Abstract

We present the results of a multi-frequency, time-averaged analysis of blazars included in the Candidate Gamma-ray Blazar Survey catalog. Our sample consists of 324 γ-ray detected (γ-ray loud) and 191 γ-ray undetected (γ-ray quiet) blazars; we consider all the data up to 2016 April 1. We find that both the γ-ray loud and γ-ray quiet blazar populations occupy similar regions in the WISE color–color diagram, and γ-ray loud sources are brighter in the radio and X-ray bands. A simple one-zone synchrotron inverse-Compton emission model is applied to derive the physical properties of both populations. We find that the central black hole mass and accretion disk luminosity ($L_{\text{disk}}$) computed from the modeling of the optical-UV emission with a Shakura–Sunyaev disk reasonably matches that estimated from the optical spectroscopic emission-line information. A significantly larger Doppler boosting in the γ-ray loud blazars is noted, and their jets are more radiatively efficient. On the other hand, the γ-ray quiet objects are more MeV-peaked and thus could be potential targets for next-generation MeV missions. Our results confirm earlier findings about the accretion-jet connection in blazars; however, many of the γ-ray quiet blazars tend to deviate from the recent claim that the jet power exceeds $L_{\text{disk}}$ in blazars. A broadband study, considering a larger set of γ-ray quiet objects and also including BL Lacs, will be needed to confirm/reject this hypothesis as well as to verify the evolution of the powerful high-redshift blazars into their low-power nearby counterparts.

Key words: galaxies: active – galaxies: jets – gamma rays: galaxies – quasars: general

Supporting material: figure sets, machine-readable tables

1. Introduction

Blazars are radio-loud (RL) active galactic nuclei (AGN) that are known to host powerful relativistic jets closely aligned to the line of sight to the observer (e.g., Urry & Padovani 1995). Blazars are known to emit radiation over the entire electromagnetic spectrum, from low-energy radio waves to very-high-energy γ-rays, and they also exhibit flux and polarization variations (Stalin et al. 2002; Sagar et al. 2004; Jorstad et al. 2010; Aleksic et al. 2011; Bachev et al. 2012; Paliya et al. 2015; Marchesini et al. 2016). All these effects are believed to arise from the Doppler boosting that occurs due to the peculiar orientation of the jet (viewing angle $\theta_v < 1/\Gamma$; where $\Gamma$ is the bulk Lorentz factor of the jet). Accordingly, for each observed blazar with a known $\Gamma$, there exist $2\Gamma^2$ intrinsically similar sources with their jets pointed in other directions.

Based on the equivalent width (EW) of the optical emission lines, blazars are classified as flat spectrum radio quasars (FSRQs) and BL Lac objects, with FSRQs exhibiting broad emission lines (EW>5 Å). The observation of strong emission lines from FSRQs indicates the presence of a luminous broad line region (BLR), which in turn suggests a high and efficient accretion process that illuminates the BLR (e.g., Sbarrato et al. 2012). In fact, the infrared-to-ultraviolet (IR to UV) spectrum of many FSRQs is found to be dominated by the thermal emission from the accretion disk (e.g., Ghisellini et al. 2010). The presence/absence of narrow emission lines in the optical spectrum of BL Lac objects, on the other hand, indicates a relatively low and inefficient accretion and/or the dominance of the non-thermal synchrotron radiation originating from the plasma moving along the relativistic jet.

The radio to γ-ray spectral energy distribution (SED) of blazars exhibits a characteristic double hump structure. The low-energy peak lies at radio to optical-UV or X-ray frequencies and is attributed to synchrotron emission, whereas the origin of the high-energy peak is often associated with the inverse Compton (IC) scattering of low-energy photons by the energetic electrons present in the jet. When the low-energy target photons are provided by synchrotron emission, the IC mechanism is called synchrotron self-Compton (SSC; e.g., Marscher & Gear 1985). This, along with the synchrotron process, is found to satisfactorily explain the broadband SEDs of BL Lac objects (e.g., Tavecchio et al. 2010; Yan et al. 2014). On the other hand, the high-energy γ-ray emission from powerful FSRQs is conventionally explained by the IC process, with low-energy photons originating outside the jet (External Compton or EC; e.g., Begelman & Sikora 1987). In this case, the reservoirs of seed photons for the IC mechanism could be the accretion disk (Dermer & Schlickeiser 1993), BLR (Sikora et al. 1994), and/or dusty torus (Blazejowski et al. 2000). The SED of blazars is also successfully reproduced by hadronic processes (e.g., Mücke et al. 2000), though the resulting parameters (e.g., magnetic field) are found to be quite extreme (e.g., Abdo et al. 2011).

It has been well-known since the Energetic Gamma Ray Experiment Telescope (Thompson et al. 1993) era that the high-energy γ-ray extragalactic sky is dominated by blazars (Hartman et al. 1999). This has later been confirmed with the advent of the Large Area Telescope onboard the Fermi Gamma-ray Space Telescope (Fermi-LAT; Atwood et al. 2009). In fact, Fermi-LAT detected more than a thousand blazars in its first four years.
of operation (Ackermann et al. 2015). The availability of good quality Fermi-LAT data, complemented by the lower-frequency monitoring from various observing facilities,\(^5\) has allowed population studies of blazars (see, e.g., Ghisellini et al. 2009, 2010; Tavecchio et al. 2010; Meyer et al. 2011; Ajello et al. 2012; Giommi et al. 2012b; Finke 2013; Ajello et al. 2014; Ghisellini et al. 2014; Kang et al. 2014; Zhang et al. 2014; Chen et al. 2015; Ghisellini & Tavecchio 2015; Fan et al. 2016; Kruū et al. 2016; Mao et al. 2016; Ghisellini et al. 2017).

Though Fermi-LAT has observed a significant γ-ray emission from a large number of blazars, an even larger number of such sources is yet to be detected in the γ-ray band (e.g., Massaro et al. 2015). Various explanations have been proposed to explain this, such as the differences in the Doppler boosting, apparent jet speed, apparent opening angle, very long baseline interferometry core flux densities, and brightness temperatures (Pushkarev et al. 2009; Lister et al. 2015).

Motivated by the availability of a good quality multi-wavelength (MW) data set for a large number of blazars, we systematically study their broadband properties using both observational and theoretical SED modeling approaches. Our primary goal is to investigate the fundamental properties of blazars, such as the accretion-jet connection, the cosmological evolution of relativistic jets, and the differences in the physical characteristics of the known γ-ray sources and γ-ray non-emitters. Compared to earlier studies, we focus on the observational results and then interpret them using a leptonic emission model. Here, we present the results of our study on the blazars included in the Candidate Gamma-ray Blazars Survey catalog (CGRaBS; Healey et al. 2008). Ours is probably the largest sample of blazars on which a physical SED model is applied. In Section 2, we describe the steps adopted to select the objects. In Section 3, details on the data-reduction procedures are given. The observational results are presented in Section 4. We briefly describe the adopted one-zone leptonic emission model in Section 5, and present the results associated with the SED modeling in Section 6. We discuss our findings in Section 7, and summarize in Section 8.

We adopt a flat cosmology with \(H_0 = 67.8\) km s\(^{-1}\) Mpc\(^{-1}\) and \(\Omega_M = 0.308\) (Planck Collaboration et al. 2016).

### 2. The Sample

CGRaBS is a flux-limited (8.4 GHz flux density >65 mJy; see also, Healey et al. 2007) catalog of 1625 high-latitude (\(|b|>10^\circ\)), flat radio spectrum objects prepared to serve for the MW follow-up of likely γ-ray emitting AGNs (Healey et al. 2008). To determine the γ-ray detected CGRaBS blazars, we cross-match CGRaBS with all of the Fermi-LAT catalogs\(^6\) (3FGL, 2FGL, 1FGL, and 0FGL, sequentially; Acero et al. 2015; Nolan et al. 2012; Abdo et al. 2010, 2009). This is done by searching for a CGRaBS counterpart of the γ-ray source within its 95\% positional uncertainty. We consider a source to be γ-ray detected if it is included in any of the Fermi-LAT catalogs. We find a total of 467 matches, but 1178 have no LAT detection. Further, we look into the HEASARC archive for the availability of MW data, particularly X-rays. In our final sample, we keep only sources that have an existing MW data

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\(^5\) https://fermi.gsfc.nasa.gov/ssc/observations/multi/programs.html

\(^6\) The motivation behind cross-matching CGRaBS with all of the Fermi-LAT catalogs is to take into account the possibility that an object might have appeared in earlier catalogs but have been left out in later ones, probably due to the detection significance of the source falling below the threshold.

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### Table 1

The CGRaBS Sample Studied in This Work

| Catalog | γ-ray Loud FSRQs | BL Lacs |
|---------|-----------------|---------|
| 3FGL    | 235             | 75      |
| 2FGL    | 8               | 0       |
| 1FGL    | 2               | 0       |

| Catalog | γ-ray Quiet FSRQs | BL Lacs |
|---------|------------------|---------|
| CGRaBS  | 185              | 6       |

**Note.** Apart from these, we also include four CGRaBS blazars that were recently reported as γ-ray emitting sources in the literature. See the text for details.

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\(^7\) We do not use the prefix CGRaBS, for the sake of clarity.

\(^8\) If a source is classified as an FSRQ in the Fermi-LAT catalog but as a BL Lac in CGRaBS, we consider it as an FSRQ. This is because the Fermi-LAT catalogs are updated with more recent results. However, for γ-ray quiet sources, we follow the CGRaBS classification.
quiet blazars, whereas Ghisellini & Tavecchio (2015) have focused solely on $\gamma$-ray loud objects.

3. Data Reduction

3.1. Fermi-LAT

We consider the Fermi-LAT Pass 8 source class photons collected for the period 2008 August 5–2016 April 1 ($\sim$92 months) for all 515 blazars studied in this work. We follow the standard data-reduction procedure, but with a few modifications (see also, Ackermann et al. 2017). A sky model is defined considering all $\gamma$-ray sources included in 3FGL (Acero et al. 2015) lying within a region of interest (ROI) of 15$^\circ$ radius centered on the target quasar. The isotropic and Galactic diffuse emission models (Acero et al. 2016) are also considered. We perform a binned likelihood analysis to derive the best-optimized spectral parameters of all of the sources and power-law normalization factors of the diffuse background models. The significance of the source detection is computed by means of the maximum likelihood test statistic $TS = 2\Delta \log L$, where $L$ denotes the likelihood function, between models with and without a point object at the position of the source of interest. The spectral models of all of the Fermi-LAT detected blazars are the same as those considered in the LAT catalogs, whereas we adopt a simple power-law model to compute the upper limits for the remaining $\gamma$-ray quiet sources.

We use a minimum energy of 60 MeV and set the energy upper limit ($E_{\text{max}}$) to 300 GeV. To account for the poorer energy resolution of the Fermi-LAT at lower energies, we enable the energy dispersion correction for all of the objects except the background diffuse models. Moreover, Pass 8 introduces the classification of photons by point-spread function (PSF) type, sub-classified into four quartiles by quality of directional reconstruction, with the lowest (PSF0) and highest (PSF3) quartiles having the worst and best angular reconstructions, respectively. We then perform a component-wise analysis for each PSF, and finally perform a joint fitting using the SUMMED likelihood method of the Science Tools.10

In order to search for faint $\gamma$-ray emitters that are present in the data but not in the 3FGL catalog, we adopt an iterative approach. This step is necessary to update the background models in order to derive accurate spectral parameters for the sources of interest. We generate a residual TS map for each ROI and scan it for unmodeled excess emissions ($TS \gtrsim 25$). Once found, the locations of such unmodeled objects are optimized and inserted in the model file with a power-law spectrum. We repeat this procedure until the TS map stops showing any excess emission.

For $\gamma$-ray quiet blazars, we calculate the $3\sigma$ Fermi-LAT flux sensitivity limit in the direction of the source, for the period covered in the analysis, assuming a photon index of 2.4. For all sources, flux upper limits are derived at 95% confidence for energy bins with $TS < 9$ while generating $\gamma$-ray spectra of the sources. All errors associated with the Fermi-LAT data analysis are 1σ statistical uncertainties, unless specified. The entire data analysis is performed using the publicly available Python package fermipy (Wood et al. 2017).

3.2. Swift

We use all of the data from the three instruments onboard the Swift satellite (Gehrels et al. 2004): the Burst Alert Telescope (BAT, 15–150 keV; Barthelmy et al. 2005), the X-ray Telescope (XRT, 0.3–10 keV; Burrows et al. 2005), and the Ultraviolet Optical Telescope (UVOT Roming et al. 2005), which can observe in six filters, $V$, $B$, $U$, UVM1, UVM2, and UVW2.

We use publicly available 70 month Swift-BAT survey (Baumgartner et al. 2013) spectra and the instrument response file to cover the hard X-ray (15–150 keV) part of the SEDs of the blazars included in it.

We generate the 0.3–10 keV XRT spectrum using the online tool “Swift-XRT data product generator” (Evans et al. 2009). The source spectra are appropriately rebinned (1 or 20 counts per bin, depending on the brightness of the source), and we perform the spectral fitting in XSPEC. The faint sources are fitted with a simple power-law model following the C-statistic (Cash 1979). For the remaining objects, we follow a $\chi^2$ fitting procedure. In the $\chi^2$ method, we fit two models, power-law and log-parabola, and choose the best-fitted model based on the outcome of the f-test.12 We consider the Galactic neutral hydrogen column densities from Kalberla et al. (2005). The uncertainties are estimated at the 90% confidence level.

We combine UVOT snapshots using the tool uvotimsum and extract source magnitudes with uvotsource. For the latter, we extract the source counts from a circular region of 5$''$ radius centered at the quasar. The background is chosen as a circular region of the radius of 30$''$ from a nearby region free from source contamination. The extracted magnitudes are corrected for Galactic reddening (Schlafly & Finkbeiner 2011) and converted to energy flux using the conversion factors of Breeveld et al. (2011).

3.3. XMM-Newton and Chandra

The XMM-Newton (Jansen et al. 2001) data (0.3–10 keV) are analyzed using the Science Analysis Software version 15.0.0. The task epproc is used to generate EPIC-PN event files. We remove the high flaring background using eveselect. To extract the source and the background spectra, we define the respective regions as circles of 40$''$ radius each, with the source region being centered at the quasar and the background from the same chip—but avoiding contaminating objects. The response files are generated using the tool rmfgen and arfgen. We bin the spectra using specgroup to have a minimum of 20 counts per bin, and use XSPEC for spectral fitting.

We reduce the Chandra (Weisskopf et al. 2000) Advanced CCD Imaging Spectrometer data (ACIS, 0.3–7 keV) using the package Chandra Interactive Analysis of Observations (CIAO, version 4.9) and the associated calibration database (v 4.7.3). The data are first reprocessed with the tool chandra_repro. The source and the background spectra are extracted from the cleaned and calibrated event file using the tool specextstract. A circular region of 3$''$ radius centered at the source of interest is chosen to extract source counts, and the background is selected as a circle of 10$''$ radius from a nearby source-free region. The data are binned to have at least 1 or 20 counts per

9 http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/
10 http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
11 http://www.swift.ac.uk/user_objects/
12 We prefer a log-parabola model over the power-law if the f-test probability of null hypothesis is $<10^{-4}$.
the \(\gamma\)-ray loud and \(\gamma\)-ray quiet sources (right panel), we find that the \(\gamma\)-ray loud blazars are brighter \((F_{\gamma} < 1.4 \text{ GHz} = 776 \text{ mJy})\) than the \(\gamma\)-ray quiet sources \((F_{\gamma} < 1.4 \text{ GHz} = 447 \text{ mJy})\). Fitting the shown distributions with a Gaussian function returns an equal dispersion of 0.4 dex.

### 4.3. WISE IR Colors

Recently, it has been noticed that \textit{Fermi}-LAT detected blazars occupy a distinct region in the \textit{Wide-field Infrared Survey Explorer} (WISE; Wright et al. 2010) mid-IR color–color diagram, named the \textit{WISE Gamma-ray Strip} (WGS; Massaro et al. 2011). In Figure 3, we show the WISE 3.4–4.6 vs 4.6–12 \(\mu\)m color–color plot for CGRaBS objects and also include MQC sources for a comparison.\(^{14}\) A majority of the \(\gamma\)-ray loud blazars are found to occupy a narrow region in this diagram (see red points and WGS for FSRQs and BL Lac objects), confirming earlier results. Interestingly, \(\gamma\)-ray quiet blazars are also found to be centered in the same region of the diagram, albeit with a larger scatter. This can be understood in terms of the origin of the IR emission. As also noticed in D’Abrusco et al. (2012), the observed correlation between 3.4–4.6 \(\mu\)m and 4.6–12 \(\mu\)m colors is tighter for the objects in which both IR and \(\gamma\)-rays originate from the same electron population via synchrotron and SSC/EC mechanisms. On the other hand, the IR emission in FSRQs could be dominated by thermal radiation from the torus and hence may not correlate with the \(\gamma\)-ray emission. Indeed, out of 191 \(\gamma\)-ray quiet blazars, 185 are FSRQs, indicating the thermal origin of the IR emission as a possible explanation for the observed scatter.

### 4.4. X-Ray Emission

There are \textit{Swift}-XRT observations for a major fraction (>90\%) of CGRaBS quasars. For bright sources (e.g., J1256−0547 or 3C 279), we also find \textit{XMM-Newton} and/or \textit{Chandra} data—though we prefer to use \textit{Swift}-XRT, as it allows us to use the simultaneous optical-UV observations from the UVOT. In Tables 2 and 3, we present the results of the \textit{Swift}-XRT data analysis for the \(\gamma\)-ray loud and the \(\gamma\)-ray quiet blazars, respectively. Furthermore, for 18 objects (2 \(\gamma\)-ray loud and 16 \(\gamma\)-ray quiet), we could find only \textit{Chandra} or \textit{XMM-Newton} observations, which we use to extract the spectral information in the X-ray band. We report the associated fitting parameters in Table 4.

We compare the X-ray properties of the \(\gamma\)-ray loud and the \(\gamma\)-ray quiet blazars in Figure 4. This is done for the absorbed power-law modeled objects, which constitute a major fraction (>93\%) of the sample, and includes all soft X-ray instruments, i.e., \textit{Swift}-XRT, \textit{Chandra}-ACIS, and \textit{XMM-Newton} EPIC-PN. For an equal comparison, we extrapolate \textit{Chandra} analysis results to 10 keV. In the 0.3–10 keV energy range, the \(\gamma\)-ray loud sources \((\Gamma_{\text{0.3–10 keV}} = 1.4 \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1})\) are brighter than the \(\gamma\)-ray quiet objects \((\Gamma_{\text{0.3–10 keV}} = 6 \times 10^{-13} \text{ erg cm}^{-2} \text{s}^{-1})\); however, the spectral slopes \((\Gamma_{\text{0.3–10 keV}} = 1.58 \text{ for both})\) of the distributions are similar (Figure 4), with a slightly larger scatter for \(\gamma\)-ray quiet blazars.

### 5. Modeling the Broadband Emission

The MW SEDs of blazars are often modeled with a one-zone synchrotron-IC model (e.g., Dermer et al. 2009; Ghisellini & Tavecchio 2009; Sikora et al. 2009). We adopt the leptonic

\(^{13}\) We derive \(F_{\gamma} < 1.4 \text{ GHz}\) from the \(F_{\gamma} < 1.4 \text{ GHz}\) provided in the CGRaBS catalog, assuming \(\alpha = 0 (F \propto \nu^{0})\). For MQC objects, we extract \(F_{\gamma} < 1.4 \text{ GHz}\) from the NRAO VLA Sky Survey (NVSS; Condon et al. 1998). This is done by searching for the NVSS counterpart of the MQC source within the positional uncertainty reported in the NVSS catalog.

\(^{14}\) We determine the \textit{WISE} counterparts within 6\(^{\circ}\) of the radio position.
emission model of Ghisellini & Tavecchio (2009) to interpret the broadband SEDs of CGRaBS blazars and briefly describe it here. The emission region is considered to have a spherical shape, located at a distance $R_{\text{diss}}$ from the central black hole of mass $M_{\text{BH}}$. It moves along the jet axis with a bulk Lorentz factor $\Gamma$. Under the assumption of a conical jet with semi-opening angle $\psi = 0.1$ radian, the size of the emission region is constrained from $R_{\text{diss}}$. We assume the initial acceleration phase of the jet by considering $G \sim \frac{4\pi}{c^2 D_j^2} \int_{R_{\text{in}}}^{R_{\text{out}}} \frac{R \, dR}{e^{h \nu/kT(R)} - 1}$, where $h$ is the Planck constant, $\theta_j$ is the angle between the jet axis and the line of sight, $D_j$ is the luminosity distance, $k$ is the Boltzmann constant, $c$ is the speed of light, and $R_{\text{in}}$ and $R_{\text{out}}$ are the inner and outer disk radii, assumed as $3R_{\text{Sch}}$ and $500R_{\text{Sch}}$, respectively. The radial dependence of the temperature is given as follows:

$$T(R) = \frac{3R_{\text{Sch}}}{16\pi \dot{M}_{\text{acc}} \sigma_{\text{SB}} R^2} \left[ 1 - \left( \frac{3R_{\text{Sch}}}{R} \right)^{1/2} \right]^{1/4},$$

Figure 2. Left: the 1.4 GHz flux density of $\gamma$-ray loud (red) and $\gamma$-ray quiet (blue) blazars as a function of their redshift. The gray data points correspond to the radio flux densities of the sources included in the Million Quasar Catalog (MQC). The horizontal dashed line represents the median flux density of MQC sources. Right: the radio flux density distributions of $\gamma$-ray loud and $\gamma$-ray quiet sources. The distributions are fitted with a Gaussian function whose width is quoted.

Figure 3. The WISE $\{3.4, 4.6, 12\}$ μm color–color diagram for CGRaBS quasars (red and blue for $\gamma$-ray loud and $\gamma$-ray quiet objects, respectively) and MQC sources (gray). The black dashed and dotted lines correspond to the WISE Gamma-ray strips for FSRQs and BL Lac objects, respectively (Massaro et al. 2012).
Table 2
Results of Spectral Analysis of Swift-XRT Data for γ-Ray Loud Blazars

| Name          | $N_H$ | Exp. | $F_X$ | $F_{X,\text{low}}$ | $F_{X,\text{high}}$ | $\Gamma_X$ | $\Gamma_{X,\text{low}}$ | $\Gamma_{X,\text{high}}$ | $\beta_{X,\text{low}}$ | $\beta_{X,\text{high}}$ | $\chi^2$/C-stat. | dof | $P_{\text{f-test}}$ | Model | Fit |
|---------------|-------|------|-------|-------------------|---------------------|-----------|-------------------------|-------------------------|----------------------|----------------------|-----------------|------|---------------------|--------|-----|
| J0004--4736   | 1.34  | 5.62 | 0.43  | 0.31              | 0.57                | 1.88       | 1.54                    | 2.23                    | ...                  | ...                  | 26.26          | 48   | ...                 | PL     | c-stat |
| J0005 + 3820  | 6.57  | 20.31| 1.91  | 1.30              | 2.10                | 0.03       | 0.00                    | 0.36                    | 1.57                 | 1.12                 | 25.33          | 30   | --6.90             | LP     | chi  |
| J0011 + 0057  | 2.67  | 10.53| 0.16  | 0.10              | 0.26                | 1.43       | 0.86                    | 2.00                    | ...                  | ...                  | 21.12          | 25   | ...                 | PL     | c-stat |
| J0016--0015   | 2.72  | 3.95 | 0.59  | 0.41              | 1.03                | 1.29       | 0.85                    | 1.72                    | ...                  | ...                  | 28.15          | 32   | ...                 | PL     | c-stat |
| J0017--0512   | 2.81  | 11.24| 2.04  | 1.88              | 2.27                | 1.84       | 1.73                    | 1.96                    | ...                  | ...                  | 31.38          | 26   | --0.22              | PL     | chi  |

Note. The column contents are as follows. Column (1): name of the CGRaBS object; Column (2): the Galactic neutral hydrogen column density, in $10^{20}$ cm$^{-2}$ (Kalberla et al. 2005); Column (3): net exposure, in ksec; Columns (4)–(6): observed 0.3–10 keV flux and its lower and upper limits, respectively, in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$; Columns (7)–(9): power-law photon index (or spectral slope of the log-parabola model at the pivot energy) and its lower and upper limits, respectively; Columns (10)–(12): the curvature parameter of the log-parabola model and its lower and upper limits, respectively; Column (13): the statistics of the model fitting; Column (14): degrees of freedom; Column (15): log of the probability of null hypothesis derived from the $t$-test; Column (16): the best-fitted model, PL: power-law, LP: log-parabola; and Column (17): adopted statistics, c-stat: C-statistics (Cash 1979), and chi: $\chi^2$ fitting.

(This table is available in its entirety in machine-readable form.)
Table 3

Results of Swift-XRT Data Analysis for γ-Ray Quiet Blazars

| Name             | $N_{\text{hit}}$ (2) | Exp. (3) | $F_X$ (4) | $F_{X,\text{low}}$ (5) | $F_{X,\text{high}}$ (6) | $\Gamma_X$ (7) | $\Gamma_{X,\text{low}}$ (8) | $\Gamma_{X,\text{high}}$ (9) | $\beta_X$ (10) | $\beta_{X,\text{low}}$ (11) | $\beta_{X,\text{high}}$ (12) | $\chi^2$/C-stat. (13) | dof (14) | $P_{\text{test}}$ (15) | Model (16) | Fit (17) |
|------------------|----------------------|----------|-----------|------------------------|--------------------------|----------------|-----------------------------|-----------------------------|----------------|-----------------------------|-----------------------------|--------------------------|-----------|-----------------------|-----------|---------|
| J0001 + 1914     | 3.19                 | 5.47     | 0.09      | 0.00                   | 0.18                     | 1.37          | 0.23                        | 2.74                        | ...            | ...                        | ...                        | 7.53                     | 6         | ...                   | PL        | c-stat |
| J0004 + 2019     | 3.78                 | 1.92     | 0.49      | 0.29                   | 0.91                     | 1.54          | 0.85                        | 2.23                        | ...            | ...                        | ...                        | 15.66                    | 15        | ...                   | PL        | c-stat |
| J0004 + 4615     | 8.41                 | 3.74     | 0.27      | 0.12                   | 0.57                     | 1.12          | 0.18                        | 2.04                        | ...            | ...                        | ...                        | 15.50                    | 11        | ...                   | PL        | c-stat |
| J0006−0623       | 3.22                 | 16.38    | 1.80      | 1.67                   | 2.00                     | 1.67          | 1.56                        | 1.77                        | ...            | ...                        | ...                        | 22.27                    | 28        | −0.06                 | PL        | chi    |
| J0008−2339       | 2.31                 | 4.96     | 0.37      | 0.28                   | 0.52                     | 1.73          | 1.31                        | 2.16                        | ...            | ...                        | ...                        | 37.00                    | 33        | ...                   | PL        | c-stat |

Note. The column contents are same as in Table 2.

(This table is available in its entirety in machine-readable form.)
where \( \sigma_{SB} \) is the Stefan–Boltzmann constant and \( \eta_{acc} \) is the accretion efficiency, adopted here as 10%.

We assume that certain fractions of the \( L_{\text{disk}} \) are reprocessed by the BLR (\( f_{\text{BLR}} = 0.1 \)) and the torus (\( f_{\text{torus}} = 0.5 \), Ghisellini & Tavecchio 2009). The radiation from the BLR and the torus are adopted to follow a simple blackbody emission profile that peaks at the hydrogen Ly\( \alpha \) line frequency and the characteristic temperature \( (T_{\text{torus}}) \) of the torus, respectively. Both the BLR and the torus are assumed as spherical shells located at distances \( R_{\text{BLR}} = 10^{17} L_{d,45}^{1/2} \) cm and \( R_{\text{torus}} = 2.5 \times 10^{18} L_{d,45}^{1/2} \) cm, respectively, from the central black hole, where \( L_{d,45} \) is the accretion disk luminosity in units of \( 10^{45} \) erg s\(^{-1}\). We also consider the presence of the X-ray corona lying close to the accretion disk, which reprocesses 30% of the disk radiation. Its spectral shape is considered as \( n_{\text{cor}} (\Gamma) \propto \exp (-\Gamma \nu / 150 \text{ keV}) \). We calculate the radiative energy densities of these components in the comoving frame following the prescriptions of Ghisellini & Tavecchio (2009) and use them to derive the EC fluxes.

### Table 4

*Chandra and/or XMM-Newton Data Analysis*

| Name            | \( N_{\text{H}} \) | Exp. | \( F_X \) | \( F_{X, \text{low}} \) | \( F_{X, \text{high}} \) | \( \Gamma_X \) | \( \Gamma_{X, \text{low}} \) | \( \Gamma_{X, \text{high}} \) | \( \chi^2/\text{C-stat.} \) | dof | \( P_{\text{test}} \) | Fit  | Telescope |
|----------------|-----------------|-----|-----------|----------------------|----------------------|------------|---------------------|----------------------|---------------------|-----|-------------|-------|-----------|
| \( \gamma \)-ray loud
| J0941–1335     | 4.08            | 19.82 | 0.42     | 0.38                 | 0.45                 | 1.76       | 1.61                | 1.92                 | 16.80               | 19  | –0.13      | chi   | Chandra   |
| J1311+5513     | 1.68            | 3.86  | 0.32     | 0.27                 | 0.36                 | 1.79       | 1.65                | 1.93                 | 21.83               | 20  | –0.12      | chi   | XMM      |
| \( \gamma \)-ray quiet
| J0148+3854     | 4.79            | 63.40 | 0.31     | 0.28                 | 0.33                 | 1.33       | 1.25                | 1.42                 | 65.33               | 53  | –0.33      | chi   | Chandra   |
| J0254+3931     | 7.58            | 8.79  | 1.63     | 1.56                 | 1.74                 | 1.70       | 1.63                | 1.78                 | 51.35               | 61  | –0.25      | chi   | Chandra   |
| J0256–3315     | 2.43            | 2.44  | 0.21     | 0.14                 | 0.32                 | 1.38       | 1.01                | 1.75                 | 39.71               | 45  | ...        | c-stat | Chandra   |
| J0324–2918     | 1.38            | 3.81  | 0.16     | 0.12                 | 0.23                 | 1.60       | 1.28                | 1.93                 | 50.64               | 51  | ...        | c-stat | Chandra   |
| J0439–0520     | 8.92            | 19.87 | 0.76     | 0.72                 | 0.79                 | 2.20       | 2.11                | 2.29                 | 77.67               | 52  | –0.85      | chi   | Chandra   |
| J0730–4049     | 6.21            | 19.81 | 0.18     | 0.15                 | 0.20                 | 1.36       | 1.18                | 1.55                 | 109.72              | 150 | ...        | c-stat | Chandra   |
| J0825+6157     | 3.82            | 18.95 | 1.50     | 1.43                 | 1.58                 | 1.50       | 1.44                | 1.56                 | 88.78               | 80  | –0.41      | chi   | Chandra   |
| J0939–4141     | 1.16            | 7.09  | 0.30     | 0.26                 | 0.35                 | 1.70       | 1.52                | 1.90                 | 5.55                | 10  | –0.36      | chi   | Chandra   |
| J1058+1951     | 1.69            | 149.90| 2.29     | 2.27                 | 2.33                 | 1.65       | 1.63                | 1.66                 | 478.85              | 346 | –2.13      | chi   | Chandra   |
| J1110–4403     | 1.30            | 8.45  | 0.21     | 0.18                 | 0.25                 | 1.35       | 1.19                | 1.51                 | 22.30               | 26  | –0.97      | chi   | XMM      |
| J1146–2447     | 4.61            | 4.96  | 0.41     | 0.35                 | 0.48                 | 1.58       | 1.41                | 1.75                 | 129.61              | 128 | ...        | c-stat | Chandra   |
| J1430+3649     | 1.04            | 3.93  | 0.32     | 0.27                 | 0.38                 | 1.70       | 1.49                | 1.91                 | 79.56               | 59  | ...        | c-stat | Chandra   |
| J1431+3952     | 1.09            | 2.86  | 1.79     | 1.64                 | 1.99                 | 1.57       | 1.46                | 1.69                 | 209.18              | 207 | ...        | c-stat | Chandra   |
| J1727+5510     | 2.72            | 34.61 | 0.60     | 0.57                 | 0.65                 | 1.58       | 1.48                | 1.67                 | 46.50               | 49  | –0.15      | chi   | Chandra   |
| J2003–3251     | 7.13            | 13.21 | 0.78     | 0.75                 | 0.82                 | 1.67       | 1.62                | 1.72                 | 121.93              | 141 | –0.17      | chi   | XMM      |
| J2354–1513     | 2.53            | 16.13 | 1.12     | 1.08                 | 1.16                 | 1.54       | 1.50                | 1.57                 | 207.26              | 211 | –0.16      | chi   | XMM      |

Note. The symbols have the same meanings as given in Table 2. The last column refers to the name of the telescope from which the X-ray measurement has been taken. It should be noted that an absorbed power-law model is preferable for all sources.

Figure 4. The distribution of the observed 0.3–10 keV X-ray flux (left) and photon index (right) for the \( \gamma \)-ray loud and \( \gamma \)-ray quiet blazars. We show the results only for those sources whose X-ray spectra are fitted with an absorbed power-law model, for an equal comparison. See the text for details.
Jet powers: We estimate the jet power carried by electrons ($P_{\text{ele}}$), Poynting flux ($P_{\text{mag}}$), radiation ($P_{\text{rad}}$), and protons ($P_{\text{kin}}$) as follows (Celotti & Ghisellini 2008):

$$P_k = 2\pi R_{\text{size}}^2 \Gamma^2 \beta_k U'_{\text{k}},$$

where the factor of 2 accounts for two-sided jets and $R_{\text{size}}$ is the size of the emission region. Here, $U'_{\text{k}}$ represents the comoving frame energy density of the magnetic field ($k = \text{mag}$), relativistic electrons ($k = \text{ele}$), and cold protons ($k = \text{kin}$), and can be estimated using the following equations:

$$U'_{\text{mag}} = B^2 / 8\pi,$$

$$U'_{\text{ele}} = m_e c^2 \int S(\gamma) \gamma d\gamma,$$

$$U'_{\text{kin}} = m_p c^2 \int S(\gamma) d\gamma,$$

where $B$ is the magnetic field and $m_e$, $m_p$ are the electron and proton masses, respectively. The radiative power is derived as follows (Ghisellini et al. 2014):

$$P_{\text{rad, ele}} = 2 \frac{4\Gamma^2}{3^4} L_{\text{bol}},$$

$$P_{\text{rad, syn/SSC}} = 2 \frac{16\Gamma^4}{5^6} L_{\text{bol}},$$

where $L_{\text{bol}}$ is the bolometric jet luminosity in the observed frame and the factor of 2 accounts for the two-sided jet. To calculate the kinetic power of the jet, we assume an equal number density of electrons and cold protons (e.g., Celotti & Ghisellini 2008).

Black hole mass and the disk luminosity: Two crucial parameters in the blazar SED modeling, particularly in FSRQs, are $M_{\text{BH}}$ and $L_{\text{disk}}$. In general, these can be constrained either from single-epoch optical spectroscopy (assuming a virialized BLR, e.g., Shaw et al. 2012) or from fitting the big blue bump at optical-UV energies via the standard Shakura & Sunyaev (1973) disk model (Calderone et al. 2013; Castignani et al. 2013). There are uncertainties associated with both approaches, e.g., the typical errors in the virial spectroscopic black hole mass calculation is ~0.4 dex (Vestergaard & Peterson 2006; Shen et al. 2011) and the disk-fitting method does not take the jet emission into account. However, when there is a sufficient coverage at optical-UV energies and the big blue bump is visible, the uncertainty in the disk-fitting method is quite small (a factor of ~2, Calderone et al. 2013). Both approaches have been thoroughly discussed in Ghisellini & Tavecchio (2015), so we refer an interested reader to this article for details.

We adopt the following steps to determine $M_{\text{BH}}$ and $L_{\text{disk}}$ for CGRABS blazars.

1. Whenever we find a big blue bump at IR-UV energies, we reproduce it with a standard accretion disk model and derive both $M_{\text{BH}}$ and $L_{\text{disk}}$. We are able to apply this method to 178 $\gamma$-ray loud and 176 $\gamma$-ray quiet blazars. They are flagged with the keyword “D” in Tables 5 and 6.

2. If the bump is not observed or there are insufficient data points at optical-UV energies, we search in the literature for availability of the optical spectrum (Shen et al. 2011; Shaw et al. 2012; Torrealba et al. 2012). Using the broad emission line ($H_{\beta}$, Mg II, and C IV) information and the empirical relations of Shen et al. (2011), we determine the mass of the black hole. From the line luminosities, we compute the BLR luminosity by following the scaling relations of Francis et al. (1991) and Celotti et al. (1997). Under the assumption that the BLR reprocesses 10% of $L_{\text{disk}}$, we derive the luminosity of the accretion disk. For parameters for more than one line are known, we take the geometric mean of the derived quantities. For 50 $\gamma$-ray loud and 5 $\gamma$-ray quiet sources, we determine their $M_{\text{BH}}$ and $L_{\text{disk}}$ via optical spectroscopic measurements. In Tables 5 and 6, they are flagged with the keyword “O.”

3. When the bump is not visible at optical-UV wavelengths and optical spectral information is also unavailable, we adopt an empirical relation between the $\gamma$-ray luminosity and the BLR luminosity, as suggested by Sbarrato et al. (2012). It is found that the $\gamma$-ray luminosity is a good tracer of the BLR luminosity and the following empirical relation holds (albeit with a large scatter, Sbarrato et al. 2012)

$$L_{\text{BLR}} \sim 4L_{\gamma}^{0.93},$$

where $L_{\text{BLR}}$ is the BLR luminosity. We then derive $L_{\text{disk}}$ from our knowledge of the BLR luminosity. In such sources, we assume a typical $M_{\text{BH}}$ of $5 \times 10^8 M_\odot$. We compute $L_{\text{disk}}$ in 83 $\gamma$-ray loud blazars using the empirical method. These objects are flagged with “E” in Table 5.

4. For $\gamma$-ray quiet blazars, the previous method could not be used due to lack of $\gamma$-ray information. In such sources, we assume an appropriate value of $L_{\text{disk}}$ while keeping in mind not to overproduce the observations (i.e., about a factor $\sim 10$–20 below the optical-UV data points, e.g., Ghisellini et al. 2010) and also to maintain sub-Eddington $L_{\text{disk}}$ and adopt $M_{\text{BH}} = 5 \times 10^8 M_\odot$. In 10 $\gamma$-ray quiet blazars (i.e., $<2\%$ of the sample size), this approach is adopted to estimate $L_{\text{disk}}$. These objects can be identified with the flag “A” in Table 6.

SED modeling guidelines: Our SED modeling code does not perform a statistical fitting. We merely reproduce the observations following a “fit-by-eye” approach. Once we have information about the $L_{\text{disk}}$ and $M_{\text{BH}}$, as described above, there are eight free parameters in the modeling: $p$, $q$, $B$, $R_{\text{disk}}$, $\Gamma$, $S_0$, $\gamma_b$, and $\gamma_{\text{max}}$. The size of the emission region is constrained from $R_{\text{disk}}$. Along with this, the following parameters are kept fixed: $\psi$, $\theta_\ast$, $\gamma_{\text{min}}$, $T_{\text{torus}}$, and $f_{\text{BLR/torus/cor}}$ (with rare exceptions). Though our modeling program does not compute uncertainties in the physical parameters, the SED parameters can be fairly well-constrained from the observations (e.g., Tavecchio et al. 1998), depending on the quality of the MW data. Below, we briefly elaborate our adopted choices to constrain the free parameters from the observations.

The leptonic model used here fails to reproduce the low-frequency (sub-mm to radio) data due to self-absorption of the synchrotron emission. In the low-synchrotron peaked objects, however, radio observations provide a clue about the typical flux level of the synchrotron radiation. For many sources, the synchrotron peak lies in the self-absorbed regime. In these objects, the synchrotron peak is the self-absorption frequency. Moreover, the measurement of $L_{\text{disk}}$, either from the disk modeling or the spectroscopic line measurements, regulates the size of the BLR and the torus—and hence the corresponding radiative energy densities of these components within $R_{\text{BLR}}$ and $R_{\text{torus}}$, respectively.
Table 5

| Name        | \(z\) | \(\theta_e\) (\(\cdot\)) | \(M_{BH}\) | Type | \(L_{\text{disk}}\) | \(R_{\text{diss}}\) | \(R_{\text{BLR}}\) | \(\delta\) | \(\Gamma\) | \(B\) | \(p\) | \(q\) | \(\gamma_{\text{min}}\) | \(\gamma_{\text{h}}\) | \(\gamma_{\text{max}}\) | \(U_1\) | CD | 
|-------------|-------|----------------------|--------|------|---------------|----------------|-------------|--------|----------|----------|--------|--------|----------------|-------------|----------------|--------|-----| 
| J0004−4736  | 0.88  | 3.0                  | 8.00   | O    | 45.11        | 0.027           | 0.037        | 15.7   | 10       | 6.4      | 1.6    | 3.9    | 115            | 3000         | −1.02          | 1.6    |     | 
| J0005−3820  | 0.23  | 3.0                  | 8.70   | E    | 43.76        | 0.033           | 0.008        | 18.6   | 15       | 0.4      | 2.2    | 3.8    | 9               | 543          | 5000           | −1.19  | 7.2 | 
| J0011−0057  | 1.49  | 3.0                  | 8.78   | D    | 45.48        | 0.037           | 0.056        | 16.5   | 11       | 1.6      | 1.8    | 3.8    | 1               | 100          | 3000           | −1.10  | 30.9| 
| J0106−0015  | 1.58  | 3.0                  | 8.87   | O    | 45.93        | 0.064           | 0.094        | 17.2   | 12       | 2.2      | 1.8    | 4.4    | 120             | 3000         | −1.29          | 20.3   |     | 
| J0117−0512  | 0.23  | 3.0                  | 7.90   | D    | 44.79        | 0.004           | 0.025        | 15.7   | 10       | 4.0      | 1.6    | 4.2    | 10              | 83           | 2000           | 0.51   | 4.8 | 

Note. The column contents are as follows: Columns (1) and (2): name and redshift of the source; Column (3): viewing angle, in degrees; Column (4): log scale black hole mass, in solar mass units; Column (5): adopted method to derive \(M_{BH}\) and \(L_{\text{disk}}\); A: assumed; D: disk fitting, E: empirical relation, O: optical spectroscopy, and N: not used (see Table 9); Column (6): log scale accretion disk luminosity, in erg s\(^{-1}\); Column (7): dissipation distance, in parsec; Columns (9) and (10): the Doppler factor and the bulk Lorentz factor, respectively; Columns (11): magnetic field strength, in Gauss; Columns (12) and (13): spectral slopes of the broken power-law electron distribution before and after the break energy \(\gamma_{\text{b}}\), respectively; Columns (14)–(16): the minimum, break, and maximum Lorentz factors of the emitting electron distribution; Column (17): the log scale particle energy density, in erg cm\(^{-3}\); and Column (18): Compton dominance. (This table is available in its entirety in machine-readable form.)

Table 6

| Name         | \(z\) | \(\theta_e\) (\(\cdot\)) | \(M_{BH}\) | Type | \(L_{\text{disk}}\) | \(R_{\text{diss}}\) | \(R_{\text{BLR}}\) | \(\delta\) | \(\Gamma\) | \(B\) | \(p\) | \(q\) | \(\gamma_{\text{min}}\) | \(\gamma_{\text{h}}\) | \(\gamma_{\text{max}}\) | \(U_1\) | CD | 
|--------------|-------|----------------------|--------|------|---------------|----------------|-------------|--------|----------|----------|--------|--------|----------------|-------------|----------------|--------|-----| 
| J0001+1914   | 3.10  | 3.0                  | 8.70   | A    | 45.00        | 0.038           | 0.032        | 17.2   | 12       | 2.7      | 2.0    | 3.6    | 2               | 177          | 4000           | −0.83  | 2.5 | 
| J0004−2019   | 0.68  | 3.0                  | 8.70   | A    | 44.00        | 0.012           | 0.010        | 14.8   | 9        | 2.5      | 2.1    | 3.6    | 1               | 38           | 4000           | 0.51   | 2.4 | 
| J0004−4615   | 1.81  | 3.0                  | 8.70   | A    | 45.00        | 0.041           | 0.032        | 16.5   | 11       | 2.1      | 1.9    | 3.6    | 2               | 53           | 4000           | −0.56  | 2.2 | 
| J0006−0623   | 0.35  | 3.0                  | 8.70   | A    | 44.00        | 0.029           | 0.010        | 14.7   | 9        | 1.5      | 1.7    | 3.8    | 20              | 467          | 3000           | −1.00  | 0.2 | 
| J0008−2339   | 1.41  | 3.0                  | 9.30   | D    | 47.00        | 0.880           | 0.323        | 15.7   | 10       | 0.2      | 1.6    | 3.8    | 1               | 234          | 3000           | −3.00  | 13.0| 

Note. The column contents are the same as in Table 5. (This table is available in its entirety in machine-readable form.)

In powerful \(\gamma\)-ray loud blazars, the shape of the \(\gamma\)-ray spectrum directly constrains the high-energy slope of the underlying broken power-law electron energy distribution (EED) \((q)\). This slope in turn controls the slope of the high-energy tail of the synchrotron component. The lack of \(\gamma\)-ray information for the \(\gamma\)-ray quiet blazars hampers the determination of \(q\). Because a majority of these sources have disk-dominated optical-UV SEDs, it is also not possible to constrain \(q\) from the synchrotron process. However, the Fermi-LAT sensitivity limits (shown with black stars in Figure 5) provide us a hint that \(q\) has to be steep to avoid the Fermi-LAT detection threshold. In FSRQs, the low-energy slope \(p\) can be constrained from the X-ray observations. In high-synchrotron-peaked (HSP) blazars, however, the X-ray spectrum exhibits a steep falling shape that originates from the high-energy tail of the synchrotron component. In such objects, the \(\gamma\)-ray spectrum has a rising shape \((\Gamma_\gamma < 2)\), and that slope can be used to get an estimation of \(p\).

A rising X-ray spectrum (photon index at 0.3–10 keV \(\lesssim 1.5–1.6\)) in FSRQs hints at a prevailing EC mechanism instead of the SSC process. This is because, in these two processes, not only are the seed photons for IC scattering different, the participating electrons are also of very different energies. In the EC-dominated scenario, the X-ray spectrum originates from the low-energy electron population, whereas relatively high-energy electrons lying close to the peak of the distribution contribute to the observed soft X-ray spectrum via the SSC mechanism (see also, a detailed discussion in Ajello et al. 2016). In other words, a flat X-ray spectrum demands the (softer) SSC component to lie below the observations. This regulates the size of the emission region and the magnetic field. An increase in the magnetic field decreases both the SSC and the EC fluxes for a given flux level of the synchrotron emission. This is due to the fact that, with increasing magnetic field, fewer electrons are required to produce the same synchrotron flux. Furthermore, we can also fine-tune the bulk Lorentz factor \(\Gamma\) from the X-ray and \(\gamma\)-ray SEDs. For larger \(\Gamma\), or the Doppler factor \(\delta\), fewer electrons are required to make the same flux level of the synchrotron radiation, thus decreasing the synchrotron photon energy density and therefore lowering the SSC flux. However, because the external photon energy densities becomes larger, an increase in \(\delta\) leads to the enhancement of the EC flux (Dermer et al. 2009; Ghisellini & Tavecchio 2009).

The Compton dominance (CD), which is the ratio of the high-to-low energy SED peak luminosities, provides us information about the relative prevalence of the external radiation energy densities compared to the magnetic energy density. Because both energy densities, in our model, are a function of \(R_{\text{diss}}\) (see also, Ghisellini & Tavecchio 2009; Sikora et al. 2009) we can derive the location of the emission region from the observed CD. A large CD \((>1)\) indicates the dominance of the external photon field, originating from the BLR/torus, and thus suggests the emission region lies either inside the BLR or outside it but still inside the torus. Another constraint comes from the observation of the fast flux variability from many blazars, indicating a compact emission region, which in turn demands that the emission region lies closer to the central black hole (cf. Narayan & Piran 2012; Marscher 2014, for alternative arguments). On the other hand, the EC-torus-dominated SED has a comparatively lower CD than...
the EC-BLR-dominant SED. The high-energy peak located at lower frequencies (~MeV energies) also indicates that the emission region is located outside the BLR but inside the torus, because a low IC peak probably hints at a smaller characteristic frequency of the seed photons participating in the EC process. A precise determination of CD in γ-ray quiet blazars is rather difficult due to lack of a γ-ray spectrum. However, along with the shape and flux level of the soft X-ray spectrum, the Fermi-LAT sensitivity limit constrains it reasonably well. Whenever the hard X-ray observations are available (see, e.g., Figure 5), CD is even further constrained.

6. Physical Characteristics

The broadband emissions of both γ-ray quiet and γ-ray loud blazars are reproduced using the simple one-zone leptonic emission model described in Section 5. In Figures 5 and 6, respectively, we show the modeled SEDs of these two populations. The parameters associated with the SED modeling are given in Tables 5 and 6. We provide the derived jet powers in Tables 7 and 8. The SEDs of 13 γ-ray loud blazars (see Table 9) are reproduced well using synchrotron and SSC emission mechanisms, i.e., without invoking the EC process. All of them are HSP BL Lac objects with synchrotron-dominated SEDs, and they are characterized by featureless optical spectra (e.g., Falomo & Treves 1990; Marcha et al. 1996). Because these objects are modeled without needing the information about $L_{\text{disk}}$ and $M_{\text{BH}}$, we do not consider them when we discuss the physical properties of the γ-ray loud blazars associated with $L_{\text{disk}}$ and $M_{\text{BH}}$.

6.1. Black Hole Mass and the Accretion Disk Luminosity

In the top panel of Figure 7, we compare $M_{\text{BH}}$ and $L_{\text{disk}}$ for the γ-ray loud (red) and the γ-ray quiet (blue) blazars. For $M_{\text{BH}}$...
distributions, we have considered only those objects whose black hole masses are measured either from the optical spectrum or from the disk-fitting method, as explained in the previous section. The fitted distribution peaks at $\log M_{\text{BH}} = 9.0$ and $8.1$, for the $\gamma$-ray quiet and the $\gamma$-ray loud objects, respectively. The fact that the $\gamma$-ray quiet blazars host slightly more massive (~2.5σ significance) black holes compared to $\gamma$-ray loud sources can be explained by noting that they are located at larger redshifts (Figure 1), possibly a selection effect of detecting only the heaviest black holes at high redshifts. On the other hand, the accretion disk luminosities in the $\gamma$-ray loud and quiet blazars show a similar distribution and peak around 10% of the Eddington luminosity ($L_{\text{Edd}}$). This implies that, in absolute units (i.e., in erg s$^{-1}$), $\gamma$-ray quiet objects host more luminous accretion disks compared to $\gamma$-ray loud blazars.

In our sample, there are a total of 138 blazars (86 $\gamma$-ray loud and 52 $\gamma$-ray quiet) that have $M_{\text{BH}}$ and $L_{\text{disk}}$ measurements from both the disk-fitting and optical spectroscopy methods. Therefore, it is interesting to check the consistency of the results derived from these two different approaches. In the bottom panel of Figure 7, we plot $M_{\text{BH}}$ and $L_{\text{disk}}/L_{\text{Edd}}$ distributions estimated from the optical spectroscopic (black) and disk-fitting (red) techniques. The $M_{\text{BH}}$ computed from the disk-fitting matches well with the virial measurements ($\langle M_{\text{BH}} \rangle = 1 \times 10^9 M_\odot$ for both). Fitting the distribution with a log-normal function returns a dispersion of 0.4 dex for the
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6.2. The Particle Distribution

The average properties of the EED can be seen in the top left and middle panels of Figure 9. For both γ-ray loud and γ-ray quiet blazars, the low- and high-energy spectral indices of the EED (\(\langle p \rangle = 1.8, 1.7 \) and \(\langle q \rangle = 3.8, 4.3\)) respectively have a narrow distribution. In powerful FSRQs, the synchrotron peak is typically located at radio to sub-mm frequencies, and due to synchrotron self-absorption, it is impossible to characterize the spectral shape of the underlying EED from the synchrotron emission alone. In such blazars, the EED can be constrained using X-ray and γ-ray data, which in (the EC scenario) constrain the spectral shapes of the low- and high-energy electron population, respectively. The availability of the Swift-BAT or the NuSTAR data for a few sources also helps in putting further constraints on the low-energy index \(p\). Note that \(p\) regulates the total number of radiating electrons that are present in the emission region, and therefore the total number of protons, which controls the kinetic power of the jet. On the other hand, the distribution of the high-energy index \(q\) shows a clear bimodality, with the high-energy electron population of the γ-ray loud blazars exhibiting a relatively hard spectrum compared to the γ-ray quiet objects. This can be understood in terms of the non-detection of the γ-ray quiet sources in the γ-ray band. In such sources, a steep falling EC spectrum is necessary to avoid the detection limit of the Fermi-LAT (see, e.g., Figure 5). The shape of the optical-UV spectrum can also provide a good constraint to \(q\) if it is synchrotron-dominated. However, out of 191 γ-ray quiet blazars, we find an accretion-disk-dominated optical-UV SED in 176 sources, implying \(q\) is rather unconstrained from the synchrotron emission.

We show the distribution of the break (\(\gamma_b\)) and maximum Lorentz factors (\(\gamma_{\text{max}}\)) of the EED in the top right and middle left panels of Figure 9, respectively. In both plots, the distribution of the γ-ray quiet blazars is relatively low-peaked (\(\langle \gamma_b \rangle \sim 56\) and \(\langle \gamma_{\text{max}} \rangle \sim 2000\)) and has narrower dispersion when fitted with a log-normal function. The wider distributions for the γ-ray loud blazars are probably due to the presence of a few HSP BL Lac objects such as J1653+3945 (or Mrk 501). These sources have their synchrotron peak located at very high frequencies (>10^{16} Hz), thus implying that the peak of the underlying EED, i.e., \(\gamma_b\), has a large value. Furthermore, \(\gamma_{\text{max}}\) is rather insensitive to the modeling for the steeply falling γ-ray spectrum FSRQs. However, a hard-rising γ-ray spectrum in HSP sources indicates a large \(\gamma_{\text{max}}\). This is the reason that the distribution of \(\gamma_{\text{max}}\) for the γ-ray loud population extends to very large values and accordingly is centered at a larger \(\gamma_{\text{max}}\) of ~4000 (Figure 9).

6.3. Magnetic Field and the Location of the Emission Region

The distribution of the magnetic field for the γ-ray loud blazars peaks around \(\langle B \rangle = 2.0\) Gauss, whereas it is centered at a low value of 1.5 Gauss for γ-ray quiet sources (see middle plot in the middle panel of Figure 9). Fitting them with a log-normal function returns a narrow width of 0.2 dex for both distributions.

The logarithmic distribution of the location of the emission region in absolute units (cm) peaks at \(R_{\text{diss}} = 2.5 \times 10^{17}\) cm and \(3.5 \times 10^{17}\) cm for the γ-ray loud and γ-ray quiet blazars, respectively (middle right panel of Figure 9). Fitting the distributions with a log-normal function gives an equal dispersion of 0.4 dex for both of them. On the other hand, considering the dissipation distance in units of \(R_{\text{sch}}\), we find no difference in the distributions of γ-ray loud and γ-ray quiet sources. On average, the emission region is found to be located inside the BLR for a majority of sources.
6.4. Doppler and the Bulk Lorentz Factors

The distributions of $\delta$ and $\Gamma$ are shown in the bottom middle and right panels of Figure 9. On average, the $\gamma$-ray loud blazars exhibit a larger $\delta$ and $\Gamma$ ($\langle\delta\rangle = 17.2$, $\langle\Gamma\rangle = 12$) compared to the $\gamma$-ray quiet blazars ($\langle\delta\rangle = 15.7$, $\langle\Gamma\rangle = 10$). Recently, based on the radio study of 1.5 Jy MOJAVE AGNs, Lister et al. (2015) have reported that the $\gamma$-ray detected blazars have significantly larger Doppler boosting factors compared to sources not detected by Fermi-LAT (see also, Savolainen et al. 2010, and references therein, for earlier results). The similarity of the results derived from two different approaches, from the SED modeling and the 15 GHz radio measurements, is rather striking. We emphasize here that the lower $\delta$ of the $\gamma$-ray quiet blazars may not be due to a large $\theta_0$ or misalignment of the jet (see also, Meyer et al. 2011). It is primarily due to small $\Gamma$ and can be explained as follows. In a majority of the FSRQs studied here, the X-ray to $\gamma$-ray SEDs are explained by the EC process (e.g., Figures 5 and 6). The EC mechanism has a stronger dependence on $\theta_0$, and due to anisotropy of the external radiation field in the comoving frame of the emission region, it has an additional boosting (Dermer 1995). A hard-rising EC emission at X-rays indicates a small $\theta_0$ and vice-versa. In other words, the X-ray spectrum in EC-dominated blazars can be used as a tool to determine $\theta_0$ (e.g.,
Sbarrato et al. (2013). We find the X-ray spectral shapes of both the γ-ray loud and the γ-ray quiet blazars to be similar (Figure 4), thus indicating a similar $\theta_\gamma$, which is further confirmed from the SED modeling (Tables 5 and 6).

6.5. Jet Powers

Figure 10 represents the distributions of various jet powers considering two-sided jets. In the bottom panel, we also show the distribution of $L_{\text{disk}}$ for a comparison with the jet power. The histograms are fitted with a log-normal function and the corresponding widths are quoted. The average values of the distributions for the γ-ray loud and the γ-ray quiet blazars, respectively, are as follows: $\langle \log P_{\text{ele}} \rangle = 44.76, 44.65$, $\langle \log P_{\text{mag}} \rangle = 45.48, 45.38$, $\langle \log P_{\text{rad}} \rangle = 45.99, 45.33$, $\langle \log P_{\text{kin}} \rangle = 47.15, 47.10$, and $\langle \log L_{\text{disk}} \rangle = 45.85, 46.23$. All units are in erg s$^{-1}$.

Figure 11. The fraction of the total jet power transformed into radiation ($\epsilon_{\text{rad}}$, top), relativistic electrons ($\epsilon_{\text{ele}}$, middle), and Poynting flux ($\epsilon_{\text{mag}}$, bottom). The Astrophysical Journal, 851:33 (23pp), 2017 December 10 Paliya et al.

Figure 10. Distributions of various jet powers considering two-sided jets. In the bottom panel, we also show the distribution of $L_{\text{disk}}$ for a comparison with the jet power. The histograms are fitted with a log-normal function and the corresponding widths are quoted. The average values of the distributions for the γ-ray loud and the γ-ray quiet blazars, respectively, are as follows: $\langle \log P_{\text{ele}} \rangle = 44.76, 44.65$, $\langle \log P_{\text{mag}} \rangle = 45.48, 45.38$, $\langle \log P_{\text{rad}} \rangle = 45.99, 45.33$, $\langle \log P_{\text{kin}} \rangle = 47.15, 47.10$, and $\langle \log L_{\text{disk}} \rangle = 45.85, 46.23$. All units are in erg s$^{-1}$.

Sbarrato et al. (2013). We find the X-ray spectral shapes of both the γ-ray loud and the γ-ray quiet blazars to be similar (Figure 4), thus indicating a similar $\theta_\gamma$, which is further confirmed from the SED modeling (Tables 5 and 6).

6.5. Jet Powers

Figure 10 represents the distributions of various jet powers. As can be seen, the γ-ray loud and the γ-ray quiet blazars share a similar distribution of the power carried by relativistic electrons, Poynting flux, and cold protons. However, the γ-ray loud sources exhibit a larger $P_{\text{rad}}$ compared to the γ-ray quiet objects. This is probably due to γ-ray emitting jets being more radiatively efficient. Also, $P_{\text{ele}}$ is substantially less than $P_{\text{rad}}$. This is the direct consequence of the rapid cooling of electrons in a time substantially smaller than the light crossing time of the emission region, so that more power is released in the form of radiation than remains in electrons. The fact that $P_{\text{mag}}$ is slightly lower than $P_{\text{rad}}$ indicates that the magnetic field alone is not responsible for the observed radiation. This leaves us to consider $P_{\text{kin}}$ as a plausible reservoir for $P_{\text{rad}}$. In fact, most of the jet power remains in the form of dynamically dominant protons that produce the large-scale radio structures. Only a small fraction ($\sim 1\%–10\%$, see also the top panel of Figure 11) of it gets converted to radiation. We have assumed an equal number density of electrons and cold protons. This assumption is crucial and often leads the total jet power in powerful FSRQs to exceed $L_{\text{Edd}}$ (e.g., Ghisellini et al. 2014). Considering the presence of the electron-positron pairs would reduce the budget of the jet power (see, e.g., Madejski et al. 2016; Pjanka et al. 2017); however, their number cannot be large (≤ 10–15 pairs per proton, e.g., Sikora & Madejski 2000; Celotti & Ghisellini 2008), in order to avoid the Compton rocket effect (Odell 1981). If present in a substantial fraction, these pairs would produce a large amount of soft X-radiation (the so-called “Sikora bump”), which is yet to be observed. Alternatively, instead of a uniform one-zone emission, if one considers the broadband emission to originate from a spine-sheath structured jet, the total power of the jet will come down (Sikora et al. 2016). Moreover, as can be seen in Figure 10, $P_{\text{mag}}$ is tiny compared to $P_{\text{kin}}$ and hints at a weak magnetization of the emission region. These observations, therefore, argue against the Poynting-flux-dominated scenario (e.g., McKinney et al. 2012, but see also, Nalewajko et al. 2014; Janiak et al. 2015; Zdziarski et al. 2015).
In Figure 11, we show the fraction of the total jet power \( P_{\text{jet}} = P_{\text{ele}} + P_{\text{mag}} + P_{\text{kin}} \) converted to radiation \( (\epsilon_{\text{rad}}) \), carried by relativistic electrons \( (\epsilon_{\text{ele}}) \) and magnetic field \( (\epsilon_{\text{mag}}) \). It can be seen in the top panel of this plot that there are a few low-power blazars that have \( \epsilon_{\text{rad}} \gtrsim 1 \). These are primarily BL Lac objects that are known to exhibit \( P_{\text{rad}} \sim P_{\text{kin}} \). In these sources, almost all of the available jet power is used to produce the radiation (see, Ghisellini et al. 2010, for a relevant discussion).

### 7. Discussion

By applying a simple leptonic emission model, we are able to study a few fundamental physical properties of blazars, which are briefly discussed in the following subsections. In order to determine the strength of the correlations, we compute the Spearman’s rank-correlation coefficient \( (\rho) \) and the probability of no correlation, PNC. Because we do not have error estimation for the derived SED parameters, we quantify the strength of the correlation by performing a Monte Carlo simulation following a bootstrapping approach that takes into account the dispersion of the plotted quantities. We create \( 10^4 \) data sets, each consisting of \( N \) data pairs \( (\xi, \eta) \) and compute \( \rho_0 \) and PNC for each data set. A pair \( (\xi, \eta) \) is randomly chosen from the original data set such that some of the original pairs may appear more than once in a given data set or not at all. Assuming that the returned values follow a Gaussian distribution, we estimate the correlation coefficient and the \( 1\sigma \) uncertainty by deriving the average and the standard deviation of the calculated values. Quoted PNC values are the average of the calculated PNC in each simulation. Note that it can be argued that the observed correlations could be due to intrinsic correlations of the input SED parameters. However, in our work, the chosen modeling parameters are independent and constrained only by the observations, thus supporting the connection of the observed correlations with the physical behavior of the sources.

In various correlation plots, the reported average errors are \( 1\sigma \) standard deviation of the plotted parameters for the whole population, i.e., including both \( \gamma \)-ray loud and \( \gamma \)-ray quiet blazars, unless specified.

#### 7.1. Accretion-jet Connection in Blazars

There is evidence for a positive correlation between the jet power and the accretion luminosity in jetted AGNs (e.g., Rawlings & Saunders 1991). More importantly, it has been claimed, both from theoretical and observational arguments, that the former exceeds the latter (Celotti & Ghisellini 2008; Tchekhovskoy et al. 2011; Ghisellini et al. 2014). We test these hypotheses on CGRaBS quasars.

In the top panel of Figure 12, we show the variation of \( P_{\text{rad}} \) as a function of \( L_{\text{disk}} \). The results of the correlation analysis are provided in Table 10. Overall, we find a strong positive correlation \( (\rho_0 = 0.63 \pm 0.03, \ PNC < 1 \times 10^{-5}) \), which remains valid if we consider the \( \gamma \)-ray loud and the \( \gamma \)-ray quiet blazar populations separately (Table 10). However, because both \( L_{\text{disk}} \) and \( P_{\text{rad}} \) depend on redshift, we also perform a partial correlation test by following the prescriptions of Padovani (1992). Even after excluding the common redshift dependence, both \( L_{\text{disk}} \) and \( P_{\text{rad}} \) still correlate, although the significance becomes a bit weaker \( (\rho_{\text{par}} = 0.19 \pm 0.08, \ PNC < 1 \times 10^{-5}) \). Interestingly, a major fraction of the \( \gamma \)-ray loud blazars lie above the best fit (black dashed line) and almost all of the \( \gamma \)-ray quiet objects occupy the low \( P_{\text{rad}} \) regime, except for a few sources. This is probably due to the fact that the \( \gamma \)-ray loud blazars are more radiatively efficient than the \( \gamma \)-ray quiet blazars, although they share a similar range of \( L_{\text{disk}} \).

We show the variation of the total jet power, \( P_{\text{jet}} \), as a function of the total available accretion power \( (M \dot{c}^2) \) in the bottom panel of Figure 12. Note that, for a maximally rotating black hole, the efficiency of accretion is \( \eta_{\text{acc}} = 0.3 \) (Thorne 1974) and we have \( M \dot{c}^2 = L_{\text{disk}}/\eta_{\text{acc}} \). The results of the correlation analysis suggest...
a strong positive correlation, which remains valid even after removing the common redshift dependence (Table 10). Therefore, we confirm the earlier findings about the accretion-jet connection, considering both γ-ray loud and γ-ray quiet blazar populations. However, comparing our results with the ones derived by Ghisellini et al. (2014), we make an interesting observation. In our sample, there are many γ-ray quiet blazars that have larger $L_{\text{disk}}$ but host a relatively moderate power jet. As can be seen in Figure 12, almost all γ-ray loud blazars lie above the one-to-one correlation (pink solid line) but there are many γ-ray quiet blazars that are located below. Accordingly, the slope of the best-fitted line in our case is softer. In other words, it is probably true that the jet power exceeds the accretion power the γ-ray loud sources; however, we may see a deviation from this trend when considering a larger γ-ray quiet blazar population.

7.2. Black Hole Mass Dependence

In Figure 13, we show the redshift dependence of $M_{\text{BH}}$ derived in this work. Note that we consider only those objects whose $M_{\text{BH}}$ are computed either from the disk-fitting or optical spectroscopic methods. For a comparison, we also show $M_{\text{BH}}$ values for SDSS quasars as reported in Kozłowski (2017). The accretion luminosity $L_{\text{disk}}$ (top right), the total jet power $P_{\text{jet}}$ (bottom left), and the Compton dominance (bottom right) are shown as a function of the derived black hole masses. In all of the plots, the black dashed line is the best fit. The quoted uncertainty in the black hole mass is a factor of 3, which is the average of that typically reported for the disk-fitting and virial estimation methods (e.g., Vestergaard & Peterson 2006; Castignani et al. 2013).

Figure 13. Top left: the redshift dependence of $M_{\text{BH}}$ for the γ-ray loud (red) and the γ-ray quiet blazars (blue). The gray dots correspond to SDSS quasars (Kozłowski 2017). The accretion luminosity $L_{\text{disk}}$ (top right), the total jet power $P_{\text{jet}}$ (bottom left), and the Compton dominance (bottom right) are shown as a function of the derived black hole masses. In all of the plots, the black dashed line is the best fit. The quoted uncertainty in the black hole mass is a factor of 3, which is the average of that typically reported for the disk-fitting and virial estimation methods (e.g., Vestergaard & Peterson 2006; Castignani et al. 2013).
Table 10  
Results of the Correlation Analysis

|        | $N$  | $\rho_s$ | $P_{\text{ps}}$ versus $L_{\text{disk}}$ | $P_{\text{ps}}$ versus $M_{\text{BH}}$ | $P_{\text{ps}}$ versus $\gamma_{\text{BH}}$ | $P_{\text{ps}}$ versus $\gamma_{\text{BH}}$ |
|--------|------|----------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| $\gamma$-ray loud | 311  | 0.66 ± 0.04 | $< 1 \times 10^{-5}$ | 0.22 ± 0.10 | $< 1 \times 10^{-5}$ | $< 1 \times 10^{-5}$ |
| $\gamma$-ray quiet | 191  | 0.67 ± 0.05 | $< 1 \times 10^{-5}$ | 0.29 ± 0.20 | $< 1 \times 10^{-5}$ | $< 1 \times 10^{-5}$ |
| All sources | 502  | 0.63 ± 0.03 | $< 1 \times 10^{-5}$ | 0.19 ± 0.08 | $< 1 \times 10^{-5}$ | $< 1 \times 10^{-5}$ |

$P_{\text{ps}}$ versus $M_{\text{BH}}$:

|        | $N$  | $\rho_s$ | $P_{\text{ps}}$ versus $M_{\text{BH}}$ | $P_{\text{ps}}$ versus $\gamma_{\text{BH}}$ |
|--------|------|----------|----------------------------------------|----------------------------------------|
| $\gamma$-ray loud | 311  | 0.67 ± 0.04 | $< 1 \times 10^{-5}$ | 0.53 ± 0.08 | $< 1 \times 10^{-5}$ |
| $\gamma$-ray quiet | 191  | 0.21 ± 0.08 | $5.0 \times 10^{-2}$ | 0.02 ± 0.13 | $6.5 \times 10^{-1}$ |
| All sources | 502  | 0.67 ± 0.03 | $< 1 \times 10^{-5}$ | 0.56 ± 0.06 | $< 1 \times 10^{-5}$ |

$P_{\text{ps}}$ versus $\gamma_{\text{BH}}$:

|        | $N$  | $\rho_s$ | $P_{\text{ps}}$ versus $\gamma_{\text{BH}}$ | $P_{\text{ps}}$ versus $L_{\text{disk}}$ |
|--------|------|----------|----------------------------------------|----------------------------------------|
| $\gamma$-ray loud | 311  | 0.51 ± 0.07 | $3.2 \times 10^{-3}$ | 0.22 ± 0.11 | $1 \times 10^{-4}$ |
| $\gamma$-ray quiet | 181  | 0.43 ± 0.08 | $1.8 \times 10^{-4}$ | 0.59 ± 0.11 | $< 1 \times 10^{-5}$ |
| All sources | 409  | 0.42 ± 0.05 | $< 1 \times 10^{-5}$ | 0.39 ± 0.06 | $< 1 \times 10^{-5}$ |

Note. Carried out by means of a Monte Carlo simulation performed on the sample of the $\gamma$-ray loud and $\gamma$-ray quiet blazars. Here, $N$ denotes the number of sources. Whenever applicable, we also provide the results associated with the partial correlation analysis. In this table, $\rho_s$ and $\rho_{\text{ps}}$ correspond to Spearman’s rank-correlation coefficients for a simple correlation and partial correlation test, respectively. The associated probabilities of no correlation are also given. We perform a semi-partial correlation test when one of the parameters is Compton dominance, a redshift-independent quantity. See the text for details.

PNC $< 1 \times 10^{-5}$), whereas $P_{\text{ps}}$ is very weakly correlated ($\rho_s = 0.17 \pm 0.09$, $\text{PNC} < 1 \times 10^{-5}$), considering the entire sample. We also find a positive correlation between CD and $M_{\text{BH}}$. However, because CD, being the ratio of two luminosities, is a redshift-independent quantity—whereas $M_{\text{BH}}$ is not—we adopt a semi-partial correlation analysis to exclude the redshift dependence of $M_{\text{BH}}$. The results of this exercise lead to the conclusion that CD does not correlate with $M_{\text{BH}}$ (see...
Although massive black-hole-hosted blazars are known to be Compton dominated (e.g., Paliya et al. 2016), our correlation analysis indicates that even blazars with low-mass black holes can also have a large CD ($>1$). The Fermi-LAT detected narrow-line Seyfert 1 galaxies (e.g., Yuan et al. 2008) are probably a good example of this (e.g., Paliya et al. 2013).

7.3. Blazar Sequence

There has been a long debate about the validity of the blazar sequence (Fossati et al. 1998), i.e., whether such a sequence has a physical origin (Ghisellini et al. 1998) or is just a selection bias (e.g., Giommi et al. 2012a). In the physical scheme, the rate of accretion onto the central compact object can explain the observed phenomena. A luminous disk implies an efficient accretion process ($L_{\text{disk}}/L_{\text{Edd}} \gtrsim 1 \times 10^{-2}$), which ionizes the BLR clouds resulting in the detection of the broad optical emission lines. Accordingly, the jet electrons interact with the dense photon field of the BLR via the EC mechanism before reaching high energies and producing luminous $\gamma$-ray emission, which makes the SEDs more Compton dominated and low-frequency peaked. On the other hand, in the low-accretion regime ($L_{\text{disk}}/L_{\text{Edd}} < 1 \times 10^{-5}$), the external radiation field becomes weaker and the SED is less Compton dominated. We test these hypotheses on our sample of CGRaBS quasars and show the results in Figure 14.

We find a significant anti-correlation between $L_{\text{disk}}$ (in Eddington units) and $\gamma_b$ ($\rho_b = -0.30 \pm 0.05$, PNC $< 1 \times 10^{-5}$). This suggests that an increase in $L_{\text{disk}}$ corresponds to a decrease in $\gamma_b$, i.e., the shift of the SED peaks to lower frequencies. Moreover, we also find that $L_{\text{disk}}$ and $R_{\text{diss}}$

**Figure 14.** Top: the variations of $\gamma_b$ (left) and the dissipation distance (right, in units of the BLR radius) as a function of the accretion luminosity (in Eddington units). The pink solid lines represent the inner and outer boundaries of the BLR. The emission region is located inside or close to the outside of the inner boundary of the BLR for objects with a large $L_{\text{disk}}$. Bottom: the Compton dominance as a function of $L_{\text{disk}}$ (left) and $P_{\text{jet}}$ (right). A significant positive correlation is found. In all plots, the black dashed line represents the best fit.

Table 10. Although massive black-hole-hosted blazars are known to be Compton dominated (e.g., Paliya et al. 2016), our correlation analysis indicates that even blazars with low-mass black holes can also have a large CD ($>1$). The Fermi-LAT detected narrow-line Seyfert 1 galaxies (e.g., Yuan et al. 2008) are probably a good example of this (e.g., Paliya et al. 2013).

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Table 10

| $L_{\text{disk}}/L_{\text{Edd}}$ | $\log \gamma_b$ | $\log R_{\text{diss}}/R_{\text{BLR}}$ |
|-----------------|----------------|-----------------------------|
| $10^{-5}$        | 0              | 0                           |
| $10^{-4}$        | -0.29          | -0.22                       |
| $10^{-3}$        | -1.0           | -2.5                        |
| $10^{-2}$        | -2.0           | -5.0                        |
| $10^{-1}$        | -3.0           | -7.5                        |
| $10^{0}$         | -4.0           | -10.0                       |

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$\gamma_b = -0.29 \log \left( \frac{L_{\text{disk}}}{L_{\text{Edd}}} \right) + 1.70$

$\log \left( \frac{L_{\text{disk}}}{L_{\text{Edd}}} \right) = -0.22 \log \left( \frac{L_{\text{disk}}}{L_{\text{Edd}}} \right) - 0.25$

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$\log CD = 0.36 \log L_{\text{disk}} - 15.95$

$\log CD = 0.38 \log P_{\text{jet}} - 17.13$

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15 Narrow-line Seyfert 1 galaxies are known to host low-mass black holes (e.g., Yuan et al. 2008).
are strongly anti-correlated ($\rho = -0.64 \pm 0.03$, PNC $< 1 \times 10^{-5}$). Both anti-correlations indicate a physical connection between $L_{\text{disk}}$ and the behavior of the SED in blazars. As discussed above, a stronger accretion disk emission implies a luminous BLR whose intense radiation field interacts with jet electrons making them lose energy primarily via EC-BLR process. This also hints that the stronger the disk emission, the closer the location of the dissipation region to the central black hole (with respect to the outside BLR scenario), which is observed.

In the bottom panels of Figure 14, we show the variation of CD with respect to $L_{\text{disk}}$ and $P_{\text{jet}}$. Strong positive correlations are found in both cases. They remain significant for CD versus $L_{\text{disk}}$ and become weaker for CD versus $P_{\text{jet}}$, after excluding the redshift dependence by means of a semi-partial correlation analysis (Table 10). This implies that more Compton-dominated blazars host more powerful disks. Connecting these findings with those discussed above, we can conclude that the accretion disk plays a major role in controlling the observed properties of powerful blazars, which supports the claim that the blazar sequence has a physical origin (see also, Ghisellini et al. 2017). However, it may be worth revisiting this hypothesis by including a large sample of BL Lac objects, especially high-redshift ones (e.g., Kaur et al. 2017).

### 7.4. Blazar Evolution Scenario

We show the redshift dependence of $L_{\text{disk}}$, $P_{\text{jet}}$, and CD in Figure 15, and the associated correlation parameters are reported in Table 10. The positive correlations observed in $L_{\text{disk}}$ and $P_{\text{jet}}$ are most likely the Malmquist bias. However, a positive correlation of CD with redshift appears more like an evolutionary effect naturally related to redshift because CD is a redshift-independent quantity. One can argue that such a correlation could be spurious because CD exhibits a positive correlation with $L_{\text{disk}}$, which itself strongly depends on redshift.

![Figure 15](image_url)
However, as we have shown earlier (see Table 10 and Figure 14), CD and $L_{\text{disk}}$ are intrinsically correlated. Our results are in line with the findings of Böttcher & Dermer (2002) and Cavaliere & D’Elia (2002), indicating the evolution of high-power, Compton-dominated sources to less-luminous, less Compton-dominated ones. We caution, however, that a strong claim cannot be made for the following two reasons. First, there are very few objects in our sample beyond redshift 3 without $\gamma$-ray detection, which poses a difficulty to accurately measuring their IC peak luminosity and hence CD. Second, only a minor fraction of our sample are BL Lac objects, which are typically low-CD sources (e.g., Tavecchio et al., 2010), and it is possible that such objects could be located at high redshifts (see, e.g., Kaur et al., 2017). In our future work, we will try to address these shortcomings by considering more BL Lac sources and $\gamma$-ray detected high-redshift blazars (Ackermann et al., 2017).

7.5. Gamma-Ray Loud versus Gamma-Ray Quiet Blazars

Fermi-LAT has detected hundreds of blazars in its first four years of observation (Ackermann et al., 2015), but an even larger number are yet to be detected in $\gamma$-rays (Massaro et al., 2015). It was found in several radio studies that the $\gamma$-ray quiet blazars have lower Doppler boosting factors. Lister et al. (2015) have reported the synchrotron peaks of the $\gamma$-ray quiet sources to be located at relatively lower frequencies (<10^{13.4} Hz), implying their high-energy IC peak to lie below the energy range covered by the Fermi-LAT. These objects are therefore less likely to be $\gamma$-ray detected. According to our analysis, the $\gamma$-ray loud and $\gamma$-ray quiet blazars share several similar observational features, such as occupying the same region in the WISE color–color diagram (albeit with a large scatter in the $\gamma$-ray quiet objects). The $M_{\text{BH}}$ and $L_{\text{disk}}$ distributions of the $\gamma$-ray loud sources are also similar to those derived from the $\gamma$-ray quiet blazars. However, the $\gamma$-ray loud blazars are relatively brighter in the radio and X-ray bands, and they exhibit larger Doppler factors compared to their $\gamma$-ray quiet counterparts. The $\gamma$-ray emission in powerful blazars is produced via the EC process (in the leptonic emission scenario), which is very sensitive to the Doppler boosting because of the anisotropic nature of the external radiation field in the emission region frame (Dermer, 1995). Therefore, the difference in the Doppler boosting could account for the $\gamma$-ray non-detection. Another crucial parameter that we find significantly different in the $\gamma$-ray loud and $\gamma$-ray quiet blazars is the break Lorentz factor, $\gamma_b$. In our SED modeling, we have constrained $\gamma_b$ from the location of the synchrotron peak. The same electron population radiates the high-energy X-ray to $\gamma$-ray emission in one-zone leptonic modeling, $\gamma_h$ also controls the location of the IC peak according to the following relation (e.g., Sahayanathan & Godambe, 2012)

\[ \nu_{\text{Syn}} \approx \frac{\delta}{1+z} \frac{\gamma_b^2}{\gamma_h} \nu_L, \]  
\[ \nu_{\text{SSC}} \approx \frac{\delta}{1+z} \frac{\gamma_h^2}{\gamma_b} \nu_L, \]  
\[ \nu_{\text{EC}} \approx \frac{\Gamma \delta}{1+z} \gamma_b^2 \nu_{\text{seed}}, \]

where $\nu_L$ is the Larmor frequency and $\nu_{\text{seed}}$ is the characteristic frequency of the BLR/torus photon field. As can be seen in the top right panel of Figure 9, $\gamma$-ray quiet blazars have smaller $\gamma_b$ compared to $\gamma$-ray loud sources, thus indicating their IC peak is located at lower frequencies. In other words, they are more MeV-peaked. A shift of the IC peak to low frequencies makes their falling part of the EC spectrum steeper and thus avoids detection by the Fermi-LAT. The fact that the $\gamma$-ray quiet blazars are bright in the MeV band makes them suitable targets for observations from facilities like NuSTAR (Harrison et al., 2013). The ideal instrument, however, would be an all-sky survey MeV mission, e.g., e-ASTROGAM (De Angelis et al., 2017) or AMEGO. In Figure 16, we plotted the modeled SEDs of all of the $\gamma$-ray quiet blazars (lime green) and overplot the 3$\sigma$ flux sensitivity of e-ASTROGAM (black line) for one year of observation. For comparison, we also show the flux sensitivity of the Fermi-LAT (red line) for its 10 years of operation for high Galactic latitude sources. As can be seen, the chances of Fermi-LAT detection for these sources are remote unless they exhibit high-amplitude flaring activity with a shift of the IC peak to higher frequencies (see, e.g., Abeysekara et al., 2015, for the detection of such an event that led to the detection of the FSRQ PKS 1441 + 25, $z = 0.94$, at TeV energies). On the other hand, according to Figure 16, 121 $\gamma$-ray quiet blazars would be detected by e-ASTROGAM (at 500 keV) in one year of observations. Therefore, our study of $\gamma$-ray quiet blazars presents a potential list of blazars to be detected by future MeV missions.

8. Summary

In this work, we have performed a broadband study of a large sample of blazars included in the CGRaBS catalog (Healey et al., 2008). Our main findings are as follows:

1. The $\gamma$-ray loud and $\gamma$-ray quiet objects do not show a major difference in the WISE color–color diagram, and their X-ray spectral shapes are also similar. However, $\gamma$-ray loud blazars are brighter in the radio and X-ray bands.

Figure 16. The broadband SEDs of all of the $\gamma$-ray quiet blazars studied in this work (lime green). Overplotted are the Fermi-LAT sensitivity in 10 years of observation (red) and the 3$\sigma$ sensitivity plot for one year of exposure of the proposed all-sky MeV mission e-ASTROGAM (black).

https://pcos.gsfc.nasa.gov/physpag/probe/AMEGO_probe.pdf
2. A comparison of $M_{BH}$ and $L_{disk}$ derived from the disk-fitting and optical spectroscopic approaches leads to similar results, thus suggesting that disk modeling could be used as a robust diagnostic to derive $M_{BH}$ and $L_{disk}$ in powerful blazars.

3. Both γ-ray loud and γ-ray quiet blazars exhibit similar distributions of $M_{BH}$ and $L_{disk}$ with γ-ray quiet sources hosting slightly more massive (~2.5σ significance) black holes.

4. We find a considerable difference in the Doppler factors of the γ-ray loud and γ-ray quiet blazars, with γ-ray loud sources more boosted. These results confirm the earlier findings derived from radio observations.

5. The γ-ray loud blazars have a larger jet power in radiation compared to the γ-ray quiet objects. This implies that the jets in the γ-ray loud blazars are more radiatively efficient.

6. We confirm that the accretion process and the jet are positively correlated, an effect that remains significant even after excluding the common redshift dependence. For a majority of the sources, the jet power exceeds the accretion luminosity; however, many γ-ray quiet blazars have more powerful disks than their jets. Therefore, it is possible that we may see a deviation from the observed trend ($P_{jet} > L_{disk}$) when one considers a larger sample of the γ-ray quiet blazars.

7. Both $L_{disk}$ and $P_{jet}$ show a positive correlation with $M_{BH}$, which remains strong for $L_{disk}$ and becomes weaker for $P_{jet}$ after excluding the common redshift dependence. On the other hand, the results of the semi-partial correlation analysis has led to the conclusion that CD does not correlate with $M_{BH}$, implying that even blazars hosting low-mass black holes can be Compton dominated.

8. According to our analysis, there is a physical connection between $L_{disk}$ and the behavior of the blazar SEDs. In other words, we find that the blazar sequence has a physical origin, at least for the sources studied in this work.

9. We notice that the high-redshift blazars are more Compton dominated, compared to their low-redshift counterparts. However, the sample size of $z > 3$ blazars needs to be enlarged, and one should consider more BL Lac objects before making a strong claim about the evolution of blazars.

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Software: SAS (v15.0.0), fermiPy (Wood et al. 2017), XSPEC (Arnaud 1996), Swift-XRT data product generator (Evans et al. 2009), CIAO (v.4.9).

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