DOES EVERY QUASAR HARBOR A BLAZAR?

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ABSTRACT

Assuming there is a blazar-type continuum in every radio-loud quasar, we find that the free-free heating due to the beamed infrared continuum can greatly enhance collisionally excited lines and thus explain the stronger $\text{C IV}$ $\lambda 1549$ line emission observed in radio-loud quasars. We further predict that the $\text{C IV}$ line should show variability not associated with observed continuum or Ly$\alpha$ variability.

Subject headings: galaxies: nuclei — quasars: emission lines — quasars: general

1. INTRODUCTION

The dichotomy between radio-loud and radio-quiet QSOs remains one of the greatest puzzles in studies of active galactic nuclei (AGNs). While their optical-UV spectra appear similar, quasars (we use the term “quasar” for radio-loud QSO) have $\text{C IV}$ $\lambda 1549$ line emission $\sim 50\%$ stronger compared with radio-quiet QSOs (Francis, Hooper, & Impey 1993). Marziani et al. (1996) find that the luminosities of $\text{C IV}$ and $\text{H}\beta$ are strongly correlated in radio-quiet QSOs but only weakly correlated in quasars. Some observed line profile differences could also be the result of an additional beamed optical-UV synchrotron continuum in quasars, but not in radio-quiet QSOs (Wills et al. 1993; Francis et al. 1993).

Unified schemes for quasars hold that there is a strong, beamed synchrotron continuum in every quasar (Urry & Padovani 1995). If the beam is toward the observer, the quasar is seen as a blazar. Blazars are known to be highly variable on timescales from days to years. For example, the BL Lacertae brightened by 3 mag in the $R$ band during the outburst in the summer of 1997 (Bloom et al. 1997). The outburst lasted for a few months, and during the outburst it showed intraday and even intrahour variation of $\sim 1$ mag.

Bregman et al. (1986) found that the Ly$\alpha$ line flux varied in proportion to the continuum flux density in the blazar 3C 446. Stephens & Miller (1984) found that the $\text{C IV}$ $\lambda 1909$ line flux varied with the continuum in 3C 446 and suggested that the beamed continuum might affect the emission-line spectra. Koratkar et al. (1998) found no variation in the flux of the Ly$\alpha$ emission line in the $Hubble Space Telescope$ spectra of the blazar 3C 279, while the continuum varied by a factor of 50. Cohen et al. (1997) found possible Mg ii line variability in the blazar AO 0235$+$164. Corbett et al. (1996) found the H$\alpha$ line in the BL Lac object to be variable, but not as a result of the beamed continuum. The emission-line variability in blazars is not easy to measure because of the large contribution from the variable continuum. Most previous studies of AGN spectral variability have focused on objects known to have large continuum variability and have concentrated on the emission-line variations following the observed continuum variations (see, e.g., Maoz et al. 1994).

In this Letter, we investigate the interactions between the beamed synchrotron radiation and the broad emission line region (BELR). Although the beam may illuminate only a small portion of the BELR, it can provide a large flux of infrared photons that heat the gas by the free-free mechanism (Ferland et al. 1992), greatly enhancing the $\text{C IV}$ $\lambda 1549$ line emission. This enhanced emission can contribute significantly to the line flux from the entire BELR, explaining the stronger line emission seen in quasars. The $\text{C IV}$ line emission is thus expected to vary in response to the rapid and large-amplitude variations of the blazar continuum, although we may not see the continuum variation if it is beamed away from us.

2. ADDITIONAL BEAMED CONTINUUM IN QUASARS

Theoretically, a simple blazar synchrotron continuum is beamed with a half-opening angle $\theta = \sin^{-1} (1/\gamma)$ for a Lorentz factor $\gamma$. The fraction of the sky area illuminated by the beam is $1/2\gamma^2$, or $\sim 2\%$ for $\gamma = 5$ and $\sim 5\%$ for $\gamma = 3$. The real beaming angle could be larger (Lind & Blandford 1985) and can be estimated from the observed fraction of blazars among quasars as a whole (see, e.g., Urry & Padovani 1995).

If the beamed synchrotron continuum originates closer to the central black hole than the BELR ($\sim 0.1$ pc in luminous quasars; see, e.g., Netzer 1990), then it may affect the emission-line spectrum. In NGC 1275, the VLBI jet probably originates within 0.1 pc at 43 GHz (Krichbaum et al. 1992). The higher frequency synchrotron radiation of interest ($\sim 10^{13}$ Hz) is likely to originate closer to the black hole. Some theoretical models predict that infrared synchrotron emission originates $\sim 0.1$ pc from the black hole and that lower frequency emission originates farther away from the center (see, e.g., Marscher 1996).

The beamed synchrotron continuum provides a high flux of IR photons because of its steep spectrum, which extends to millimeter wavelengths. In contrast, the normal QSO continuum provides only weak IR flux, with much of the observed IR emission almost certainly arising from dust beyond the BELR (Barvainis, Antonucci, & Coleman 1992). Moreover, if the observed IR continuum in radio-quiet QSOs were within BELR distances, it would significantly overpredict the observed $\text{C IV}$ strength.

3. MODELS

Ferland et al. (1992) show that a high flux of IR photons incident on BELR clouds could enhance the flux of the $\text{C IV}$ and O $\text{iv}$ emission lines by free-free heating of the BELR. As discussed above, a strong IR central continuum is unlikely in radio-quiet QSOs. However, for BELR gas exposed to the beamed synchrotron radiation, free-free heating is the most important heating process.

The heating rate is proportional to (see, e.g., Netzer 1990)

$$F_{\nu} \exp(-\nu/\nu_0) \nu^{-1/2} \nu_0 N_{\gamma}\exp(-1 - e^{-3\hbar \nu/\kappa T_{	ext{cm}}}).$$  (1)
Collisional results in an important emission-line cooling process in optically thick BELR gas, and the rate is proportional to

$$N_c \Omega_c e^{-E_b/2kT_e} T_e^{-1/2},$$

(2)

where $\Omega_c$ is the collision strength. For $C IV$ $\lambda 1549$, $E_b \sim 8$ eV, and the cooling rate increases with temperature. At $\sim 16$ eV, this line intensity stops increasing with $T_e$ because the collision cross sections become smaller for higher velocity electrons. Roughly speaking, the IR heating leads to a higher electron temperature, which results in stronger $C IV$ lines.

In Figure 1, we plot for model A the abundance ratio $n_C/n_H = 10^{-3}$ to $10^5$ cm$^{-3}$ and the fixed ionization parameter $U = 10^{-0.5}$. Because we are using $L_{agn} = 10^{46}$ ergs s$^{-1}$ for the input continuum, $U = 10^{-0.5}$ constrains the cloud distance to $r = 10^{17.67}$ cm. The column density for the cloud is set to be $10^{37.5}$ cm$^{-2}$.

In the more realistic model B, we follow the model of Goad, O'Brien, & Gondhalekar (1993), in which discrete clouds are distributed from $10^{17}$ to $10^{25}$ cm$^{-3}$ from the continuum source. The density starts from $10^{17}$ cm$^{-3}$ and has a power-law distribution $n \propto r^{-2}$. The column density is set to be $N(r) \propto r^{-4/3}$, starting from $10^{25}$ cm$^{-2}$ at the inner radius. The differential covering factor varies as proportional to $r^{-1/6}$, to fulfill the mass conservation of the clouds. The calculated emission-line luminosities are integrated from inner to outer radius.

| TABLE 1 | Model A | Observed |
|---------|---------|---------|
| Line (1) | $L_{beam}$ (2) | 10$^{46}$ | 10$^{46.5}$ | 10$^{47}$ | Ratio (6) |
| Ly$\alpha$ 1216 | 25.3 | 25.3 | 25.3 | 25.5 | 8–15 |
| C IV $\lambda 1549$ | 11.4 | 11.9 | 13.1 | 16.0 | 5–8 |
| C IV $\lambda 1909$ | 6.0 | 6.1 | 6.5 | 7.5 | 2–4 |
| C IV $\lambda 977$ | 0.9 | 0.9 | 1.2 | 2.6 | <1 |
| H$\beta$ 4861 | 43.59 | 43.60 | 43.61 | 43.61 | 1 |
| H$\alpha$ 6563 | 2.3 | 2.3 | 2.3 | 2.3 | 4–6 |
| He I $\lambda 5876$ | 0.2 | 0.2 | 0.2 | 0.2 | 0.1–0.2 |
| He II $\lambda 1640$ | 1.1 | 1.1 | 1.1 | 1.1 | 0.6 |
| Mg II $\lambda 2798$ | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Si IV, O IV $\lambda 1400$ | 1.6 | 1.7 | 1.9 | 2.7 | 1.3 |
| O III $\lambda 1665$ | 3.4 | 3.5 | 3.8 | 5.0 | 0.5 |
| N III $\lambda 1750$ | 0.9 | 0.9 | 1.0 | 1.4 | 0.4 |
| O IV $\lambda 1035$ | 3.0 | 3.2 | 3.5 | 4.2 | 3.0 |
| N V $\lambda 1240$ | 1.0 | 1.1 | 1.1 | 1.3 | 3.0 |

| TABLE 2 | Model B | Observed |
|---------|---------|---------|
| Line (1) | $L_{beam}$ (2) | 10$^{46}$ | 10$^{46.5}$ | 10$^{47}$ | Ratio (6) |
| Ly$\alpha$ 1216 | 37.4 | 37.4 | 37.4 | 37.6 | 8–15 |
| C IV $\lambda 1549$ | 5.9 | 6.4 | 7.4 | 10.1 | 5–8 |
| C IV $\lambda 1909$ | 2.4 | 2.4 | 2.4 | 2.5 | 2–4 |
| C IV $\lambda 977$ | 1.1 | 1.4 | 2.2 | 5.1 | <1 |
| H$\beta$ 4861 | 43.99 | 44.00 | 44.00 | 44.01 | 1 |
| H$\alpha$ 6563 | 4.7 | 4.7 | 4.7 | 4.6 | 4–6 |
| He I $\lambda 5876$ | 0.7 | 0.7 | 0.7 | 0.7 | 0.1–0.2 |
| He II $\lambda 1640$ | 2.4 | 2.4 | 2.4 | 2.4 | 0.6 |
| N V $\lambda 1406$ | 0.3 | 0.3 | 0.3 | 0.3 | 0.1 |
| Mg II $\lambda 2798$ | 9.7 | 9.8 | 9.9 | 10.2 | 3 |
| Si IV, O IV $\lambda 1400$ | 1.4 | 1.6 | 1.9 | 2.9 | 1.3 |
| O III $\lambda 1665$ | 1.1 | 1.2 | 1.2 | 1.5 | 0.5 |
| N III $\lambda 1750$ | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 |
| O IV $\lambda 1035$ | 10$^{-3}$ | 0.002 | 0.003 | 0.001 | 3 |
| N V $\lambda 1240$ | 0.02 | 0.03 | 0.05 | 0.1 | 3 |

4. RESULTS

In Tables 1 and 2, we list the calculated emission-line luminosities for models A and B. For the H$\beta$ line, we give the logarithm of luminosity in units of ergs s$^{-1}$, and the other line luminosities are given as the ratio to H$\beta$.

Column (2) is the result for $L_{agn} = 10^{46}$ ergs s$^{-1}$ with no $L_{beam}$ in column (3) is for $L_{agn} = 10^{46}$ ergs s$^{-1}$ mixed with $L_{beam} = 10^{46}$ ergs s$^{-1}$, and $L_{beam}$ affects only 2% of the sky area. A small covering factor (~0.1) for the clouds is assumed everywhere in the sky, including in the beam. Columns (4) and (5) correspond to $L_{beam} = 10^{46.5}$ and $10^{47}$ ergs s$^{-1}$, respectively. The observed line ratios in column (6) are taken from Netzer (1990).

From Tables 1 and 2, it can be seen that among strong lines, C IV $\lambda 1549$ is enhanced by $\sim 50\%$ when $L_{beam} = 10^{47}$ ergs s$^{-1}$, while hydrogen lines show little change. The line C IV $\lambda 977$ is also strongly dependent on the IR heating. These two lines actually set up an upper limit of $L_{beam} \approx 10^{47}$ ergs s$^{-1}$, otherwise they would be too strong. However, we note that C IV $\lambda 977$ is difficult to observe because of intervening absorption, especially at higher redshifts. Model A predicts a slight enhancement of lines O IV $\lambda 1035$ and N V $\lambda 1240$. We do not consider their enhancement in model B, because the strengths of these two lines are not well predicted.

In Figure 1, we plot for model A the abundance ratio C$^{++}$/C and the electron temperature versus the depth into the cloud. As expected, the C$^{++}$ density is not strongly affected by the beamed continuum, and C IV $\lambda 1549$ is an effective coolant.

In Figure 2, we give the cloud surface temperature and various line luminosities versus the radius in model B. The free-free heating is more important at small radii, since it is proportional to the photon flux as shown in equation (1), while photoelectric heating by ionizing photons is determined by the number density and the recombination coefficient and does not depend explicitly on photon flux (Ferland et al. 1992).

Some line profiles with and without a beamed continuum are compared in Figure 3. We show the profiles here primarily for the purpose of showing the enhancement of integrated emission-line flux due to the beamed continuum, although affecting only a small portion of the BELR clouds. The BELR cloud distribution and velocity field are probably anisotropic, with velocities having a strong disk component in addition to
Fig. 1.—Temperature and C\textsuperscript{+}/C profiles inside the cloud in model A. The solid lines correspond to the case with $L_{\text{syn}} = 10^{46}$ ergs s\textsuperscript{-1}, and the dashed lines correspond to the case with $L_{\text{syn}} = 10^{46}$ ergs s\textsuperscript{-1} mixed with $L_{\text{beam}} = 10^{47}$ ergs s\textsuperscript{-1}.

Fig. 2.—Surface temperature of clouds and emission-line luminosity vs. radius in model B. The solid lines correspond to the case with $L_{\text{syn}} = 10^{46}$ ergs s\textsuperscript{-1}, and the dashed lines correspond to the case with $L_{\text{syn}} = 10^{46}$ ergs s\textsuperscript{-1} mixed with $L_{\text{beam}} = 10^{46}$, $10^{47}$, and $10^{48}$ ergs s\textsuperscript{-1}, respectively. $L_{\text{beam}}$ and $L_{\text{syn}}$ both illuminate 4\pi sr.

5. DISCUSSION

The IR-optical continuum of the synchrotron radiation is steep, and hence the fraction of hydrogen-ionizing photons it can offer is small compared with the normal AGN continuum. In addition, the beam illuminates only a small fraction of the BELR clouds, while the emission lines we see are integrated over all the clouds. Consequently, the effect on the H\textalpha and Ly\alpha lines is negligible. For collisionally excited lines such as C\textsc{iv} \( \lambda 1549 \), the line emissivity can be enhanced by over 2 orders of magnitude in the beam, and the line intensity integrated over the whole BELR consequently increases by a factor of \( \sim 50\% \).

If there is a beamed blazar-type continuum in every radio-loud quasar, we should be able to see C\textsc{iv} line variability not associated with observed continuum variability or Ly\alpha variability. This phenomenon could well have escaped detection in previous observations because high-redshift quasars have not been monitored extensively. Also, this phenomenon may be seen only when the blazar continuum is in the outburst stage. We are planning observations to search for C\textsc{iv} \( \lambda 1549 \) line variability among \( z \sim 2.5 \) quasars, which are thought to be less variable compared with low-luminosity AGNs. If the C\textsc{iv} line variability at the level of \( \sim 50\% \) is observed, while the lines for comparison (Ly\alpha, C\textsc{iii} \( \lambda 1909 \), or Mg\textsc{ii} \( \lambda 2798 \)) do not change significantly, it will be strong support for our models and for quasar unified schemes. In addition, the disk-wind model (see, a random component (see, e.g., Wills & Browne 1986). For simplicity, here we consider only spherically distributed clouds with a Keplerian velocity field, and the velocity direction is assumed to be random. The maximum cloud velocity is $10^4$ km s\textsuperscript{-1} at $r = 10^{17}$ cm. The flat tops of the profiles come from the lowest gas velocity, $10^3$ km s\textsuperscript{-1} at $r = 10^{19}$ cm.
e.g., Emmering, Blandford, & Shlosman 1992) for the BELR will be ruled out, since it does not include any gas in the polar regions.

We also expect quasars to have statistically stronger C iv λ1549 line emission. The strength of line C iv λ1549 depends strongly on the blazar continuum and should not be well correlated with the Hβ line strength as shown by Marziani et al. (1996). The intensity variation may be seen in the line core or line wings and thus offers information about the gas kinematics in the polar regions (e.g., whether the gas clouds have lower velocity or whether they have large radial velocities driven by the jet).

In reality, the line emission depends on the details of the BELR geometry. If the line is strongly beam ed backward (see, e.g., Ferland et al. 1992), we may not be able to see the enhanced C iv emission when the angle between the line of sight and the beam is large. However, the excited lines are at least more isotropic than the beam ed continuum, and we do expect to see the line variability without seeing the beam.

If the phenomenon suggested by us is not detected, this will still give strong constraints on models. Three possibilities are left. First, the IR synchrotron radiation originates outside the BELR. Second, the observed blazar continuum variability may be caused by a change of the jet direction rather than a change in strength of the beam (see, e.g., Abraham & Carrara 1998). Third, there is no broad-line ± emitting gas in the polar regions. The last possibility would favor the disk-wind model and may rule out the bloated star model (see, e.g., Alexander & Netzer 1994).

Finally, we note that if the BELR is made of small clouds confined by a hot medium (Krolik, McKee, & Tarter 1981), then the jet might destroy the clouds. However, if the BELR is made of bloated stars, the jet may enhance the mass-loss rate of the stars and increase the amount of broad-line ± emitting gas in the beam.

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