zhou (1999) give expressions for super-Eddington accretion. As shown above, the Eddington ratio is less than unity, although there are substantial uncertainties and the ratio may be larger than 1. For simplicity, we assume a sub-Eddington thin disc that satisfies the standard α-disc model (Shakura & Sunyaev 1973) and assume $\alpha = 0.1$. For parts of the disc dominated by gas pressure and free–free absorption, the relation between disc temperature and radius $\alpha = \frac{L_v}{T}$ (defined in Section 2.1) and the lower graph shows the temperature as a function of radius $r$. Parameters of Mrk 766 are used in this figure.

For simplicity, we can assume that the source of light at that frequency is a peak at some radius and then vanishes rapidly. For simplicity and is plotted in Fig. 2. This shows that light at a frequency whose centre is the black hole and whose radius is radius, $\nu$ is frequency, $\Delta r$ is unit length and $B_v(T) = (2\nu^3/h\nu)(\exp(h\nu/kT) - 1)^{-1}$ is the Planck law. The differential luminosity is then

$$L_v(r) = 2\pi r \Delta r B_v(T).$$

If $T_0$ is the temperature at some radius $r_0$, then the ratio $\eta_v(r) = \frac{L_v(r)}{L_v(r_0)} = \frac{(r/r_0)(B_v(T)/B_v(T_0))}$ is the relative differential luminosity and is plotted in Fig. 2. This shows that light at a frequency rises to a peak at some radius then vanishes rapidly. For simplicity, we can assume that the source of light at that frequency is the accretion disc at the radius of maximum emission. With this assumption, the linear scale of the UV/optical continuum source is $10^{13} - 10^{15}$ cm, several to hundreds of times larger than clouds’ scale. This has important consequences for what we observe at UV/optical wavelengths.

### 2.2 Global and LOS covering factors

The global covering factor is the fraction of sky as seen from the central engine that clouds cover. This can, for instance, be obtained from the equivalent width of the lines (Korista, Baldwin & Ferland 1997a). A typical global covering factor is 40 per cent (Dunn et al. 2007; Gaskell et al. 2007, 2008).

However, when we observe a galaxy, the absorption effects of clouds upon the spectrum of the central engine are determined by the LOS covering factor, the fraction of the continuum source obscured by clouds. If the geometry is spherically symmetric, then the global and LOS covering factors will be the same. However, the geometry of an AGN is thought to have cylindrical symmetry, so a particular LOS may or may not intersect clouds. The LOS covering factor may be larger or smaller than the global covering factor, depending on where clouds lie with respect to our LOS. The R11 results do suggest that clouds occur on the LOS for the objects they studied. In the remainder of this paper, we will only consider the LOS covering factor.

### 2.3 Geometry of clouds

Here we will show the spectroscopic differences between two models: the classical standard model that assumes that no clouds lie on the LOS and the R11 model in which some clouds lie along the LOS. We will refer to the second as the intervening BLR cloud model (IBC model) in the remainder of this paper. Differences in the predicted spectra could be used to determine the LOS covering factor.

The standard model (Fig. 3) presents the geometry most often assumed in the literature. We receive light directly from the central continuum source and have an unobstructed view of it. The clouds, which are energized by the central engine, do not lie along the sight line between observer and the central engine. This model was motivated by the fact that the column density in a typical BLR cloud is large enough for it to be quite optically thick in the H$^\alpha$ Lyman continuum. The standard model was originally suggested by the fact that we do not observe the strong Lyman limit absorption that would be produced by clouds between the observer and the central engine. We show below that realistic BLR clouds do not produce a feature at the Lyman limit due to the presence of other opacity sources.

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**Figure 2.** The upper graph shows the differential luminosity ratio $\eta_v(r)$ (defined in Section 2.1) and the lower graph shows the temperature $T$ as a function of radius $r$ for the standard α-disc model described in the text. Parameters of Mrk 766 are used in this figure.

**Figure 3.** Structure of the standard model. Clouds are not in the LOS between the observer and light source.
The IBC model is shown in Fig. 4. As in the standard model, the clouds reprocess the radiation field emitted by the central engine, but some occur along our sight line to central regions. The cloud emission properties are unchanged, but intervening clouds can absorb parts of the continuum produced by the central regions. Intervening clouds can change the observed spectrum, especially the SED of the central engine.

Below we quantify differences in the observed properties of these two models as a way to test what actually occurs.

3 PHOTOIONIZATION CALCULATIONS

3.1 Calculations

It is not the goal of this paper to create full models of the BLR such as the LOC picture of Baldwin et al. (1995). Rather, we shall use typical values for cloud parameters as given, for instance, by Peterson (1997) or Korista et al. (1997a). Since the R11 geometry will not alter the emission-line spectrum, we concentrate on the absorption produced by the clouds. We assume that the clouds have a hydrogen number density of \( n(H) = 10^{19} \text{cm}^{-3} \). R11 infer two components to a cloud, a core and a halo, from their X-ray analysis. Accordingly, we consider clouds with column densities ranging between \( N(H) = 10^{15} \) and \( 10^{23} \text{cm}^{-2} \). Similarly, we consider a range in distance between the central black hole and the cloud between \( r = 10^{13} \) and \( 10^{17} \text{cm} \). The effect of varying both density and radius is to cover parts of the LOC plane described in Korista et al. (1997b). We vary the column density because we are mainly interested in determining the UV/optical absorption properties. Korista et al. (1997b) consider the effects of various column densities in detail. As we show below, the range of \( N(H) \) does change the observed absorption, while previous work has shown that it has only a weak effect on the emission spectrum (Korista et al. 1997b).

We simulate the spectrum with version 10.0 of the plasma code CLOUDY, last described by Ferland et al. (1998). The properties of such photoionization models are described by Osterbrock & Ferland (2006) and Ferland (1999, 2003). These properties are not changed by the assumptions introduced in this paper. We adopt the observed luminosity of Mrk 766 of \( 10^{44.2} \text{erg s}^{-1} \) given above and use the Mathews & Ferland (1987) SED. Solar abundances are assumed. We will show and discuss the results in following sections.

The predicted X-ray spectra are shown on the right-hand side of Figs 5, 6 and 7. These correspond to clouds at distances from the black hole of \( 10^{15}, 10^{16} \) and \( 10^{17} \text{cm} \), respectively. The X-ray spectrum is nearly unchanged by clouds at the smaller radius, except for a few absorption lines produced at high column densities. As the radius increases, the ionization of the gas goes down and X-ray absorption increases. These figures also show the well-known effect that lower energy photons, with longer wavelengths, are more easily absorbed due to the larger gas opacity.

The UV/optical spectra are shown on the left-hand side of the figures. Clouds close to the continuum source have little effect due to their high ionization and low opacity. Emission and absorption lines begin to appear as the radius increases and the ionization decreases. These features also become stronger when the cloud column density is increased. The UV/optical absorption spectra, the new result of this paper, are described next.

These results suggest that IBC could affect the X-ray and UV/optical spectra of AGNs in different ways. We next discuss a single cloud’s effect on the spectrum; then consider the BLR cloud as the X-ray absorber and finally give the UV/optical spectra of an ensemble of clouds that lie along our sight line. We assume that all clouds have the canonical BLR parameters for simplicity (Korista et al. 1997b). We use this representative cloud’s spectrum and combine this with the covering factor to evaluate the net spectrum.

3.2 A single cloud’s effect on the spectrum

Clouds will have very different effects on the X-ray and UV/optical spectra because of the significant differences between the linear scales of the clouds, the X-ray source and the UV/optical source. The X-ray source is smaller than \( \sim 10^{13} \text{cm} \) (R11), so that a single cloud can obscure a considerable part of the X-ray source, as R11 point out. A single high column density, low-ionization cloud will produce strong absorption, leading to remarkable X-ray time variability when it crosses our sight line.

The simple \( \alpha \)-disc computed above (Fig. 2) suggests that the UV/optical source has a linear scale of \( \sim 10^{13}–10^{16} \text{cm} \), which is several to hundreds times larger than the cloud. Because of this size difference, a single cloud passing in front of the accretion disc will have no observable effect since it would only cover 10 to 0.0001 per cent of the disc’s visible surface. However, as Arav et al. (1997, 1998) point out, there is likely to be an ensemble consisting of a large number of clouds. Although individual clouds may come and go along our sight line, it is most likely that there is no net change in the total ensemble of clouds along this sight line. The ensemble of clouds will not produce time variations in the UV/optical band. However, if the ensemble has a global covering factor of \( \sim 40 \) per cent (Dunn et al. 2007; Gaskell et al. 2007, 2008) and if LOS covering factor is similar to this value, the clouds will change the observed SED. We show their effect upon the observed spectrum below.

3.3 The BLR cloud as the X-ray absorber

Which BLR clouds are responsible for the X-ray absorption? The absorption depends strongly on the state of ionization. If the cloud is highly ionized, there is very little X-ray absorption, as shown in Figs 5 and 6. These clouds are near the black hole and have higher ionization than the more distant clouds as shown in Fig. 7. The high-ionization clouds have little spectroscopic effect except for Compton scattering of a small fraction of the incident radiation field. But the more distant low-ionization clouds strongly absorb at X-ray wavelengths. We also show this in Fig. 8 by comparing the transmitted spectrum, the light we observe looking through a cloud, with its original intensity. Here we use the X-ray deduced covering factor of 40 per cent (R11 estimate that this is between 20 and 80 per cent). The graph shows that X-ray absorption becomes

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Figure 5. Simulated X-ray (right-hand side) and UV/optical (left-hand side) spectra for clouds at \( r = 10^{15} \) cm away from the continuum source and the column densities of clouds are \( 10^{21}, 10^{22} \) and \( 10^{23} \) cm\(^{-2} \), respectively. The black line is the incident spectrum and would be observed if it is not covered by clouds. The red line indicates the spectrum absorbed by clouds but with no emission. The blue line is the transmitted plus emitted spectrum.

obvious for clouds with column densities of \( \sim 10^{22} - 10^{23} \) cm\(^{-2} \) and for clouds that are farther from the black hole. This means that lower ionization clouds have stronger X-ray absorption and will be more distant since these have larger opacity. This provides an explanation for the R11 conclusion that the obscuring clouds have neutral cores with column densities of a few \( 10^{23} \) cm\(^{-2} \) and are surrounded by highly ionized haloes.

3.4 The UV/optical spectra of clouds along our LOS

Next consider the effects of the same clouds on the UV/optical spectrum. These clouds generate strong emission lines in this band, which is a defining feature of BLR clouds. But IBC will also produce absorption, as described here. We focus on the spectral region between 800 and 3000 Å, where intervening clouds have the most obvious effects.

We first consider the simplest case where clouds fully cover the continuum source. We consider a typical BLR cloud with \( n(H) = 10^{10} \) cm\(^{-3} \) and \( N(H) = 10^{23} \) cm\(^{-2} \) (Korista et al. 1997b) as representative. The resulting spectrum is shown in Fig. 9(b). The incident spectrum, light directly received from the continuum source, is shown as the red line, and the transmitted spectrum, which is the light that passes through the clouds, is the black line. Many absorption features are visible. The lower panel in Fig. 9 shows the continuous optical depths integrated across the cloud. This illustrates the atomic processes that produce the features shown in Fig. 9(b). In Fig. 9(c), the total optical depth is shown in red. The scattering optical depth, dominated by Ly\( \alpha \) scattering, which removes photons in the neighbourhood of the line. There are three continuous absorption features shown in black. These are due to the photoionization of the ground state \( H^0 \) (912 Å), O I
Figure 6. Simulated spectra of X-ray and UV/optical with clouds at $r = 10^{16}$ cm away from the continuum source. Others are the same as in Fig. 5.

($\sim 1060\,\text{Å};$ this is the first excited $^1D$ term of O I; Ralchenko et al. 2011), and a weak feature due to the ground-state photoionization of C0.

The net effect of these opacity sources is to remove nearly all light shortwards of 1060 Å, and much of the light around Ly$\alpha$, as shown in the lower curve in Fig. 9(b). Thus, LOS clouds do not produce an additional strong absorption feature at the Lyman limit. This is because nearly all light shortwards of Ly$\alpha$ has already been removed by O I absorption. The lack of an absorption feature at the Lyman limit was the reason that clouds were thought not to lie along the LOS.

To quantify this, in the top panel of Fig. 9, we show the net observed spectrum for a representative covering factor of 40 per cent. The red line in Fig. 9(a) presents the standard model, with no intervening clouds, while the intervening cloud model is the black line. Intervening clouds produce strong extinction between the Lyman limit and Ly$\alpha$. These features distinguish between cases with and without clouds along the sight line. These features begin to be obvious when the hydrogen column density reaches $\sim 10^{23}$ cm$^{-2}$, as shown in Fig. 7. Due to the obvious difference of the two models, we believe that this strong absorption can be used to determine whether there are clouds partially blocking the LOS.

These figures show the spectra of a static ensemble of clouds and so have sharp absorption features. In reality, the clouds will also have a distribution of velocities, and the absorption features will reflect this distribution. We show simulated spectra with this velocity dispersion next.

Osterbrock & Pogge (1985) find that the H$\beta$ full width at half-maximum (FWHM) is 2400 km s$^{-1}$ for Mrk 766. We adopt this in our spectral simulations (Fig. 10). The red line is the standard model, while the black line is the intervening cloud model with 40 per cent covering factor. The blue line is the Hubble Space Telescope (HST) STIS spectrum retrieved from their website (observation ads/Sa.HST#O5L502030). A redshift of $z = 1.026$ (Rines et al. 2003) was assumed. The HST data were smoothed by averaging over 5 Å intervals and negative fluxes were not plotted.
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Figure 7. Simulated spectra of X-ray and optical with clouds at $r = 10^{17}$ cm away from the continuum source. Others are the same as in Fig. 5.

The comparison in Fig. 10 suggests that intervening clouds do exist in Mrk 766, as R11 found for the X-ray absorber. The HST data have a slope similar to the IBC model. This also suggests that the intrinsic SED of Mrk 766 is more like the red line in Fig. 10 and appears softer due to the intervening clouds.

Intervening clouds may exist in other AGNs, where the line widths are broader than Mrk 766. We plot spectra with an FWHM of 10,000 km s$^{-1}$, which is the typical velocity dispersion of BLR clouds (Peterson 1997), in Fig. 11. The red, black and blue lines represent the standard model spectrum with no intervening clouds, and spectra with intervening clouds having covering factors of 20 and 40 per cent, respectively. We plot this range of covering factors because it may change from object to object.

The observational consequences of a range of covering factors can be judged from Fig. 11. The different LOS covering factors do not change the emission features, which depend on the global covering factor. The standard model is the same as the IBC model with a 0 per cent covering factor and has the harder SED. The effect of changing the covering factor is to change the SED of the FUV continuum. A non-zero covering factor depresses the spectrum around and below 1200 Å, with the effect increasing with increasing covering factor.

The feature we predict may also have been seen in surveys. The composite spectrum obtained from the Large Bright Quasar Survey (Francis et al. 1991) may suggest that LOS clouds are universal in AGNs. In fig. 2 of that paper, it is clear that the SED is depressed below Lyα, which is very similar to our results for a large LOS covering factor. However, this composite spectrum is strongly affected by the Lyα forest, which is uncorrectable, at wavelengths below Lyα.

Observations of low-z AGNs (Zheng et al. 2001; Shang et al. 2005) should have far less forest absorption. These show a change in the slope of the SED around the region we predict. Shang et al. (2005) point out that most objects exhibit a spectral break around 1100 Å and that this break is intrinsic to an AGN. We suggest that
this break is actually the depression feature predicted by the IBC model. This is qualitatively what we predict: there is a depression feature, in other words, a ‘break’ in the spectrum. Since this break is shown in most AGNs, we suggest that intervening clouds are a common feature in most AGNs. A range of covering factors may explain why the ‘break’ seen by Shang et al. (2005) changes from object to object.

4 CONCLUSIONS

We have simulated the UV/optical and X-ray spectrum produced by an ensemble of BLR clouds that lie along the LOS to the central engine. We assume the geometry proposed by R11 to explain the observed X-ray variability. Our goal is to quantify what we would see in the optical/UV when BLR clouds lie along the LOS to the central continuum source. Our findings are as follows.

(1) The UV/optical continuum source has a size much larger than a single cloud. This distinguished the UV/optical spectral region from the X-ray, where a single cloud can cover a large fraction of the emission source. One single cloud crossing the LOS will have almost no observed effect on the UV/optical spectrum since it covers a tiny fraction of the visible accretion disc.

(2) It is far more likely that an ensemble of clouds will be present along the sight line, if the emission-line regions have the deduced global covering factor. In this case, there will not be time variability, since we see the ensemble of clouds, but the clouds will produce a net absorption in the optical/UV continuum. The clouds also produce strong emission lines, of course.

(3) We predict that a strong broad extinction feature will be present between Ly$\alpha$ and the Lyman limit. This is produced by a combination of Ly$\alpha$ scattering and O I absorption in the clouds.

(4) There is no spectral break at the Lyman limit because the clouds have continuous optical depths greater than unity for much of the region below Ly$\alpha$. Instead, the FUV spectrum is depressed by a factor related to the LOS covering factor of the ensemble of clouds.

(5) The comparison of HST data and the IBC model spectra for Mrk 766 suggests that intervening clouds do occur and change the SED.

(6) The predicted FUV absorption feature may be present in observations of broad-line AGNs. This suggests that LOS BLR clouds may be present for most AGNs.
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Figure 10. Simulated and observed spectra for Mrk 766. The FWHM of simulated spectra is 2400 km s$^{-1}$.

Figure 11. Simulated spectra for broad-line AGNs. The FWHM is 10 000 km s$^{-1}$. The different curves represent covering factors of, from top to bottom, 0, 20 and 40 per cent.

ACKNOWLEDGMENTS

YW thanks IHEP AGN Group for the hospitality of Beijing International AGN summer school and C. Gaskell for his help. We acknowledge support by NSF (0908877, 1108928 and 1109061), NASA (07-ATFP07-0124, 10-ATP10-0053 and 10-ADAP10-0073), JPL (RSA No 1430426) and STScI (HST-AR-12125.01 and HST-GO-12309).

We thank the anonymous referees for their help in improving the paper.

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