Black hole masses and Doppler factors of 
\(\gamma\)-ray active galactic nuclei

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ABSTRACT

The sizes of the broad-line regions (BLRs) in \(\gamma\)-ray active galactic nuclei (AGNs) are estimated from their optical continuum luminosity by using the empirical relation between \(R_{\text{BLR}}\) and \(L_{\lambda,\text{opt}}\). Using the broad emission line data, we derive the photon energy density in the relativistic blobs near the massive black holes in AGNs. We calculate the power of the broad-line photons Compton up-scattered by the relativistic electrons in the blobs. Compared with observed \(\gamma\)-ray emission data, the Doppler factors \(\delta\) of the blobs for a sample of 36 \(\gamma\)-ray AGNs are derived, which are in the range of \(\sim 3 - 17\). We estimate the central black hole masses of these \(\gamma\)-ray AGNs from the sizes of the BLR and the broad line widths. It is found that the black hole masses are in the range of \(\sim 10^8 - 10^{10} M_\odot\). A significant correlation is found between the Doppler factor \(\delta\) and the core dominance parameter \(R\). The results are consistent with the external radiation Compton (ERC) models for \(\gamma\)-ray emission from AGNs. The soft seed photons are probably from the broad-line regions.

Subject headings: galaxies: active — gamma rays: theory — radiation mechanisms: nonthermal — black hole physics

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1. Introduction

All $\gamma$-ray AGNs are identified as flat-spectrum radio sources. The third catalog of high-energy $\gamma$-ray sources detected by the Energetic Gamma Ray Experiment Telescope (EGRET) on the Compton Gamma Ray Observatory (CGRO) includes 66 high-confidence identifications of blazars and 27 lower confidence potential blazar identifications (Hartman et al. 1999). This offers a good sample for the explorations on the radiative mechanisms of $\gamma$-rays from AGNs. The violent variations in very short time-scales imply that the $\gamma$-ray emission is closely related with the relativistic jets in blazars. There are two kinds of models, namely, leptonic models and hadronic models, proposed for $\gamma$-ray emission in blazars (see Mukherjee 2001 for a review). According to the different origins of the soft photons, the leptonic models can be classified as two groups: synchrotron self-Compton (SSC) models and ERC models (see Sikora & Madejski 2001 for a review).

In the frame of SSC models, the synchrotron photons are both produced and Compton up-scattered by the same population of relativistic electrons in the jets of $\gamma$-ray blazars. The synchrotron radiation is responsible for the low energy component in radio bands, and the synchrotron photons are Compton up-scattered to $\gamma$-ray photons by the same population of relativistic electrons in the jets (Maraschi, Ghisellini & Celotti 1992). However, SSC models meet difficulties with the observed rapidly variable fluxes in MeV-GeV for some blazars. It has been realized that the processes other than SSC may occur at least in some $\gamma$-ray blazars. One possibility is soft seed photons being from the external radiation fields outside the jets, namely, ERC models. The origins of soft seed photons may include the cosmic microwave background radiation, the radiation of the accretion disk (including photons from the disk scattered by surrounding gas and dust), infrared emission from the dust or/and a putative molecular torus, and broad-line regions, etc (Dermer & Schlickeiser 2002). Recently, Sikora et al. (2002) proposed that the external radiation is from the BLRs for GeV $\gamma$-ray blazars with flat $\gamma$-ray spectra, while the near-IR radiation from the hot dust is responsible for MeV $\gamma$-ray blazars with steep $\gamma$-ray spectra. In their model, the electrons are assumed to be accelerated via a two-step process and their injection function takes the form of a double power law with a break at the energy that divides the regimes for two different electron acceleration mechanisms.

The Doppler boosting factor $\delta$ of the jets is a crucial quantity in studying the physical processes at work in the regions near the massive black holes in AGNs. Several different approaches are proposed to estimate the Doppler factors $\delta$ of the jets in AGNs. Ghisellini et al. (1993) derived the synchrotron self-Compton Doppler factor $\delta_{\text{SSC}}$ of the jets in AGNs from the VLBI core sizes and fluxes, and X-ray fluxes, on the assumption of the X-ray emission being produced by the SSC processes in the jets. Güijosa & Daly (1996) assumed
energy equipartition between the particles and the magnetic fields in the jet components, and derived the equipartition Doppler factor $\delta_{eq}$. More recently, the variability Doppler factor $\delta_{var}$ is derived on the assumption that the associated variability brightness temperature of total radio flux density flares are caused by the relativistic jets (Lähteenmäki & Valtaoja 1999).

In this paper, we use broad-line and $\gamma$-ray emission data to derive the Doppler boosting factors $\delta_\gamma$ for a sample of $\gamma$-ray blazars in the frame of the ERC model. The cosmological parameters $H_0=75$ km s$^{-1}$Mpc$^{-1}$ and $q_0=0.5$ have been adopted in this work.

2. Model

2.1. Inverse Compton radiative processes

In this work, we calculate the power of $\gamma$-ray emission from blazars by the external Compton processes mainly following the calculations of Dermer, Sturmer & Schlickeiser (1997). We then extend it to the case of the soft seed photons being from the BLRs of the blazars.

Assuming that blobs are moving with a constant velocity at an angle $\mu_{\text{obs}}=\cos i$ with respect to the line of sight, we have the inverse Compton scattered $\gamma$-ray flux density $S_C$ (Dermer, Sturmer & Schlickeiser 1997):

$$S_C = \frac{\delta_\gamma^{1+2\alpha} \epsilon_{\text{obs}} \sigma_T n_{\text{eo}} V_b (1 + z)^{1-\alpha} (1 + \mu_{\text{obs}})^{2+\alpha} \epsilon_{\text{obs}}}{16\pi d_L^2 \mu_{\text{obs}} (\bar{\epsilon}^*)^{1-\alpha}},$$

(1)

where $\delta_\gamma$ is the Doppler factor, $\alpha$ is the $\gamma$-ray photon energy spectral index, $z$ is the cosmological redshift, $u_i^* = \epsilon_{\text{obs}} \sigma_T n_{\text{eo}} V_b$ is the energy density of the soft seed photons in the blob’s frame in units of ergs cm$^{-3}$, $d_L$ is the luminosity distance, $\bar{\epsilon}^*$ is the dimensionless monochromatic mean soft photon energy in units of the electron rest mass energy, $n_{\text{eo}}$ is the number density of electron in the blob, $V_b$ is the volume of the blob, and $\sigma_T$ is the Thomson cross section.

An optically thin, homogenous spherical blob is assumed to be located very near the central black hole, so most of the soft seed photons from the BLRs only experience one or a few inverse Compton scatters in the blob. The total cross section $S_T \simeq \sigma_T n_{\text{eo}} V_b = \xi \pi r_b^2$, where $r_b$ is the radius of the blob. For the homogenous spherical blob, we have $\xi = 4\tau/3$, where $\tau = \sigma_T n_{\text{eo}} r_b$ is the optical depth of the blob. As we do not know the value of the electron density $n_{\text{eo}}$ in the blob, the parameter $\xi$, which is required $\xi \leq 1$, is adopted to describe the optical depth of the blob in our calculations.

For $\gamma$-ray blazars, the jets are believed to move in the direction very close to the line of
sight, so \( \mu_{\text{obs}} \approx 1 \) is taken and Eq. (1) becomes

\[
S_C = \frac{\delta^{4+2\alpha} c r_b^2 u_i^4}{\alpha + 2} \frac{1 + z}{16\pi d_L^2} (1 - \alpha) \frac{\epsilon_{\text{obs}}}{(\epsilon^*)^{1-\alpha}}.
\] (2)

The soft seed photons are assumed to be from the different line emission. The observed \( \gamma \)-ray flux density is the sum of inverse Compton scattered flux densities contributed by different emission lines:

\[
S_C = S_{C,H\beta} + S_{C,MgII} + S_{C,CIV} + S_{C,\text{Ly} \alpha} \cdots = \sum_i n S_{C,i}.
\] (3)

### 2.2. Size of the blob

The size of the blob can be estimated from the observed \( \gamma \)-ray variability time-scale. Hartman et al. (1996) derived the size of the blobs \( \sim 100R_g \) \((R_g = 2GM_\text{bh}/c^2)\) from the time-scale for substantial \( \gamma \)-ray variations of 3C279, if a \( 10^8M_\odot \) black hole is present in 3C279. Ghisellini & Madau (1996) derived the upper limit on the blob-to-disc distance from the observed variability timescale \( t_{\text{var}} \) of the \( \gamma \)-ray fluxes. As the timescale \( t_{\text{var}} \sim (r_b/\delta c) \), the radii of the blobs are around \( 3 \times 10^{16}(t_{\text{var}}/d)(\delta/10) \) cm. As the typical variable timescale, \( t_{\text{var}} \sim 1 \) day, we can infer the radii of the blobs are \( \sim 3 \times 10^{16} \) cm if the Doppler factor \( \delta \sim 10 \) is adopted. For typical radio-loud quasars having masses of black holes around \( 10^9M_\odot \), so the radii \( r_b \) of the blobs are around \( 200R_g \). Montigny et al. (1997) employed the ERC model to explain \( \gamma \)-ray emission from the blazars. The comparisons of their model with the observed spectrum of 3C273 give the radius of the blob \( r_b \sim 2 \times 10^{16} \) cm. The central black hole mass of 3C273 is around \( 5.5 \times 10^8M_\odot \) (Kaspi et al. 2000). Thus, we get \( r_b \sim 123R_g \) for the blob in 3C273. In this paper, we take \( r_b = 120R_g \) in our calculations.

### 2.3. Soft photon energy density in the blob’s flame

The observed flux of the broad emission line is

\[
f_{\text{line},i} = \frac{L_{\text{BLR},i}}{4\pi d_L^2},
\] (4)

where \( L_{\text{BLR},i} \) is the luminosity of a single broad emission line.

The energy density of this emission line in the blob is given by

\[
u_i^* = \frac{1}{c} \left( \frac{d_L}{R_{\text{BLR},i}} \right)^2 f_{\text{line},i},
\] (5)
where \( u^*_i \) is monochromatic seed photon energy density of the broad line in the blobs and \( R_{\text{BLR},i} \) is the radius of the BLR. The total soft seed photon energy density \( u^*_{\text{tot}} = \sum u^*_i \) is the sum of all emission lines. Eq. (5) is only valid for the blob near the central black hole. At further distance away from the central black hole, the energy density of BLR photons in the blob is anisotropic and can be treated analogously to the approach for the dust torus (Arbeiter, Pohl & Schlickeiser 2002). In this paper, however, we only consider the case of the blob being located near the central black hole.

### 2.4. Sizes of broad emission line regions

Based on the long-time observations of 17 nearby Seyfert 1 galaxies and 17 Palomar-Green quasars, Kaspi et al. (2000) found an empirical relation between the size of the BLR \( R_{\text{BLR}} \) of H\( \beta \) and the monochromatic continuum luminosity at 5100 Å:

\[
R_{\text{BLR}} = 32.9 \times \left( \frac{\lambda L_{5100}}{10^{37} \text{W}} \right)^{0.7} \text{lt - day.} \tag{6}
\]

McLure & Jarvis (2002) suggested that Mg II is a low-ionization line as H\( \beta \), so that Mg II is expected to be produced in the same region as H\( \beta \). For a sample of 22 objects, they found a correlation between the FWHM of Mg II and H\( \beta \):

\[
V_{\text{FWHM,MgII}} \sim V_{\text{FWHM,H\beta}}^{1.02}. \tag{7}
\]

It is therefore reasonable to expect that Mg II and H\( \beta \) are produced in the same region. Using the same sample and the size of the BLR derived by Kaspi et al. (2000), they obtained a correlation between \( R_{\text{BLR}} \) and the monochromatic continuum luminosity at 3000 Å:

\[
R_{\text{BLR}} = 28.4 \times \left( \frac{\lambda L_{3000}}{10^{37} \text{W}} \right)^{0.47} \text{lt - day}, \tag{7}
\]

which has been corrected to the cosmological parameters used in this paper.

Vestergaard (2002) suggested a relation between the black hole mass \( M_{\text{bh,UV}} \) and the monochromatic continuum luminosity at 1350 Å. The black hole mass \( M_{\text{bh,UV}} \) is the central black hole mass based on the calibration of the single-epoch UV spectral measurements. They derived

\[
M_{\text{bh,UV}} = 1.6 \times 10^6 \left( \frac{V_{\text{FWHM,CIV}}}{10^3 \text{kms}^{-1}} \right)^2 \left( \frac{\lambda L_{1350}}{10^{37} \text{W}} \right)^{0.7} M_\odot, \tag{8}
\]

where \( V_{\text{FWHM}} \) is the full width at half-maximum of the line C IV. The relation between \( R_{\text{BLR}} \) and the monochromatic continuum luminosity at 1350 Å is therefore available:

\[
R_{\text{BLR}} = 10.9 \times \left( \frac{\lambda L_{1350}}{10^{37} \text{W}} \right)^{0.7} \text{lt - day}, \tag{9}
\]
Now, we can derive the sizes of broad emission lines $H\beta$, $Mg\, II$, and $C\, IV$ from the optical or UV continuum luminosity by using the empirical relations (6), (7) and (9), respectively.

### 2.5. The black hole mass

We can estimate the central black hole masses of AGNs on the assumption that the motions of the gases in BLRs are virialized from the width of the emission line, if the size of the BLR is available. We use the empirical relation between the size of the BLR $R_{BLR}$ and the optical continuum luminosity $L_{\lambda}$ given in last subsection to estimate the size of the BLR $R_{BLR}$. The black hole mass is given by

$$M_{bh} = 2.25 \times R_{BLR} \frac{V^2}{FWHM} G^{-1},$$

(10)

if the FWHM of any broad-line of $H\beta$, $Mg\, II$, and $C\, IV$ is available (Gu, Cao & Jiang 2001).

### 2.6. The Doppler factor $\delta_\gamma$

The Doppler factor $\delta_\gamma$ is given by

$$\delta_\gamma = 2 \frac{2-\alpha}{4+2\alpha} (1 + z) \frac{\alpha - 1}{4 + 2\alpha} (\alpha + 2) \frac{1}{4 + 2\alpha} \left( \frac{c \xi r_b^2}{S c d_f^2} \right)^{-\frac{1}{4 + 2\alpha}} \left( \sum \frac{u_i^*}{(\epsilon_i)^{1-\alpha}} \right)^{-\frac{1}{4 + 2\alpha}} \epsilon_{\text{obs}}^{-\frac{1}{4 + 2\alpha}}.$$

(11)

Using the observed $\gamma$-ray flux, the Doppler factor $\delta_\gamma$ is available from Eq. (11), if the soft seed photon energy density $u_i^*$ in the blob, the radius of the blob $r_b$, and $\xi$ are available. As the parameter $\xi$ is required to be less than unit, we can obtain the lower limit of $\delta_\gamma$, if $\xi = 1$ is adopted.

### 3. The sample

We search the literature and collect all available data of broad emission lines of $\gamma$-ray AGNs in EGRET catalog III. The selection criterion is that the sources of which the FWHM of at least one of the following broad emission lines $H\beta$, $Mg\, II$ and $C\, IV$ and the fluxes are available. This leads to 36 sources, of which 30 sources are the high-confidence identification blazars and 6 sources are the lower confidence potential blazar identifications listed in Hartman et al. (1999). For the source 0954+658, only the FWHM and the flux of the broad line $H\alpha$ are available. We estimate the BLR size of $H\alpha$ using the empirical relation $R_{BLR}(H\alpha) = 1.19R_{BLR}(H\beta)$ proposed by Kaspi et al. (2000).
In principle, all broad emission line fluxes are needed to calculate the total soft seed photon energy in the blobs contributed by different broad emission lines. Usually, the fluxes of only one or several broad emission lines are available for most sources in our sample due to the restriction of redshift. In our calculations, we consider fluxes for the following lines: Hβ, MgII, CIV, CIII, Lyα and Hα, which contribute about 60 per cent of the total broad line emission. We use the line ratios presented by Francis et al. (1991), in which the relative strength of Lyα is taken as 100, to calculate the total broad line emissions. Celotti, Padovani & Ghisellini (1997) added the contribution from the flux of Hα \( F_{\text{H} \alpha} \), with a value of 77. This gives a total relative flux \( < F_{\text{BLR}} > = 536.04 \) (narrow lines are not included). For the lines Hβ, MgII and CIV, we use Eq. (6), (7) and (9) to estimate their radii of the BLRs. For other lines of which the FWHM is available, we compare their FWHM with that of any one of those three lines Hβ, MgII and CIV to estimate the radii of the BLRs. We use Eq. (5) to calculate the soft photon energy density in the blob for the lines with available FWHM and flux data. We calculate the total soft seed photon energy density \( u_{\text{tot}}^{*} \) in the blob as

\[
u_{\text{tot}}^{*} = \sum_{i} u_{i}^{*} = 536.04 \times \frac{\sum_{i} u_{i,\text{obs}}^{*}}{\sum_{i} F_{i,\text{re}}},
\]

where \( \sum_{i} u_{i,\text{obs}}^{*} \) is the photon density in the blob contributed by the lines with available emission line data, \( \sum_{i} F_{i,\text{re}} \) is the sum of relative fluxes of these lines.

4. Results

Using the method described in § 2, we derive the parameters for all the sources in our sample. All the observational data and the results are listed in Tables 1 – 3. The \( \gamma \)-ray emission is violently variable. For each source, we derived two values of the Doppler factor \( \delta_{\gamma} \), corresponding to the lowest and highest values of the observed \( \gamma \)-ray fluxes.

In Figs. 1 and 2, we compare the Doppler factors \( \delta_{\gamma} \) for the lowest and highest \( \gamma \)-ray flux cases with \( \delta_{\text{var}} \) derived from the variability time-scale of radio emission, respectively (Lähteenmäki & Valtaoja 1999). It is found that the values of \( \delta_{\text{var}} \) are higher than that of \( \delta_{\gamma} \) for most sources in our sample.

In Fig. 3, we plot the relation between the core dominance parameter \( R \) and the Doppler factor \( \delta_{\gamma,\text{min}} \) derived from the lowest \( \gamma \)-ray flux. The core dominance parameters \( R \) are taken from Cao & Jiang (2001), except those of the sources of 0454−234, 0521−365 and 1741−038 taken from Dondi & Ghisellini (1995). A correlation between \( R \) and \( \delta_{\gamma,\text{min}} \) is found at a significant level of 97.5 per cent (Spearman correlation coefficient \( \rho \)). The results are plotted in Fig. 4 for the Doppler factor \( \delta_{\gamma,\text{max}} \) derived from the highest \( \gamma \)-ray flux. The significant level of the correlation becomes 95.2 per cent.
The distribution of the central black hole mass $M_{\text{bh}}$ in $\gamma$-ray blazars is plotted in Fig. 5. The black hole masses $M_{\text{bh}}$ are in the range of $10^8 - 10^{10} M_\odot$ with an average of around $2 \times 10^9 M_\odot$.

We plot the relation of the black hole mass $M_{\text{bh}}$ with the lowest and highest $\gamma$-ray luminosity $L_\gamma$ in Figs. 6 and 7, respectively. The correlations between them are found at the significant levels of 97.8 and 96.6 per cent for the lowest and highest $\gamma$-ray emissions, respectively.

5. Discussion

In this work, we estimate the size of the BLR from the optical or UV continuum luminosity. The observed optical/UV continuum emission from $\gamma$-ray blazars is a mixture of the emission from the disks and jets. The optical/UV continuum emission may be strongly beamed to us, since the viewing angles of the relativistic jets in these blazars are small. The emission from the jets may dominate over that from the disks at least in some blazars. So, the BLR size derived from the observed optical/UV continuum luminosity may be overestimated, and the derived black hole mass is a upper limit (Gu, Cao & Jiang 2001).

The size of the blob $r_b$ is assumed to be $120 R_g$ in our calculations (see discussion in Section §2.2). As the black hole mass $M_{\text{bh}}$ is derived from the size of the BLR and the line width, the size of the blob $r_b$ is proportional to the BLR size $R_{\text{BLR}}$. From Eq. (5), we know that the energy density in the blob $u^* \propto 1/R_{\text{BLR}}^2$. The derived Doppler factor $\delta_{\gamma}$ in this work is therefore independent of the BLR size $R_{\text{BLR}}$ (see Eq. (11)). It indicates that the overestimate of the BLR size caused by the contamination of the optical/UV continuum emission has not affected the values of derived Doppler factor $\delta_{\gamma}$.

In our calculations, we adopted a parameter $\xi$ to describe the optical depth of the blob, since we do not know the exact value of the actual number density $n_{\text{eo}}$ of the electrons in the blob. From Eq. (11), it is found that the Doppler factor $\delta_{\gamma} \propto \xi^{-1/(4+2\alpha)}$. For a typical value of $\alpha \sim 1.5$, we found that the derived $\delta_{\gamma}$ becomes about twice of its initial value, if the parameter $\xi$ is changed from 1 to 0.01. The uncertainty of $\xi$ in our calculations would not affect our results significantly.

We only consider the photons from the BLRs as the soft seed photons. Other sources of soft seed photons (e.g., emission from the disks, synchrocyclotron emission in the blobs, etc.) have not been included in the calculations. The Doppler factor $\delta_{\gamma}$ derived in this work are in the range of 3.04 and 17.00, if $\xi = 1$ is adopted. It is generally consistent with the results derived by other methods (Ghiostellini et al. 1993; Güijosa & Daly 1996; Lähteenmäki &
Valtaoja 1999). It may imply that the soft seed photons are indeed mainly from the BLRs in these sources.

The variability Doppler factors $\delta_{\text{var}}$ of 20 $\gamma$-ray blazars in our sample have been derived from the radio variable time-scales are available (Lähteenmäki & Valtaoja 1999). Comparing with the Doppler factors $\delta_\gamma$ derived in this work, we find that the variability Doppler factor $\delta_{\text{var}}$ are higher than $\delta_\gamma$ derived in this work for most sources (see Figs. 1 and 2). This may be due to the fact that we adopt $\xi = 1$ and the derived Doppler factor $\delta_\gamma$ are then the lower limits. The value of $\xi$ may possibly be estimated roughly by letting $\delta_{\text{var}} = \delta_\gamma$. It can be found that the values of $\xi$ can be low as $10^{-3} - 10^{-2}$ for some sources (see Eq. (11), Figs. 1 and 2).

The core dominance parameter $R = f_c/f_e$, where $f_c$ and $f_e$ are the core and extended flux densities at 5 GHz in the rest frame of the source. The core dominance parameter $R$ is believed to be a good indicator of the Doppler factor of the jet. We find a significant correlation between the core dominance parameter $R$ and the derived Doppler factor $\delta_\gamma$. This implies that the derived Doppler factors $\delta_\gamma$ are reliable for the $\gamma$-ray blazars in this sample and the soft seed photons are mainly from the BLRs.

It was argued that the SSC radiative mechanism is dominant in BL Lac objects (Sikora et al. 2002). However, we cannot find significant differences between BL Lac objects and quasars in our investigations. The reason may be that the BL Lac objects in our sample have relative stronger broad line emission compared with other BL Lac objects listed in EGRET catalog III, since we only select the $\gamma$-ray blazars with broad-line emission data as our sample. So these BL Lac objects in our sample are more like quasars as they have rather strong broad-line emission (Véron-Cetty & Véron 2000). For these BL Lac objects with relative strong broad-line emission, the ERC radiative mechanism may probably be important as that in quasars.

The black hole masses of $\gamma$-ray blazars in this sample are in the range of $10^8 - 10^{10} M_\odot$. This is consistent with some previous results for radio-loud AGNs (Mclure & Dunlop 2001; Laor 2000). We have found significant correlations between the black hole mass $M_{\text{bh}}$ and the $\gamma$-ray luminosity $L_\gamma$. The reason may be that the $\gamma$-ray flux depends sensitively on the Doppler factor $\delta_\gamma$ and the values of the Doppler factor of the $\gamma$-ray AGNs in our sample spread over a large range ($\sim 3 - 17$). On the other hand, it is expected that the $\gamma$-ray flux is independent of the black hole mass in ERC mechanisms with the soft seed photons being from the BLRs (see Eq. (2) and discussion in the second paragraph of this section).

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Table 1. Broad emission line data, black hole masses and $\gamma$-ray luminosities

| Source     | Redshift | Line | FWHM a | Ref. | $\log M_{bh}/M_\odot$ | $\log L_{\gamma,\text{min}}^{b}$ | $\log L_{\gamma,\text{max}}^{b}$ |
|------------|----------|------|--------|------|-----------------------|---------------------------------|---------------------------------|
| 0119+041 d| 0.637    | Hβ   | 4444   | G01  | 8.855                 | 46.309                          | 46.909                          |
| 0208−512 a| 1.003    | Hβ   | 4070   | W86  | 9.208                 | 47.916                          | 48.497                          |
| 0336−019  | 0.852    | Hβ   | 4875   | G01  | 9.459                 | 47.903                          | 48.580                          |
| 0414−189  | 1.536    | Mg II| 1713   | H78  | 8.075                 | 47.310                          | 47.996                          |
| 0420−014  | 0.915    | Hβ   | 3000   | G01  | 9.510                 | 46.987                          | 47.826                          |
| 0440−003  | 0.844    | Mg II| 3900   | B89  | 8.813                 | 47.071                          | 47.908                          |
| 0454−234 a| 1.009    | Mg II| 7891   | S89  | 9.173                 | 46.823                          | 47.082                          |
| 0454−463  | 0.858    | Mg II| 2700   | F83  | 8.626                 | 46.587                          | 47.204                          |
| 0458−020  | 2.286    | C IV | 5200   | B89  | 8.662                 | 47.878                          | 48.734                          |
| 0521−365 c,d| 0.055 | Hβ   | 6758   | SK93 | 8.708                 | 44.584                          | 44.889                          |
| 0537−441 a| 0.894    | Mg II| 3200   | W86  | 8.709                 | 47.228                          | 47.970                          |
| 0539−057 a| 0.839    | Mg II| 8598   | S93  | 9.411                 | 48.015                          | 48.015                          |
| 0804+499 d| 1.430    | Mg II| 2259   | L96  | 8.634                 | 47.522                          | 47.781                          |
| 0836+710  | 2.172    | Mg II| 3062   | L96  | 9.450                 | 47.723                          | 48.312                          |
| 0851+202  | 0.306    | Hβ   | 3441   | S89  | 8.919                 | 46.215                          | 46.427                          |
| 0954+556  | 0.901    | C IV | 10503  | W95  | 9.718                 | 46.990                          | 47.851                          |
| 0954+658  | 0.368    | Hα   | 2084   | L96  | 8.526                 | 46.182                          | 46.618                          |
| 1127−145 a| 1.187    | Mg II| 2750   | W86  | 8.850                 | 47.168                          | 47.964                          |
| 1222+216  | 0.435    | Hβ   | 2197   | SM87 | 8.435                 | 46.235                          | 47.078                          |
| 1226+023  | 0.158    | Hβ   | 3416   | K00  | 9.298                 | 45.268                          | 46.026                          |
| 1229−021  | 1.045    | Mg II| 5000   | B89  | 9.118                 | 46.698                          | 47.199                          |
| 1253−055 a| 0.538    | Hβ   | 3100   | G01  | 8.912                 | 46.770                          | 48.299                          |
| 1331+170  | 2.084    | Mg II| 5740   | C92  | 9.171                 | 47.472                          | 48.348                          |
| 1334−127 a| 0.539    | Mg II| 7077   | SK93 | 9.294                 | 46.188                          | 46.753                          |
| 1424−418  | 1.522    | Mg II| 9144   | S89  | 9.652                 | 47.860                          | 48.418                          |
| 1504−166 d| 0.876    | Mg II| 5139   | H78  | 9.130                 | 47.450                          | 47.754                          |
| 1510−089  | 0.361    | Hβ   | 3180   | G01  | 9.130                 | 46.233                          | 46.827                          |
| 1611+343  | 1.401    | Hβ   | 5600   | G01  | 10.05                 | 47.716                          | 48.276                          |
| 1633+382  | 1.814    | Mg II| 9657   | L96  | 10.09                 | 48.332                          | 48.861                          |
| 1725+044  | 0.296    | Hβ   | 2090   | G01  | 8.545                 | 46.001                          | 46.251                          |
| 1739+522  | 1.375    | Mg II| 2559   | L96  | 8.866                 | 47.410                          | 48.076                          |
| 1741−038  | 1.054    | Mg II| 11574  | S89  | 9.566                 | 47.231                          | 47.851                          |
| 2230+114  | 1.037    | C IV | 3340   | W95  | 9.164                 | 47.217                          | 47.847                          |
| 2251+158  | 0.859    | Hβ   | 2800   | G01  | 9.643                 | 47.467                          | 48.141                          |
| 2320−035  | 1.411    | C IV | 3300   | B89  | 8.079                 | 47.605                          | 48.273                          |
| 2351+456  | 1.922    | Mg II| 5118   | L96  | 9.190                 | 47.867                          | 48.427                          |

a in unit of km s$^{-1}$

b in unit of ergs s$^{-1}$

c BL Lac object

d lower confidence potential blazar identifications

e the data of black hole masses from Gu, Cao & Jiang (2001)

References. — B89: Baldwin, Wampler & Gaskell (1989); C92: Corbin (1992); F83: Fricke, Kollatschny & Witzel (1983); G01: Gu, Cao & Jiang (2001); H78: Hunstead, Murdoch & Shobbrook (1978); K00: Kaspi et al. (2000); L96: Lawrence et al. (1996); S89: Stickel, Fried & Kühr (1989); S93: Stickel & Kühr (1993); SK93: Stickel, Kühr & Fried (1993); SM87: Stockton & Mackenty (1987); W86: Wilkes (1986); W95: Wills et al. (1995).
Table 2. Broad emission lines data and the total energy density of the blob

| Source Lines | References | log $u^*_\text{tot}$ |
|--------------|------------|---------------------|
| 0119+041 Hβ | JB91       | −1.896              |
| 0208−512 Mg II, C III | W86, S97 | −2.461              |
| 0336−019 Hβ, Mg II, C III | B89, JB91 | −2.794              |
| 0414−189 Mg II, C IV, C III | H78 | +0.026              |
| 0420−014 Mg II, C III | B89, S97 | −2.924              |
| 0440−003 Mg II | B89 | −2.069              |
| 0454−234 Mg II, C III | S89 | −1.872              |
| 0454−463 Mg II | F83 | −1.837              |
| 0458−020 C IV | B89 | −1.702              |
| 0521−365 Hβ | SK93 | −2.722              |
| 0537−441 Mg II | W86, S97 | −2.234              |
| 0539−057 Mg II | S93 | −1.390              |
| 0804+449 Mg II, C IV, C III | L06 | +0.411              |
| 0836+710 Mg II, C IV, C III, Lyα | L06 | +0.258              |
| 0851+202 Hβ | S89 | −4.109              |
| 0954+556 C IV, Lyα | W95 | −2.063              |
| 0954+658 Hα | L06 | −4.425              |
| 1127−145 Mg II, C IV, C III | W86, W95 | −0.317              |
| 1222+216 Hβ | SM87 | −2.109              |
| 1226+023 Hβ, Mg II, C IV, C III, Lyα, Hα | K00, U80, CB96, B87 | −2.067              |
| 1229−021 Mg II | B98 | −1.729              |
| 1253−055 Hβ, Mg II, C IV, C III, Lyα | W95, M96 | −1.797              |
| 1331+170 C IV | C92 | −1.716              |
| 1334−127 Mg II | SK93 | −2.370              |
| 1424+418 Mg II, C III | S89 | −2.194              |
| 1504−199 Mg II | H78 | −1.898              |
| 1510−089 Hβ | O94 | −2.595              |
| 1611+343 Hβ, C IV, C III, Lyα | W95 | −3.075              |
| 1633+382 Mg II, C IV, C III, Lyα | L06 | −2.537              |
| 1725+044 Hβ | R84 | −2.819              |
| 1739+522 Mg II, C IV, C III | L06 | −1.446              |
| 1741−038 Mg II | S89 | −1.816              |
| 2230+114 C IV, C III, Lyα | W95 | −1.856              |
| 2251+158 Hβ, C IV, C III, Lyα | W95 | −2.632              |
| 2320−035 C IV | B89 | −1.653              |
| 2351+456 Mg II, C IV, C III | L06 | −1.480              |

References. — B75: Baldwin (1975); B89: Baldwin, Wampler & Gaskell (1989); C92: Corbin (1992); CB96: Corbin & Boroson (1996); F83: Fricke, Kollatschny & Witzel (1983); G01: Gu, Cao & Jiang (2001); H78: Hunstead, Murdoch & Shobbrook (1978); JB91: Jackson & Browne (1991); K00: Kaspi et al. (2000); L96: Lawrence et al. (1996); M96: Mariziani et al. (1996); O94: Osmer, Porter & Green (1994); R84: Rudy (1984); S97: Scarpa & Falomo (1997); S89: Stickel, Fried & Kühr (1989); S93: Stickel & Kühr (1993); SK93: Stickel, Kühr & Fried (1993); SM87: Stockton & Mackenty (1987); U80: Ulrich et al. (1980); W86: Wilkes (1986); W95: Wills et al. (1995).
| Source     | $\gamma$ | $F_{\gamma,\text{min}}$ | $F_{\gamma,\text{max}}$ | $\delta_{\gamma,\text{min}}$ | $\delta_{\gamma,\text{max}}$ | $\delta_{\text{var}}$ | $R$   |
|------------|----------|--------------------------|--------------------------|------------------------------|-------------------------------|------------------------|-------|
| 0119+041   | 2.63     | 5.1                      | 20.3                     | 5.98                         | 7.23                          | ...                    | 15.85 |
| 0208−512   | 1.99     | 35.2                     | 134.1                    | 7.76                         | 9.71                          | ...                    | ...   |
| 0336−019   | 1.84     | 37.4                     | 177.6                    | 7.27                         | 9.56                          | 19.01                  | 31.62 |
| 0414−189   | 3.25     | 10.2                     | 49.5                     | 7.63                         | 9.19                          | ...                    | ...   |
| 0420−014   | 2.44     | 9.3                      | 64.2                     | 6.61                         | 8.75                          | 11.72                  | 251.3 |
| 0440−003   | 2.37     | 12.5                     | 85.9                     | 8.52                         | 11.3                          | 11.46                  | 19.95 |
| 0454−234   | 3.14     | 8.1                      | 14.7                     | 5.94                         | 6.39                          | ...                    | 5.00  |
| 0454−463   | 2.75     | 5.5                      | 22.8                     | 7.15                         | 8.65                          | ...                    | ...   |
| 0458−020   | 2.45     | 9.5                      | 68.2                     | 10.1                         | 13.5                          | 17.80                  | 5.01  |
| 0621−365   | 2.63     | 15.8                     | 31.9                     | 4.46                         | 4.91                          | ...                    | 1.00  |
| 0537−441   | 2.41     | 16.5                     | 91.1                     | 9.03                         | 11.6                          | ...                    | 199.6 |
| 0539−057   | 2.00     | 66.5                     | 66.5                     | 4.60                         | 4.60                          | ...                    | 7.61  |
| 0804+499   | 2.15     | 8.3                      | 15.1                     | 3.82                         | 4.20                          | 26.21                  | 151.9 |
| 0830+710   | 2.62     | 8.6                      | 33.4                     | 3.19                         | 3.85                          | 10.67                  | 34.93 |
| 0851+202   | 2.03     | 9.7                      | 15.8                     | 9.62                         | 10.4                          | 18.03                  | 781.0 |
| 0854+556   | 2.12     | 6.5                      | 47.2                     | 3.44                         | 4.73                          | 4.63                   | 10.81 |
| 0954+658   | 2.08     | 6.6                      | 18.0                     | 14.5                         | 17.0                          | 6.62                   | 110.5 |
| 1127−145   | 2.70     | 9.9                      | 61.8                     | 4.87                         | 6.24                          | ...                    | 50.12 |
| 1222+216   | 2.28     | 6.9                      | 48.1                     | 7.12                         | 9.57                          | 8.16                   | ...   |
| 1226+023   | 2.58     | 8.5                      | 48.3                     | 3.04                         | 3.87                          | 5.71                   | 6.31  |
| 1229−021   | 2.85     | 4.9                      | 15.5                     | 5.45                         | 6.33                          | ...                    | 3.43  |
| 1253−055   | 1.96     | 9.3                      | 267.3                    | 5.18                         | 9.14                          | 16.77                  | 12.59 |
| 1331+170   | 2.41     | 4.4                      | 33.1                     | 6.20                         | 8.34                          | ...                    | ...   |
| 1334−127   | 2.62     | 5.5                      | 20.2                     | 4.71                         | 5.64                          | ...                    | 12.87 |
| 1424−418   | 2.13     | 15.3                     | 55.3                     | 5.28                         | 6.48                          | ...                    | 2.38  |
| 1504−166   | 2.00     | 16.5                     | 33.2                     | 5.58                         | 6.27                          | ...                    | 19.95 |
| 1510−089   | 2.47     | 12.6                     | 49.4                     | 5.84                         | 7.11                          | 13.18                  | 31.62 |
| 1611+343   | 2.42     | 19.0                     | 68.9                     | 6.36                         | 7.68                          | 5.04                   | 25.12 |
| 1633+382   | 2.15     | 31.8                     | 107.5                    | 5.22                         | 6.33                          | 8.83                   | 79.44 |
| 1725+044   | 2.67     | 13.3                     | 23.7                     | 8.68                         | 9.39                          | 2.46                   | 125.8 |
| 1739+522   | 2.42     | 9.7                      | 44.9                     | 6.72                         | 8.40                          | 12.12                  | 50.1  |
| 1741−038   | 2.42     | 11.7                     | 48.7                     | 4.44                         | 5.47                          | 8.92                   | 4.00  |
| 2230+114   | 2.45     | 12.1                     | 51.6                     | 5.92                         | 7.31                          | 14.23                  | 25.12 |
| 2251+158   | 2.21     | 24.6                     | 116.1                    | 5.97                         | 7.61                          | 21.84                  | 15.85 |
| 2320−035   | 2.00     | 8.2                      | 38.2                     | 12.1                         | 15.6                          | ...                    | ...   |
| 2351+456   | 2.38     | 11.8                     | 42.8                     | 6.37                         | 7.71                          | ...                    | ...   |
Fig. 1.— The variability Doppler factor $\delta_{\text{var}}$ vs. the Doppler factor $\delta_{\gamma,\text{min}}$ derived in this work. The circles represent BL Lac objects, while the triangles represent quasars.
Fig. 2.— Same as Fig. 1, but the Doppler factor $\delta_{\gamma,\text{max}}$ rederived from the highest $\gamma$-ray fluxes.
Fig. 3.— The core dominance parameter $R$ vs. the Doppler factor $\delta_{\gamma,\text{min}}$. 
Fig. 4.— Same as Fig. 3, but the Doppler factor $\delta_{\gamma,\text{max}}$ rederived from the highest $\gamma$-ray fluxes.
Fig. 5.— The distribution of the black hole masses.
Fig. 6.— The lowest $\gamma$-ray luminosity $L_{\gamma,\text{min}}$ vs. the black hole mass $M_{\text{bh}}$. 
Fig. 7.— Same as Fig. 6, but for the highest $\gamma$-ray luminosity $L_{\gamma,\text{max}}$. 