Blazars at the Cosmic Dawn

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Abstract

The uncharted territory of the high-redshift ($z \geq 3$) universe holds the key to understanding the evolution of quasars. In an attempt to identify the most extreme members of the quasar population, that is, blazars, we have carried out a multiwavelength study of a large sample of radio-loud quasars beyond $z = 3$. Our sample consists of nine $\gamma$-ray-detected blazars and 133 candidate blazars selected based on the flatness of their soft X-ray spectra ($0.3-10$ keV photon index $\leq 1.75$), including 15 with Nuclear Spectroscopic Telescope Array (NuSTAR) observations. The application of the likelihood profile stacking technique reveals that the high-redshift blazars are faint $\gamma$-ray emitters with steep spectra. The high-redshift blazars host massive black holes ($\langle \log M_{BH,M} \rangle > 9$) and luminous accretion disks ($\langle L_{\text{disk}} \rangle > 10^{46} \text{ erg s}^{-1}$). Their broadband spectral energy distributions are found to be dominated by high-energy radiation, indicating their jets are among the most luminous ones. Focusing on the sources exhibiting resolved X-ray jets (as observed with the Chandra satellite), we find the bulk Lorentz factor to be larger with respect to other $z > 3$ blazars, indicating faster moving jets. We conclude that the presented list of high-redshift blazars may act as a reservoir for follow-up observations, such as with NuSTAR, to understand the evolution of relativistic jets at the dawn of the universe.

Unified Astronomy Thesaurus concepts: Blazars (164); Active galactic nuclei (16); High-redshift galaxies (734); Radiative processes (2055)

Supporting material: figure set, machine-readable tables

1. Introduction

Relativistic jets are the manifestation of the extreme processes that occur within the central regions of galaxies (see Blandford et al. 2019 for a review). Active galactic nuclei (AGNs) hosting relativistic jets closely aligned to the line of sight are called blazars. Due to their peculiar orientation, the relativistic amplification of the nonthermal jetted radiation (Doppler boosting; see, e.g., Rybicki & Lightman 1979) leads to the observation of a number of interesting phenomena. A few examples are detection at all accessible frequencies (e.g., Abdo et al. 2011), observation of temporal and spectral variability (Gaidos et al. 1996; Acciari et al. 2011; Fuhrmann et al. 2014; Paliya et al. 2017b), and superluminal motion and high brightness temperature (Scheuer & Readhead 1979; Lister et al. 2019). The optical and radio emissions detected from blazars are found to be significantly polarized (e.g., Fan et al. 2008; Itoh et al. 2016). The flux enhancement also makes blazars a dominating class of $\gamma$-ray emitters in the extragalactic high-energy sky (Ajello et al. 2020) and one of the very few astrophysical source classes detected at cosmic distances (e.g., Romani et al. 2004; Sbarrato et al. 2013). Blazars are classified as flat-spectrum radio quasars (FSRQs) and BL Lac objects based on their optical spectroscopic properties. FSRQs are characterized by broad emission lines (rest-frame equivalent width $> 5$ Å), whereas BL Lac sources exhibit weak or no emission lines in their optical spectra, thereby making it challenging to detect their redshift (Stickel et al. 1991). BL Lac objects are known to exhibit a negative or mildly positive evolution compared to the strong positive evolution noticed in FSRQs (Ajello et al. 2012, 2014). Altogether, FSRQs dominate the known population of high-redshift ($z \geq 3$) blazars and are found to be much more luminous than the BL Lac population (e.g., Ajello et al. 2009; Ackermann et al. 2017; Paliya et al. 2019).

The broadband spectral energy distribution (SED) of a blazar is dominated by nonthermal emission from the jet and shows a characteristic double-hump structure. The low-frequency hump is associated with synchrotron radiation emitted by relativistic electrons in the presence of a magnetic field. On the other hand, in the leptonic radiative scenario, the high-energy X-ray-to-$\gamma$-ray emission from blazars is attributed to inverse-Compton up-scattering of low-energy photons by the jet electrons. The reservoir of the seed photons for the inverse-Compton emission could be the synchrotron photons originated within the jet (so-called synchrotron self-Compton or SSC; Marscher & Gear 1985). Alternatively, thermal IR to UV radiation emitted by various AGN components such as the accretion disk, broad-line region (BLR), and dusty torus can also get up-scattered to X-ray to $\gamma$-ray energies, a process termed the external Compton or EC mechanism (see, e.g., Sikora et al. 1994; Georganopoulos et al. 2001), because the seed photons originate externally to the jet. The high-energy radiation from BL Lac sources is primarily explained via SSC process peaking at megaelectronvolt-to-teraelectronvolt energies (e.g., Tavecchio et al. 2010), thereby making them bright in this energy range. The X-ray to $\gamma$-ray emission observed from FSRQs, on the
other hand, peaks at relatively low frequencies (megaelectronvolt energies) and is found to be well explained by the EC mechanism (e.g., Ajello et al. 2016).

Based on the location of the synchrotron peak, blazars have also been classified as low-synchrotron peaked (LSP, $\nu^{\text{syn}}_{\text{peak,Hz}} < 10^{14}$), intermediate-synchrotron peaked ($10^{14} \leq \nu^{\text{syn}}_{\text{peak,Hz}} < 10^{15}$), and high-synchrotron peaked (HSP, $\nu^{\text{syn}}_{\text{peak,Hz}} > 10^{15}$) objects (Abdo et al. 2010). BL Lac objects display a wide range of synchrotron peak location, that is, from LSP to HSP, whereas FSRQs are mostly LSP-type blazars (e.g., Ajello et al. 2020). Since the synchrotron peak in FSRQs is located in the submillimeter-to-infrared band, the emission from the accretion disk, the so-called big blue bump, has been observed in many FSRQs, especially the high-redshift ones, at optical to ultraviolet frequencies (see Ghisellini et al. 2010; Paliya et al. 2016). The inverse-Compton peak in the high-redshift blazars, on the other hand, is usually located at the hard X-ray-to-megaelectronvolt energy band, as peak in the high-redshift blazars, on the other hand, is usually located at optical-to-ultraviolet frequencies.

The prevalence of the inverse-Compton peak over the synchrotron one can be quantified with the term “Compton dominance,” which is defined as the ratio of the inverse-Compton to synchrotron peak luminosities (see, e.g., Finke 2013).

The inverse-Compton peak is dominant in LSP blazars, whereas HSP blazars show higher synchrotron peak luminosity compared to the inverse-Compton one. This is likely due to the faintness, intrinsic rareness, or difficulty in identifying blazars among the high-redshift radio-loud quasars. A $\gamma$-ray detection with the Fermi Large Area Telescope (LAT) could be a definitive signature for the presence of a closely aligned relativistic jet (Ackermann et al. 2017); however, the energy shift of the SED peaks to low frequencies, along with $\gamma$-ray attenuation due to extragalactic background absorption (see Domínguez et al. 2011; Desai et al. 2019), makes high-redshift blazars fainter and steepens their $\gamma$-ray spectrum in the Fermi-LAT energy range. Most importantly, the current Fermi-LAT sensitivity is likely to be too low to detect a large number of $z > 3$ blazars, due to their great distances and hence low flux. A large radio loudness and the observation of a flat radio spectrum provide evidence supporting the beamed nature of the observed radiation. However, most of the known radio-loud, high-redshift quasars only have single-frequency radio flux density measurements from the NRAO VLA Sky Survey (NVSS; Condon et al. 1998). Faint Images of the Radio Sky at Twenty-centimeters (FIRST; White et al. 1997; Helfand et al. 2015), or the Sydney University Molonglo Sky Survey (SUMSS; Mauch et al. 2003). The fact that many well-studied, high-redshift blazars exhibit gigahertz peaked spectra (e.g., QSO J0906+6930 at $z = 5.47$; Coppejans et al. 2017) indicates that a flat radio spectrum alone cannot be a definitive feature. A large brightness temperature ($\gtrsim 10^{14}$ K) can also give some hints about the relativistic beaming (see Coppejans et al. 2016). Other methods, such as the observation of superluminal motion, requires multiepoch monitoring covering long time periods and thus are limited to studying only the brightest radio sources (e.g., Zhang et al. 2019).

Since the high-redshift blazars are usually LSP-type objects, they are expected to exhibit a flat or rising X-ray spectrum (in the $\nu F_{\nu}$ versus $\nu$ plane), especially in the hard X-ray band. This, along with the radio loudness, can be used to ascertain the blazar nature of a high-redshift, radio-loud quasar. Again, due to limited sensitivity of the hard X-ray surveying instrument the Swift Burst Alert Telescope (BAT, 14–195 keV; Barthelmy et al. 2005), only a few ($<10$) extremely bright, $z > 3$ quasars are confirmed as beamed AGNs using this approach (Oh et al. 2018). The Nuclear Spectroscopic Telescope Array (NuSTAR; Harrison et al. 2013), on the other hand, has a considerably improved sensitivity, which has led to the confirmation of relatively faint radio-loud quasars as blazars (Sbarrato et al. 2013). However, due to the limited field of view of NuSTAR, only one source can be observed in a single pointing. In this regard, a useful strategy could be to explore the soft X-ray spectral behavior of the high-redshift, radio-loud quasars and identify “candidate” blazars among them (see, e.g., Ghisellini et al. 2015 for a similar approach). This is because hundreds of the high-redshift quasars are observed with soft X-ray instruments either as targets of interest or lying as background objects in the field of other observations (e.g., Chandra X-ray Observatory, XMM-Newton, and the Swift X-ray Telescope (XRT)), and hence a meaningful population study can be done. The best candidates can then be followed up, for example, with NuSTAR and the Very Large Array (VLA; see, e.g., Gobeille et al. 2014) to confirm their blazar identity and study the physical properties of relativistic jets at the beginning of the universe. This is the primary objective of the work discussed in this article.

Here we present the results of an exhaustive investigation to explore the multifrequency behavior of 142 $z > 3$ radio-loud quasars that are likely to be blazars, using all of the publicly available data. Other than studying the physical properties, our goal is also to prepare a list of the most promising high-redshift, radio-loud quasars that have a high probability of hosting closely aligned relativistic jets. This list would serve as...
a reservoir from which sources can be picked to follow up with NuSTAR and other multiwavelength observing facilities. We discuss the criteria to define the sample in Section 2. The data reduction techniques are described in Section 3, and the adopted leptonic radiative model is elaborated in Section 4. We present the derived results in Sections 5 and 6. Section 7 is devoted to our findings on extended X-ray jets, and we summarize in Section 8. We adopt a cosmology of $H_0 = 67.8$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.308$, and $\Omega_{\Lambda} = 0.692$ (Planck Collaboration et al. 2016).

2. The Sample

We started with the Million Quasar Catalog (MQC v6.4; Flesch 2019) and considered all sources with $z \geq 3$. This catalog is a regularly updated compendium of 757,991 type 1 quasars or AGNs and $\sim 1.1$ million candidate quasars with high confidence ($\geq 80\%$ likelihood). It is primarily based on the Sloan Digital Sky Survey (SDSS) and AllWISE catalogs and also covers the southern hemisphere using the 2$^\circ$ field quasar redshift survey and 6$^\circ$ field galaxy survey (Boyle et al. 2000; Jones et al. 2009), along with $> 1000$ individual publications. Both spectroscopically confirmed quasars and sources with photometric redshifts have been considered in MQC.

The 75,940 $z > 3$ objects selected from MQC were then cross-matched with the NVSS, SUMSS, and FIRST radio catalogs using a 3$''$ search radius to identify radio-detected, high-redshift quasars. Using the R-band magnitude from MQC and the flux density information from the matches in the radio catalogs, we computed the radio-loudness parameter ($R$: Kellermann et al. 1989) for the selected quasars. To determine the rest-frame 5 GHz and optical B-band flux densities, we extrapolated the measured radio fluxes assuming a flat radio spectrum ($\alpha = 0$, $F_{\nu} \propto \nu^\alpha$) and considered an optical spectral index of $\alpha = -0.5$ (Anderson et al. 2007). At this stage, we only retained radio-loud ($R > 10$) quasars, leading to a total of 2226 sources. We also cross-matched this subsample with the fifth ROMA-BZCAT catalog (Massaro et al. 2015) and found that all but one of the $z \geq 3$ BZCAT sources are already included in our sample. We included the missing object BZQ J0941$-$8615 ($z = 3.697$; Titov et al. 2013) to ensure that all BZCAT blazars are considered in our work. Then, we searched for the availability of the X-ray data in the Chandra, XMM-Newton, and Swift-XRT data archives and kept 156 objects with existing X-ray observations. These high-redshift, radio-loud, X-ray-detected quasars were subjected to X-ray spectral analysis as described in the next section.

The average X-ray spectral shape of radio-quiet quasars is found to be softer (X-ray photon index $\Gamma_X \geq 1.9$, Shemmer et al. 2005) than for relativistically beamed, radio-loud quasars (e.g., Wu et al. 2013). To identify the best blazar candidates, we, therefore, considered only those objects that have $\Gamma_X \leq 1.75$ (see also Igihina et al. 2019 for a similar approach). This exercise led to a final sample of 142 high-redshift, radio-loud candidate blazars. For the sake of brevity, we simply call them high-redshift blazars in the rest of the paper.

The recently released fourth catalog of the Fermi-LAT-detected AGNs (4LAC; Ajello et al. 2020) has listed 10 $\gamma$-ray-emitting $z \geq 3$ blazars. All but one, 4FGL J1219.0$+3653$ ($z = 3.52$; Päris et al. 2017), are present in our sample. The source 4FGL J1219.0$+3653$ had no existing X-ray data, and our two Swift target-of-opportunity observations (target IDs: 12058 and 13082, summed exposure $\sim 4$ ks) failed to determine the spectral parameters of the source. Therefore, it is not considered in this work. Altogether, our sample consists

| Name             | R.A. (deg) | Decl. (deg) | Redshift | $R_{\text{mag}}$ | $F_{\text{radio}}$ (mJy) |
|------------------|-----------|------------|----------|-----------------|--------------------------|
| NVSS J033755$-$120404 | 54.48104  | $-12.06793$ | 3.442    | 20.19           | 475.3                    |
| NVSS J053954$-$283956  | 84.97617  | $-28.66554$ | 3.104    | 18.97           | 862.2                    |
| NVSS J073357$+$045614   | 113.48941 | 4.93736    | 3.01     | 18.76           | 218.8                    |
| NVSS J080518$+$614423   | 121.32575 | 61.73992   | 3.033    | 19.81           | 828.2                    |
| NVSS J083318$-$045458   | 128.32704 | $-4.9165$  | 3.5      | 18.68           | 356.5                    |
| NVSS J113506$-$020603   | 208.52873 | $-2.10089$ | 3.716    | 19.64           | 733.4                    |
| NVSS J142921$+$540611   | 217.34116 | 54.10399   | 3.03     | 19.84           | 1028.3                   |
| NVSS J151002$+$570243   | 227.51216 | 57.04538   | 4.313    | 19.89           | 202.0                    |
| NVSS J163547$+$362930   | 248.94681 | 36.49164   | 3.615    | 20.55           | 151.8                    |

| Name             | R.A. (deg) | Decl. (deg) | Redshift | $R_{\text{mag}}$ | $F_{\text{radio}}$ (mJy) |
|------------------|-----------|------------|----------|-----------------|--------------------------|
| NVSS J000108$+$191434 | 0.28589  | 19.24269   | 3.1      | 20.5            | 265.1                    |
| NVSS J000657$+$141546 | 1.73971  | 14.26299   | 3.2      | 18.86           | 183.4                    |
| NVSS J001708$+$813508 | 4.28531  | 81.58559   | 3.387    | 16.61           | 692.5                    |
| NVSS J012100$-$280623 | 20.25309 | $-28.10616$ | 3.119    | 18.82           | 122.0                    |
| NVSS J012201$+$031002 | 20.50794 | 3.16733    | 4.0      | 19.78           | 98.4                     |

Note. The positional coordinates (R.A. and decl., in J2000), redshift, and R-band magnitudes are adopted from the NVSS, SUMSS, or FIRST catalogs depending on which catalog the radio counterpart was identified in. For the source SUMSS J094156$-$861502 (or BZQ J0941$-$8615), we provide the relevant information from the BZCAT catalog.

(This table is available in its entirety in machine-readable form.)
of nine $\gamma$-ray-detected and 133 Fermi-LAT-undetected blazars. The basic properties of these 142 sources are presented in Table 1.

3. Data Reduction Methods

3.1. Gamma-Ray Analysis

We analyzed the Fermi-LAT data for all sources present in the sample including blazars from 4LAC. The goals are to (1) update the spectral parameters of the known $\gamma$-ray emitters, (2) identify new $\gamma$-ray-emitting blazars, and (3) determine the flux sensitivity limits for undetected objects and stack their likelihood profiles to derive the cumulative $\gamma$-ray detection significance. The data cover the period of almost 11 yr of the Fermi-LAT operation (2008 August 5 to 2019 July 14). We defined a region of interest (ROI) of 15° centered at the target quasar and selected P8R3 SOURCE class events (evclass=128 and evtype=3) in the energy range 0.1–300 GeV. A filter “DATA_QUAL>0 & LAT_CONFIG==1” was also applied to determine the good time intervals. Additionally, a zenith angle cut of $z_{\text{max}} = 90°$ was used to limit the contamination from the Earth limb $\gamma$-rays. To generate the $\gamma$-ray sky model, we adopted the sources present in the recently released Fermi-LAT Fourth Source Catalog (4FGL; The Fermi-LAT collaboration 2019) and lying within 25° of the target position. The latest diffuse background models,10 gll_iem_v07.fits and iso_P8R3_SOURCE_V2_v1.txt, were also adopted in the analysis. We computed the maximum-likelihood test statistic as $TS = 2 \log(L_1 - L_0)$, where $L_0$ and $L_1$ denote the likelihood values without and with a point source at the position of interest, respectively (Mattox et al. 1996). We first optimized the ROI to get a crude estimation of the TS for each source and then allowed the spectral parameters of all the sources with $TS > 25$ to vary during the likelihood fit. Since the time period considered in this work is longer than that covered in the 4FGL catalog, TS maps were generated to search for $\gamma$-ray-emitting objects present in the data but not in the catalog. Whenever an excess emission with $TS > 25$ was identified, we modeled it with a power law and inserted it in the sky model. Once all excess emissions were found and included in the sky model, we performed a final likelihood fit to optimize the spectral parameters left free to vary and to determine the parameters and detection significance for the target quasar. In this work, a source is considered to be $\gamma$-ray-detected if the derived TS is larger than 25. The entire data analysis was performed using the publicly available package fermipy (Wood et al. 2017) and fermiutils.11 The uncertainties were computed at the 1σ confidence level.

We stacked the likelihood profiles of all the $\gamma$-ray-undetected sources to calculate the overall detection significance of the sample. This was done by computing the likelihood values for each object over a grid of photon flux and photon index. Such likelihood profiles were generated for all high-redshift blazars and then stacked to estimate the combined TS and spectral parameters associated with the TS peak. Further details of this technique can be found in Paliya et al. (2019c).

3.2. Hard X-Ray Analysis

Fifteen sources in our sample have existing NuSTAR observations. We adopted the tool nuproducts to reduce the raw NuSTAR data and calibrate the event files. To extract the source and background spectra, circular regions of 30″ and 70″ radii, respectively, were considered from the same chip. We used the pipeline nuproducts to extract the spectra and response matrix and ancillary files. The spectra of bright sources were grouped to have 20 counts per bin, whereas we adopted a binning of one count per bin for faint objects using the tool grppha. We performed the spectral fitting in XSPEC (v 12.10.1; Arnaud 1996) with a power-law model. The uncertainties are estimated at the 90% confidence level.

We used publicly available 14–195 keV spectra of nine high-redshift blazars present in the 105 month Swift-BAT catalog12 (Oh et al. 2018) and applied a power-law model in XSPEC to extract the spectral data points.

3.3. Soft X-Ray Analysis

The observations from the Advanced CCD Imaging Spectrometer (ACIS, 0.5–7 keV) on board the Chandra X-ray observatory were reduced using the Chandra Interactive Analysis of Observations (CIAO, version 4.11) software package and CALDB version 4.8.2. For sources with more than one Chandra pointing, we considered the observation that has the longest exposure. We first ran the tool chandra_repro to generate the cleaned and calibrated event files and then used the tool specextract to extract the source and background spectra. For this purpose, we adopted a source region of 3″ centered at the target quasar, and a 10″ circle was considered from a nearby source-free region to represent the background. In seven out of 54 sources, we have found evidence for the presence of extended X-ray jets. We selected a source region as a circle of 1.5–2″ excluding the extended X-ray emission in these objects. For the spectral analysis, the generated source spectra were binned to have at least one count per bin, and the fitting was performed in XSPEC following the C-statistics (Cash 1979). We considered an absorbed power-law model and adopt the Galactic neutral hydrogen column density from Kalberla et al. (2005).

In order to ascertain the detection of extended X-ray jets, we generated exposure-corrected 0.5–7 keV images using the tool fluximage and adjusted the X-ray core position to match with the VLA position using the task wcs_update.

The XMM-Newton data were analyzed following the standard procedure13 using the package Science Analysis Software 15.0.0. In particular, we adopted the task epfproc to create EPIC-PN event files and then used evselect to remove the high flaring background periods. We considered the source region as a circle of 40″ radius centered at the source of interest, and the background region was selected as a circle of the same size from the same chip, but free from source contamination. The tool evselect was also used to extract the source and background spectra. The pipelines rmfgen and arfgen were used to generate the response and ancillary files. Finally, we bin the source spectra using specgroup with 20 counts per bin and performed the fitting in XSPEC.

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10 https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html
11 https://github.com/fermi-lat/Fermiutils-conda/wiki
12 https://swift.gsfc.nasa.gov/results/bst05mon/
13 http://www.cosmos.esa.int/web/xmm-newton/sas-threads
We used the online Swift-XRT data product facility\(^{14}\) (Evans et al. 2009) to generate the source, background, and ancillary response files. This tool automatically determines the sizes of the source and background regions based on the count rate of the source (see also Evans et al. 2009). We rebinned the source spectra with one or 20 counts per bin, depending on the source brightness, and performed the fitting in XSPEC, keeping the neutral hydrogen column density fixed to the Galactic value. We derived the uncertainties in the parameters at the 90% confidence level.

### 3.4. Optical Spectral Analysis

One of the \(\gamma\)-ray-emitting sources present in our sample, 4FGL J0833.4–0454 or NVSS J083318–045458, had only photometric redshift information in MQC \((z_{\text{phot}} = 3.5; \text{Richards et al. } 2015\)\(^ {15}\)). We observed this object with the Goodman Spectrograph mounted on the 4.1 m SOAR (Southern Astrophysical Research Telescope) on 2017 February 14. The data were obtained with a 4001/mm grating in conjunction with a 1′.07 slit. Three spectra were obtained for a total exposure of 3600 s \((1200 \text{ s } \times 3)\) and then combined in order to remove any artificial features due to cosmic-ray or instrumental effects. The standard optical spectroscopic reduction procedure was utilized using the IRAF (Tody 1986) pipeline. The obtained spectra were first cleaned by subtracting bias and applying flat-field normalization. These cleaned data were then wavelength calibrated using Fe–Ar lamp spectra, which were obtained after every source observation. All of the spectra were flux calibrated using a spectrophotometric standard obtained during the night of observation. Finally, each spectrum was corrected for Galactic extinction using the \(E(B-V)\) values obtained from Schlafly & Finkbeiner (2011). The resultant optical spectrum of J083318–045458 is shown in Figure 1. Various broad emission lines, such as Ly\(\alpha\) and C \(\text{IV}\), are labeled, that enabled the spectroscopic redshift measurement and confirmed the high-redshift nature of the source with \(z_{\text{spec}} = 3.45\).

![Figure 1](http://www.swift.ac.uk/user_objects/)  
**Figure 1.** Optical spectrum of NVSS J083318–045458 taken with the Goodman spectrograph mounted at the 4 m SOAR telescope. A few prominent emission lines are labeled that enabled the spectroscopic redshift measurement and confirmed the high-redshift nature of the source with \(z_{\text{spec}} = 3.45\).

\(^{14}\)\url{http://www.swift.ac.uk/user_objects/}

\(^{15}\)\url{https://archive.nrao.edu/archive/advquery.jsp}

### 3.5. Radio Analysis

We analyzed VLA data of the seven high-redshift blazars that have exhibited traces of extended X-ray emission. In order to find the radio counterparts for these X-ray jets, we reprocessed the raw data downloaded from the VLA Archive.\(^{15}\) The data reduction was conducted in the NRAO Astronomical Image Processing System (AIPS; Greisen 2003). The sources were first calibrated, and then the amplitude and phase solutions were transferred to the targets. The calibrated data were imaged in Difmap (Shepherd 1997). We prefer to use the data acquired with the VLA at the \(L\) band and in a configuration to obtain better resolution and better sensitivity for resolving and detecting the extended radio emission, which usually has a steep spectrum. For the source NVSS J090915 +035443, the \(C\)-band data were used. The observing and image information are summarized in Table 2.

#### 3.6. Other Archival Observations

To cover the radio-to-UV part of the SED, we relied on the archival spectral measurements from the Space Science Data Center SED Builder.\(^{16}\) These measurements primarily come from NVSS, SUMSS, FIRST, Planck, Wide-field Infrared Survey Explorer, and Sloan Digital Sky Survey quasar catalogs and allowed us to determine the level of the synchrotron emission and also constrain the accretion disk spectrum at optical to UV energies.

### 4. The Leptonic Radiative Model

We used the conventional synchrotron, inverse-Compton emission model (see, e.g., Dermer & Menon 2009) to reproduce the broadband SEDs of the high-redshift blazars, and we explain it here in brief. We assume a spherical emission region of radius \(R_{\text{blob}}\) covering the whole cross section of the jet and moving along with the bulk Lorentz factor \(\Gamma\). The jet is considered to be of conical shape with semiopening angle of 0.1 radian, and this connects \(R_{\text{blob}}\) with the distance of the emission region \(R_{\text{disk}}\) from the central engine. The energy distribution of the relativistic electrons present in the emission region is adopted to follow a smooth broken power law. In the presence of a uniform but tangled magnetic field, these relativistic electrons radiate via synchrotron, SSC, and EC processes. For the latter, we compute the comoving-frame radiative energy densities of the BLR, dusty torus, and accretion disk following the prescriptions of Ghisellini & Tavecchio (2009). The radiative profile of the standard optically thick, geometrically thin accretion disk (Shakura & Sunyaev 1973) is assumed to follow a multicolor blackbody (Frank et al. 2002). Both the BLR and dusty torus are considered as thin spherical shells whose radii depend on the luminosity of the accretion disk as \(R_{\text{BLR}} = 10^{17} L_{\text{disk},45}^{1/2} \text{ cm},\) \(R_{\text{torus}} = 2.5 \times 10^{11} L_{\text{disk},45}^{1/2} \text{ cm},\) respectively, where \(L_{\text{disk},45}\) is the accretion disk luminosity \((L_{\text{disk}})\) in units of \(10^{45} \text{ erg s}^{-1}\). We assume that 10% and 30% of \(L_{\text{disk}}\) are reprocessed by the BLR and the torus, respectively. Various jet powers are computed following Celotti & Ghisellini (2008), and we assume no pairs in the jet, that is, an equal number density of electrons and cold protons, while deriving the kinetic jet power.

\(^{16}\)\url{https://tools.ssdc.asi.it/}
SED Modeling Guidelines: Our model does not perform any statistical fit, and we merely reproduce the observed SED following a fit-by-eye approach. The uniqueness of the SED parameters mainly depends on the availability of the simultaneous observations covering all accessible bands as much as possible. There is a clear dearth of multiwavelength data for the high-redshift blazars. Most of them are undetected in the γ-ray band, and only a few have existing hard X-ray observations. Due to their great distances and hence faintness, the measured uncertainties are also large at soft X-rays. Furthermore, most of the X-ray observations were carried out with different science objectives, for example, to search for soft X-ray flaring (see Fabian et al. 2001) and extended X-ray jets (e.g., Marshall et al. 2018), and thus, they do not represent any particular high or low activity state of the sources. Therefore, we collected all available “nonsimultaneous” data sets and treated them as a representation of the average behavior of the blazars under consideration. The motivation here is to study the overall physical properties of the high-redshift jetted population and determine interesting objects that can be followed up for deeper studies. While doing so, we were driven by our current understanding of blazar radiative processes based on previous works reported in the literature, and we tried to constrain the SED parameters as described below.

Two crucial parameters in the modeling of FSRQs are $L_{\text{disk}}$ and the mass of the central black hole ($M_{\text{BH}}$). Since these sources exhibit strong emission lines in their optical spectra, one can reliably derive the luminosity of the BLR and $L_{\text{disk}}$ from the emission line information (e.g., using scaling relations of Francis et al. 1991) and $M_{\text{BH}}$ assuming the virial relations hold valid (e.g., Vestergaard & Peterson 2006; Shaw et al. 2012). Above redshift 3, only the C IV line remains in the wavelength range covered by the optical spectroscopic facilities, for example, SDSS. However, as demonstrated in various studies (e.g., Richards et al. 2011; Chen et al. 2014), C IV is likely not suitable for deriving $M_{\text{BH}}$, due to blueshifts or absorption troughs, indicating strong outflows. An alternative approach to determining $L_{\text{disk}}$ and $M_{\text{BH}}$ is by modeling the optical-to-UV spectrum with the accretion disk model, provided the big blue bump is visible (e.g., Calderone et al. 2013). In this technique, there are two free parameters: the mass accretion rate and $M_{\text{BH}}$. The level of the optical-to-UV spectrum constrains the former, and hence $L_{\text{disk}}$ for a certain accretion efficiency, leaving only $M_{\text{BH}}$ as a free parameter. A small mass refers to a smaller accretion disk surface, and for a given $L_{\text{disk}}$, it implies a hotter disk and thus the accretion disk radiation peaking at higher frequencies. A few studies have recently shown that $L_{\text{disk}}$ and $M_{\text{BH}}$ derived from this method agree well with that computed from optical spectroscopy (Ghisellini & Tavecchio 2015; Paliya et al. 2017a, 2019d). Therefore, we derive the two central engine parameters by adopting the accretion disk modeling approach.

The accuracy of the above-mentioned technique depends on the visibility of the peak of the big blue bump. For a source with $L_{\text{disk}} \sim 10^{47}$ erg s$^{-1}$, the peak lies in the far-UV (i.e., $>10^{15}$ Hz, in the rest frame) if the mass of the central black hole is $<10^8 M_\odot$. Constraining $M_{\text{BH}}$ for such objects with a disk modeling approach may not be possible because the emission bluer than the Lyα frequency is severely absorbed by the intervening clouds. To overcome this problem, we determined $L_{\text{disk}}$ from the C III, C IV, or Lyα line luminosity information taken from the literature (e.g., Osmer et al. 1994; Stern et al. 2003; Shen et al. 2011; Shaw et al. 2012; Torrealba et al. 2012) by using the flux scaling of Francis et al. (1991) and Celotti et al. (1997) to calculate the BLR luminosity and assuming 10% of the disk emission is reprocessed by the BLR. Assuming an uncertainty of 0.3 dex, we found that this additional piece of information provided a range of $L_{\text{disk}}$ values that can be used to estimate the peak of the disk emission (e.g., Ghisellini et al. 2015). Finally, for a good IR-to-optical data coverage, both $M_{\text{BH}}$ and $L_{\text{disk}}$ can be reasonably constrained within a factor of two. Even for objects with poorer data availability, the uncertainty is of the order of that associated with virial estimations, that is, $\sim$0.3 dex. This has been demonstrated in Appendix A.

The high-energy index of the particle energy distribution can be constrained from the optical-to-UV data provided it is dominated by the falling part of the synchrotron radiation. However, all of the sources studied here are LSP FSRQs with synchrotron emission peaking in the unobserved far-IR to submillimeter wavelengths, leaving the accretion disk emission naked at optical to UV frequencies. We also cannot use the γ-ray spectral shape to constrain the high-energy index, as is usually done in LSP FSRQs (e.g., Paliya et al. 2019b; van den Berg et al. 2019), since most of the high-redshift blazars are not detected with Fermi-LAT. Therefore, we froze it to a value of 5.4 derived from the γ-ray photon index estimated using the stacking technique. To reduce the number of free parameters, we fixed the maximum value of the random Lorentz factor of the electron population ($\gamma_{\text{max}}$) to 1500. The viewing angle ($\theta_0$) was also frozen to 3°, which is typically adopted in the blazar SED modeling and consistent with that inferred from radio

| Name       | Obs. Date    | Freq. (GHz) | Beam Size (arcsec) | PA (deg) | Peak br. (mJy beam$^{-1}$) | ms (mJy beam$^{-1}$) |
|------------|--------------|-------------|--------------------|----------|---------------------------|---------------------|
| 035443     | 1984 Dec 17  | 4.8         | 0.5 × 0.3          | −41.0    | 188.9                     | 0.3                 |
| 041536     | 1987 Aug 16  | 1.4         | 1.3 × 1.2          | 12.4     | 590.3                     | 0.3                 |
| 064355     | 2004 Dec 22  | 1.4         | 1.4 × 1.1          | 2.0      | 342.8                     | 0.2                 |
| 040436     | 2004 Dec 6   | 1.4         | 1.4 × 1.0          | 53.0     | 155.0                     | 0.1                 |
| 057024     | 1995 Jul 14  | 1.4         | 1.6 × 1.1          | −6.8     | 227.0                     | 0.1                 |
| 081143     | 1987 Aug 16  | 1.4         | 1.2 × 1.1          | −6.8     | 203.9                     | 0.3                 |
| 022654     | 1991 Sep 8   | 1.4         | 1.7 × 1.0          | −69.7    | 477.1                     | 0.4                 |

Note. All of the experiments were carried out in VLA A-configuration. Column 2: observing date; Column 3: observing frequency; Column 4: restoring beam size at FWHM; Column 5: position angle of the restoring beam major axis, measured north through east; Column 6: peak brightness of the CLEAN images; Column 7: off-source image noise.
Figure 2. Stacked TS profile of γ-ray-undetected high-redshift blazars (left) and empty γ-ray sky positions representing the background (right). The confidence contours are at σ, 2σ, and 3σ levels as labeled, and “+” shows the peak of the TS profile. In the left plot, we masked the negative TS values to highlight the positive γ-ray signal. A negative TS indicates that the alternative hypothesis for the presence of a point source characterized by a given flux and photon index is strongly rejected with respect to the null hypothesis of no source.

studies of blazars (Jorstad et al. 2005). Note that because blazar jets are viewed within a maximum θc of 1/Γ, one can get a meaningful constraint on the average viewing angle directly from Γ also.

In all high-redshift blazars, the synchrotron emission peak was found to be located at self-absorbed frequencies (<10^{12} Hz). Therefore, we considered the observed radio emission to get an idea about the typical flux level of the synchrotron radiation, which was found to be low. Accordingly, the computed SSC emission remained well below the observed X-ray spectrum, allowing us to constrain the size of the emission region, and hence R_{diss} and the magnetic field. By reproducing the X-ray spectrum with the EC process, we were able to determine the low-energy index of the electron energy distribution from the observed X-ray spectral shape. The level of the X-ray flux constrained the bulk Lorentz factor and also controlled R_{diss}. This is because the radiative energy densities of various AGN components used to estimate the EC flux vary as a function of R_{diss} (Ghisellini & Tavecchio 2009). Note that because of the lack of hard X-ray data and γ-ray nondetection, the high-energy peak is not well constrained. Therefore, we use the soft X-ray spectrum and the Fermi-LAT sensitivity limits (shown with black stars in Figure 4) to get an idea about the approximate position of the inverse-Compton peak. Similarly, the level of the synchrotron emission is not well constrained, especially for those that have a single-point radio detection. In such cases, we are driven by our current understanding about jet physics. We know that FSRQ SEDs are Compton dominated, but the Compton dominance (CD) cannot be very large (>1000). Since it is the ratio of inverse Compton to synchrotron peak luminosities, the synchrotron peak cannot have an extremely low flux value, and the inverse-Compton peak cannot have a very large flux. The former should be, on average, of the order of the observed radio emission or probably larger, keeping in mind the synchrotron self-absorption. The high-energy peak cannot have a very large flux, as constrained from the Fermi-LAT sensitivity limits. Also, an extremely bright peak demands a large bulk Lorentz factor (>20–30), which is likely to be unrealistic based on previous blazar population studies (e.g., Ghisellini & Tavecchio 2015; Paliya et al. 2017a). Altogether, this leaves a limited allowed range for both SED peaks. Further details about the adopted methodology can be found in Paliya et al. (2017a).

5. Observed Properties

5.1. Gamma-Rays

The analysis of ~11 yr of the Fermi-LAT data has not revealed any new γ-ray-emitting blazars beyond z = 3, other than those present in the 4FGL catalog. The faintness of the high-redshift blazars in the γ-ray band is not only due to their large distances but also probably has a physical origin. Since the same electron population is expected to radiate both the low- and high-energy peaks, the LSP nature of these sources, in turn, suggests the high-energy SED bump is located at relatively lower (megaelectronvolt) frequencies. Due to the k-correction effect (Hogg et al. 2002), the SED peak shifts toward hard X-rays, making the γ-ray spectrum steeper in the Fermi-LAT energy range. The enhancement in the luminosity as redshift increases also contributes to this effect, causing high-redshift blazars to become fainter in γ-rays and brighter in the hard X-ray-to-megaelectronvolt band.

We search for the cumulative γ-ray signal from the 133 Fermi-LAT undetected sources by stacking their likelihood profiles (Paliya et al. 2019c). The derived results are shown in Figure 2, where we also show the stacked TS profile of 133 empty γ-ray sky positions representing the cumulative background emission. This exercise was done in the 0.3–300 GeV energy range. The motivation behind using the minimum energy of 300 MeV instead of 100 MeV is to avoid the bright background emission embedded in the data (see Appendix B for details). We estimate a combined TS of TS_{peak} = 26.1 and average photon flux f_{0.3–300 GeV} = 9.2^{+1.8}_{-1.9} \times 10^{-11} \text{ ph cm}^{-2} \text{ s}^{-1} and photon index Γ_{0.3–300 GeV} = 3.3^{+0.4}_{-0.3}. This observation suggests that the population of the high-redshift blazars is a γ-ray emitter, though individual objects are too faint to detect with Fermi-LAT. Furthermore, the steep γ-ray spectrum is expected from the high-redshift blazar population. The computed photon flux is also about an order of magnitude lower than the detection threshold of the Fermi-LAT, revealing the capabilities of the
Table 3
Results of the Spectral Analysis of the Analyzed X-Ray Data Obtained with Swift-XRT, XMM-Newton, and Chandra Satellites

| Name                  | $N_{H}$ | Exp. | Soft X-Ray Flux | Photon Index | $\chi^2$/C-stat. | dof | Stat. | Mission |
|-----------------------|---------|------|-----------------|--------------|-----------------|-----|-------|---------|
|                       | [1]     | [2]  | [3]             | [4]          | [5]             | [6] | [7]   |         |
| J001018+191434        | 3.16    | 5.56 | 0.91            | 0.00         | 2.55            | 1.38| 0.23  | 2.74    | 7.55 | 6    | c-stat | Swift |
| J000657+141546        | 4.62    | 11.68| 6.04            | 4.64         | 8.08            | 1.37| 1.11  | 1.63    | 91.65| 83   | c-stat | Swift |
| J01708+813508         | 13.50   | 13.41| 45.30           | 50.50        | 52.20           | 1.40| 1.38  | 1.42    | 521.18| 494  | chi    | XMM   |
| J012100−280623        | 1.60    | 5.70 | 2.01            | 0.78         | 6.18            | 1.33| 1.28  | 1.37    | 128.01| 112  | chi    | Swift |

Note. Column 1: name of the source (for brevity, we do not use the prefix NVSS, SUMSS, or FIRST); Column 2: the Galactic neutral hydrogen column density, in $10^{20}$ cm$^{-2}$; Column 3: observing exposure, in ksec; Columns 4–6: observed 0.3–10 keV for Chandra flux and its lower and upper limits, respectively, in units of $10^{-13}$ erg cm$^{-2}$ s$^{-1}$; Columns 7–9: power-law photon index and its lower and upper limits, respectively; Column 10: the $\chi^2$ or C-statistics value derived from the model fitting; Column 11: degrees of freedom; Column 12: adopted statistics, c-stat: C-statistics (Cash 1979), and chi: $\chi^2$ fitting; and Column 13: name of the satellite.

This table is available in its entirety in machine-readable form.

Table 4
Results of the Spectral Analysis of the Analyzed Hard X-Ray Data Obtained with NuSTAR

| Name                  | Exp. | Hard X-Ray Flux | Photon Index | $\chi^2$/C-stat. | dof | Stat. |
|-----------------------|------|-----------------|--------------|-----------------|-----|-------|
|                       | [1]  | [2]             | [3]          | [4]             | [5] |       |
| J001708+813508        | 31.00| 10.73           | 9.98         | 11.48           | 1.77| 1.71  |
| J012201+031002        | 30.83| 2.14            | 1.65         | 2.60            | 1.61| 1.41  |
| J013126−100931        | 29.91| 11.19           | 9.97         | 12.14           | 1.43| 1.35  |
| J020346+1113445       | 31.66| 2.62            | 2.15         | 3.01            | 1.77| 1.59  |
| J052506−233810        | 20.93| 11.70           | 10.07        | 12.93           | 1.38| 1.29  |
| J064632+445116        | 32.16| 2.02            | 1.64         | 2.36            | 1.76| 1.56  |
| J090630+693031        | 79.33| 0.20            | 0.05         | 0.28            | 1.93| 1.41  |
| J102623+254259        | 59.39| 0.21            | 0.00         | 0.32            | 1.43| 0.61  |
| J102838−084438        | 30.69| 3.00            | 2.42         | 3.49            | 1.63| 1.47  |
| J1135460−020603       | 53.11| 2.22            | 1.69         | 2.66            | 1.31| 1.14  |
| J143023+420436        | 49.19| 5.32            | 4.62         | 5.88            | 1.52| 1.43  |
| J151002+570243        | 36.86| 2.91            | 2.19         | 3.48            | 1.19| 1.00  |
| J155930+030447        | 53.39| 0.41            | 0.23         | 0.53            | 1.91| 1.52  |
| J193957−100240        | 39.26| 2.30            | 1.95         | 2.60            | 2.02| 1.86  |
| J212912−153841        | 33.32| 28.45           | 26.71        | 29.99           | 1.56| 1.51  |

Note. Column 1: name of the source (for brevity, we do not use the prefix NVSS, SUMSS, or FIRST); Column 2: net exposure, in ks; Columns 3–5: observed 3–79 keV flux and its lower and upper limits, respectively, in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$; Columns 6–8: power-law photon index and its lower and upper limits, respectively; Column 9: the $\chi^2$ or C-statistics value derived from the model fitting; Column 10: degrees of freedom; and Column 11: adopted statistics, c-stat: C-statistics (Cash 1979), and chi: $\chi^2$ fitting.

5.2. X-Rays

There are a total of 104 Swift-XRT, 54 Chandra, and 18 XMM-Newton observations of the high-redshift blazars present in the sample. The X-ray spectral parameters derived by fitting a simple absorbed power-law model for all sources are provided in Tables 3 and 4 and shown in Figure 3. High-redshift blazars are faint X-ray sources with average X-ray flux $\langle \log F_X \rangle = -12.71$ (in logarithmic scale of erg cm$^{-2}$ s$^{-1}$). Their average X-ray spectral shape is hard with $\langle \Gamma_X \rangle = 1.42$. This might be due to our criterion of considering only the hardest spectrum objects. The estimated $k$-corrected, rest-frame X-ray luminosity reveals that the high-redshift sources are luminous (Figure 3) with $\langle \log L_X \rangle = 46.09$ (in logarithmic scale of erg s$^{-1}$), likely due to Malmquist bias.

6. Physical Properties Inferred from the SED Modeling

We generate the broadband SEDs of all sources considered in this work using the methodology described in Section 3 and reproduce them with a single-zone leptonic emission model as explained in Section 4. The modeled SEDs are shown in Figure 4, and we provide the associated SED parameters in Table 5. In Table 6, we provide the mean and 1$\sigma$ standard deviation for all of the SED parameters.

6.1. Central Engine

We compute $M_{BH}$ and $L_{\text{disk}}$ for all sources by reproducing their IR-to-optical emission with a standard Shakura & Sunyaev (1973) accretion disk model. This approach is similar to that adopted in various recent studies (e.g., Ghisellini et al. 2015; Sbarrato et al. 2016). As discussed in Section 4, we...
considered only data points redder than the rest-frame frequency of the Lyα line. This is because the bluer data points may not reveal the true flux level of the disk, due to absorption by the intervening Lyα clouds, whose nature is uncertain. In the top panel of Figure 5, we show the estimated $M_{\text{BH}}$ and $L_{\text{disk}}$ values. For the sake of completeness, we have compared the $M_{\text{BH}}$ values derived from the disk fitting approach with the C IV emission line based on measurements for 45 blazars also studied by Shen et al. (2011). As can be seen in Figure 6, a majority of sources have comparable $M_{\text{BH}}$ values within the uncertainties associated with the virial technique. There is a large spread in $M_{\text{BH}}$ values derived from the virial method, likely due to the complexity involved with the C IV emission lines (e.g., narrow absorption troughs; see Chen et al. 2014).

The top panels of Figure 5 demonstrate that the high-redshift sources host powerful central engines. The mean luminosity of the accretion disk is found to be $\langle \log L_{\text{disk}} \rangle = 46.7$ (in units of $\text{erg s}^{-1}$) for the sources present in our sample. Moreover, the high-redshift blazars are powered by massive black holes with $\langle \log M_{\text{BH}} \rangle = 9.5$. These numbers are on the higher side with respect to the low-redshift blazar population (Paliya et al. 2017a, 2019d). This observation is likely due to a selection effect because only the most powerful objects are expected to be detected at high redshifts. However, this is a favorable bias as it allows us to identify and study the most massive black holes at the beginning of the universe.

6.2. Other SED Parameters

In Figure 5, we show the distributions of various SED parameters derived from the leptonic modeling and also overplot the same computed for low-redshift blazars for comparison.

Particle Energy Distribution: The distribution of the low-energy index of the broken power law spectrum peaks at $\langle p \rangle = 1.8$. Interestingly, the break Lorentz factor $\Gamma_b$ for the high-redshift blazars has an average value $\langle \log \Gamma_b \rangle = 1.8$ with a narrow dispersion (Table 6). Since $\Gamma_b$ indicates the SED peak locations, the derived results suggest that the SED peaks of the high-redshift objects lie at low frequencies. These results support the idea of the high-redshift blazars being megelectronvolt-peaked and thus brighter in the hard X-ray band (e.g., Ghisellini et al. 2010).

Magnetic Field and the Dissipation Distance: According to our analysis, the average magnetic field strength in the high-redshift sources is $B = 1.0 \text{ G}$ (Figure 5, panel (c)). Considering the distance of the emission region from the central black hole in absolute units, the mean is $\langle \log R_{\text{diss, cm}} \rangle = 17.8$. When normalized in $R_{\text{BLR}}$ units, we noticed that a majority of the high-redshift blazars have a dissipation region located within the BLR (Figure 5, panel (g)). This is because, in our model, the sizes of the BLR and dusty torus are a function of $L_{\text{disk}}$ (see also Ghisellini & Tavecchio 2009), which is found to be larger, hence giving a bigger BLR, for the high-redshift sources.

Compton Dominance: The SEDs of the high-redshift blazars are found to be Compton dominated (Table 6). This can be understood in terms of a relatively enhanced X-ray emission noticed in the high-redshift sources with respect to their radio emission (see, e.g., Saez et al. 2011; Wu et al. 2013; Zhu et al. 2019). Since the X-ray and radio fluxes are used to constrain the inverse-Compton and synchrotron spectra, respectively, a larger CD is expected. In addition to that, CD is reported to be positively correlated with $L_{\text{disk}}$ (Paliya et al. 2017a). Therefore, the observation of Compton-dominated SEDs in the high-redshift blazars can be understood because they have luminous accretion disks (Figure 5).

Jet Velocity: The derived bulk Lorentz factor and Doppler factor for the high-redshift blazar population (Figure 5, panels (i) and (j)) are $\langle \Gamma \rangle = 7$ and $\langle \delta \rangle = 12.3$, which are relatively smaller than that determined for other blazars located at $z < 3$ (see Ghisellini et al. 2014). In fact, Volonteri et al. (2011) proposed a decrease in $\Gamma$ as a likely factor to explain the deficiency of the parent population members of blazars at high redshifts. This is because, for each blazar with the jet Lorentz factor $\Gamma$, there are $2\Gamma^2$ sources expected to be present in the same redshift bin, and hence a low value of $\Gamma$ indicates fewer misaligned radio-loud quasars. Though model dependent, our findings provide crucial insights into the blazar evolution scenario, and they are consistent not only with other studies where a low $\Gamma$ was estimated from the SED modeling (An & Romani 2018), but also with that inferred from radio studies (e.g., An et al. 2020). However, we cannot make a strong claim because there is a lack of $>10 \text{ keV}$ data for most of the sources.

Figure 3. Histograms of the observed X-ray flux (left), photon index (middle), and luminosity (right) for the high-redshift blazars. Note that for sources with X-ray observations taken with more than one satellite, we consider the one with the smallest uncertainty in the X-ray photon index.
Observations in the hard X-ray band, such as with NuSTAR, are crucial in constraining $\Gamma$ better, as shown in recent studies (see, e.g., Sbarrato et al. 2013; An & Romani 2018).

**Jet Powers:** The jet powers derived from the SED modeling can be found in Table 7, and we plot their distributions in Figure 7. On average, the high-redshift sources have powerful jets, especially the proton and radiative jet powers, as can be seen in Table 6. On comparing the jet powers with the respective accretion luminosities (Figure 8), we find that the high-redshift blazars follow the accretion–jet connection known for other, relatively nearby objects (e.g., Ghisellini et al. 2014). We quantify the correlation by determining the partial Spearman’s correlation coefficient ($\rho_s$; Padovani 1992) and probability of no correlation (PNC), which takes into account the common redshift dependence. The derived values are $\rho_s = 0.23 \pm 0.07$, PNC $< 10^{-10}$ and $\rho_s = 0.58 \pm 0.05$, PNC $< 10^{-10}$ for the $L_{\text{disk}}$ versus $P_{\text{rad}}$ and $L_{\text{disk}}$ versus $P_{\text{jet}}$ correlations, respectively.

Interestingly, as can be seen in the top panel of Figure 8, a major fraction of the high-redshift blazar population lies below the one-to-one correlation line, indicating their accretion power
is larger than their radiative jet luminosity. Considering the total jet power versus $L_{\text{disk}}$ (Figure 8, bottom panel), most of the sources do exhibit jet powers that exceed their accretion luminosities, though about one-quarter of them have lower jet powers. Keeping in mind the fact that the presence of pairs in the jet can reduce the total jet power by a factor of a few (e.g., Pjanka et al. 2017), we conclude that $L_{\text{disk}}$ in the high-redshift blazars is comparable to their total jet powers. Additionally, we caution that the results derived in this work are mainly driven by the soft X-ray observations. In order to better estimate the SED parameters and jet powers, observations in the hard X-ray band are necessary. This is because the NuSTAR data permit us to put tighter constraints on the low-energy slope of the particle energy distribution and also, along with the soft X-ray measurements, the minimum energy of the emitting electron population and the bulk Lorentz factor. These parameters are crucial for accurately computing the jet powers. In the future, observations from the next-generation all-sky megarontvolt missions, for example, the All-sky Medium Energy Gamma-ray Observatory (AMEGO, energy coverage 200 keV to 10 GeV; McEnery et al. 2019), will allow us to cover the broad range of the inverse-Compton emission, including the high-energy SED peak (e.g., Paliya et al. 2019a), leading to an unprecedented measurement of the physical properties of the high-redshift blazars.

Note in Figure 8 that both $L_{\text{disk}}$ and jet power appear to saturate around $10^{48}$ erg s$^{-1}$. This observation might be connected to the upper limit of the black hole mass that can be achieved via accretion (about a few times $10^{10}$ $M_\odot$, see, e.g., Inayoshi & Haiman 2016; King 2016), and hence, to the maximum accretion rate in Eddington units. In other words, the average jet power and $L_{\text{disk}}$ appear to saturate around the maximum possible Eddington luminosity.

Figure 5. Histograms of the SED parameters for the high-redshift blazars.
Table 5 Parameters Used or Derived from the SED Modeling of the High-redshift Blazars

| Name                  | $z$  | $M_{BH}$ | $L_{disk}$ | $R_{disk}$ | $R_{BLR}$ | $\delta$ | $\Gamma$ | $B$  | $\beta$ | $\gamma_{\text{min}}$ | $\gamma_{b}$ | $U_c$ | CD |
|-----------------------|------|----------|------------|------------|-----------|----------|----------|------|---------|----------------------|--------------|-------|----|
| J000108+191434        | 3.10 | 9.30     | 46.23      | 0.165      | 0.133     | 12.3     | 7        | 1.2  | 1.7     | 99                   | −1.39        | 4.3   |    |
| J000557+141546        | 3.20 | 9.18     | 47.00      | 0.144      | 0.323     | 14.7     | 9        | 1.0  | 1.9     | 71                   | −1.37        | 89.8  |    |
| J01708+181508         | 3.37 | 10.00    | 48.00      | 0.383      | 1.020     | 12.2     | 8        | 2.2  | 1.9     | 41                   | −1.55        | 25.3  |    |
| J012100−280623        | 3.12 | 9.00     | 46.76      | 0.191      | 0.244     | 12.3     | 7        | 1.5  | 1.7     | 89                   | −1.89        | 18.0  |    |
| J012201+031002        | 4.00 | 9.43     | 46.08      | 0.116      | 0.112     | 15.7     | 10       | 0.8  | 2.0     | 65                   | −0.90        | 159.9 |    |

Note. Column 1: source name; Column 2: redshift of the blazar; Column 3: log-scale black hole mass, in units of the solar mass; Column 4: log-scale luminosity of the accretion disk, in erg s$^{-1}$; Column 5: distance of the emission region from the central black hole, in parsecs; Column 6: radius of the spherical BLR, in parsecs; Columns 7 and 8: Doppler factor and bulk Lorentz factor, respectively; Column 9: magnetic field, in Gauss; Column 10: slopes of the broken-power-law electron energy distribution before the peak; Columns 11 and 12: minimum and break Lorentz factors of the radiating electrons; Column 13: log-scale electron energy density, in erg cm$^{-3}$; and Column 14: the Compton dominance.

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

Table 6 Statistical Summary of the SED Parameters Derived for the High-redshift Blazars Studied in This Work

| Parameters                                        | Mean   | Range     |
|---------------------------------------------------|--------|-----------|
| Disk luminosity (log scale, in erg s$^{-1}$)       | 46.7 ± 0.4 | 45.9–48.0 |
| Black hole mass (log scale, in $M_\odot$)          | 9.5 ± 0.3 | 8.7–10.3  |
| Electron spectral index ($p$)                      | 1.8 ± 0.2 | 1.1–2.2   |
| Break Lorentz factor (log scale)                   | 1.8 ± 0.2 | 1.3–2.3   |
| Magnetic field (in Gauss)                          | 1.0 ± 0.5 | 0.2–3.2   |
| Dissipation distance (log scale, in cm)            | 17.8 ± 0.2 | 17.3–18.5 |
| Compton dominance (log scale)                      | 1.6 ± 0.5 | 0.5–2.8   |
| Bulk Lorentz factor                                | 7.0 ± 1.9 | 5.0–14.0  |
| Doppler factor                                     | 12.3 ± 2.3 | 9.3–22.6  |
| Electron jet power (log scale, in erg s$^{-1}$)     | 45.0 ± 0.5 | 43.4–46.1 |
| Magnetic jet power (log scale, in erg s$^{-1}$)     | 45.2 ± 0.6 | 43.4–46.6 |
| Radiative jet power (log scale, in erg s$^{-1}$)    | 46.1 ± 0.6 | 44.4–47.7 |
| Kinetic jet power (log scale, in erg s$^{-1}$)      | 47.5 ± 0.5 | 45.8–48.7 |

Note. Quoted uncertainties in the mean values are the 1σ standard deviation.

Table 7 Various Jet Powers Derived from the SED Modeling

| Name                  | $P_{\text{ele}}$ | $P_{\text{mag}}$ | $P_{\text{rad}}$ | $P_{\text{kinc}}$ | $P_{\text{jet}}$ |
|-----------------------|------------------|------------------|------------------|------------------|-----------------|
| J000108+191434        | 44.98            | 45.13            | 45.59            | 47.38            | 47.38           |
| J000557+141546        | 45.10            | 45.07            | 46.47            | 47.67            | 47.68           |
| J01708+181508         | 45.67            | 46.51            | 47.29            | 48.18            | 48.19           |
| J012100−280623        | 44.61            | 45.45            | 46.03            | 47.03            | 47.04           |
| J012201+031002        | 45.48            | 44.79            | 46.65            | 48.12            | 48.12           |

Note. Column 1: name of source; Columns 2, 3, 4, 5, and 6: log-scale electron, magnetic, radiative, kinetic, and total jet power, respectively. Note that $P_{\text{jet}} = P_{\text{ele}} + P_{\text{mag}} + P_{\text{kinc}}$.

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

7. Extended X-Ray Jets

Seven high-redshift blazars have exhibited traces of extended X-ray emission in their Chandra observations. We show 0.5–7 keV Chandra images of these sources in Figure 9 and overplot the VLA radio contours to look for radio counterparts of the X-ray jets. Note that the presence of X-ray jets in these objects has already been reported in various previous works (see, e.g., Siemiginowska et al. 2003; Cheung 2004; Cheung et al. 2006, 2012; McKeough et al. 2016; Schwartz et al. 2019). However, instead of focusing on the properties of the extended X-ray emission as done in those works, we explore the properties of the blazar core with the motivation to search for any possible pattern in the physical properties that may reveal the origin of kiloparsec-scale X-ray jets.

Figure 6 shows the distribution of $M_{\text{BH}}$ values reported by Shen et al. (2011) using the C IV emission line with that derived using the disk modeling method in this paper. The shaded area demonstrates an uncertainty factor of four associated with the virial technique.

Cheung (2004; Cheung et al. 2006, 2012; McKeough et al. 2016; Schwartz et al. 2019). Interestingly, recent VLBA observations of the most distant X-ray jetted blazar, NVSS J143023 +420436 ($z = 4.71$), also revealed a rapidly moving jet with...
$\Gamma = 14.6 \pm 3.8$ (Zhang et al. 2019), similar to $\Gamma = 14$ found by us via SED modeling. Therefore, it appears that the plasma in X-ray jetted blazars remains highly relativistic at parsec-scale distances or even farther down the jet. However, the sample of the known extended X-ray jets in the parent sample of the high-redshift objects is small, and therefore a strong claim cannot be made. One needs also to consider relatively nearby (i.e., $z < 3$) X-ray jets to increase the sample size and ascertain the findings reported here.

The X-ray emission in the high-redshift, radio-loud quasars is found to be significantly enhanced compared to low-redshift sources with matched properties in other wave bands (Wu et al. 2013). One of the possible explanations put forward is the interaction of the jet electrons with the cosmic microwave background (CMB) photons, whose energy density has a strong redshift dependence: $U_{\text{CMB}} \propto (1+z)^4$. Considering the fact that the radio-loudest quasars usually belong to the blazar population, it may be instructive to use the high-redshift blazars to study this problem. In Figure 11, we show the variations of the energy densities of various AGN components, for example, BLR/torus, as a function of the distance from the central black hole, as seen in the comoving frame of the jet plasma at $z = 5$ (Ghisellini & Tavecchio 2009). We assume $M_{\text{BH}} = 5 \times 10^9 M_\odot$ and $L_{\text{disk}} = 10^{47}$ erg s$^{-1}$ and $\Gamma = 8$. According to this diagram, the CMB energy density becomes dominant over other AGN components only after a kiloparsec from the black hole and even larger if the disk is more luminous. Therefore, if the observed X-ray enhancement is due to inverse-Compton scattering of CMB photons (IC-CMB), the emission region is

Figure 7. Distributions of various jet powers, as labeled. Other information is the same as in Figure 4. The statistics of the parameters are provided in Table 6.

Figure 8. Radiative jet power ($P_{\text{rad}}$) and total jet power ($P_{\text{jet}} = P_{\text{ele}} + P_{\text{mag}} + P_{\text{kin}}$) as a function of $L_{\text{disk}}$ are shown in the top and bottom panels, respectively. The high-redshift and $z < 3$ blazars are displayed with black squares and red circles, respectively. We also plot seven X-ray jetted blazars with blue stars. The pink line corresponds to the one-to-one correlation of the plotted quantities.
expected to be located far (>1 kpc) from the central engine, which is rather unconvincing, due to the rapid flux variability observed from blazars. In fact, CMB energy density is comparatively small and may not be able to explain the bright X-ray emission, which would be dominated by emission regions located closer to the central black hole because of the strong BLR/torus photon field. An alternative possibility to explain the enhanced X-ray brightness could be the shift of the SED peaks to lower frequencies as the redshift increases, thereby making the blazar more luminous in the X-ray band. Due to synchrotron self-absorption, however, this hypothesis cannot be tested at gigahertz frequencies, where the peak of the synchrotron emission is located. In addition to that, the presence of multiple emission regions cannot be excluded with a fraction of the observed X-ray emission being originated via the IC-CMB mechanism. Even in this case, the observed...
X-ray radiation will be dominated by that produced within the central few parsecs from the black hole. Therefore, a pure IC-CMB model is not supported by the observations (see also Zhu et al. 2019).

8. Summary

We have carried out a broadband study of 142 high-redshift (z > 3), radio-loud quasars that exhibit blazar-like characteristics, including nine γ-ray detected and 15 with hard X-ray observations with NuSTAR. Below we summarize our main findings:

1. The members of the high-redshift blazar population are faint γ-ray emitters with steep spectra, as revealed by the stacking analysis.
2. In the X-ray band, these objects have been selected in order to have flat (Γ_X) spectra and are luminous.
3. High-redshift blazars present in our sample host massive black holes (>10^8 M☉) and luminous accretion disks (> 10^{46} erg s⁻¹) at their centers.
4. Based on a simple one-zone lepton emission modeling, we have found that the high-redshift objects are megaelectronvolt-peaked and have Compton-dominated SEDs, thus indicating that a major fraction of their bolometric output is radiated in the form of high-energy X- to γ-ray emission. Furthermore, a rather low value of the bulk Lorentz factor based on available data can possibly explain the identification of fewer numbers of their parent population. However, a strong claim cannot be made, due to the lack of hard X-ray observations, for example, with NuSTAR, which are necessary to accurately constrain Γ.
5. The known accretion–jet connection noticed in the low-redshift blazars is also followed by the high-redshift ones. There are indications that both jet power and accretion luminosity have a maximum at ~10^{48} erg s⁻¹.
6. A small fraction of our sample that have available Chandra observations (seven out of 54) exhibit extended X-ray jets. These sources tend to have higher total jet powers with respect to other z > 3 blazars and, more importantly, have faster moving jets, though the results are model dependent. Further investigation considering a larger sample of X-ray jetted AGNs is needed to confirm this finding.
7. The observed X-ray enhancement of the high-redshift sources cannot be explained with a pure IC-CMB model. Among a few alternative possibilities, one could be the presence of multiple emission regions, with those located hundreds of parsecs away from the central black hole possibly contributing via the IC-CMB mechanism, though the overall emission may be dominated by those lying within the central parsec region of the AGN. A shift of the high-energy SED peak to lower frequencies (i.e., toward X-rays) as the redshift increases could be another possible explanation.

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This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013, 2018).

Facilities: Fermi-LAT, Swift, XMM-Newton, NuSTAR, Chandra.
Software: CIAO (v.4.9), SAS (v.15.0.0), XSPEC (v.12.10.1; Arnaud 1996), Astropy (Astropy Collaboration et al. 2013, 2018), Swift-XRT data product generator (Evans et al. 2009), fermiPy (Wood et al. 2017).

Appendix A
Uncertainty Measurement in the Disk Fitting Technique

As with any fitting method, the accuracy of the $M_{\text{BH}}$ and $L_{\text{disk}}$ computed from the accretion disk modeling technique depends on the IR-to-UV data coverage. For a good-quality

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Figure 12. Left: $\chi^2$ grid map of $M_{\text{BH}}$ and $L_{\text{disk}}$ for NVSS J144516+095836. The “+” sign denotes the minimum of the $\chi^2$ surface corresponding to the best-fitted $M_{\text{BH}}$ and $L_{\text{disk}}$ values. Confidence contours are at $1\sigma$ (black solid), $2\sigma$ (blue dotted), and $3\sigma$ (red dashed) levels. Right: IR–UV SED of the same object. Black data points are archival observations from SSDC, and the SDSS spectrum (not used in the fit) is shown with the red line. The blue dashed line refers to the best-fitted accretion disk model corresponding to the $M_{\text{BH}}$ and $L_{\text{disk}}$ values derived from the grid scan, as shown in the left panel. The green shaded area denotes the $1\sigma$ uncertainty in the fitted model.

Figure 13. Left: stacked TS profile of 133 $\gamma$-ray-undetected sources when $E_{\text{min}}$ for the analysis is set as 100 MeV. The black dashed line shows the Fermi-LAT sensitivity limit for the time period covered in this work. Middle: distributions of the TS for $\gamma$-ray-undetected sources. The blue dashed line shows the $\chi^2$ distribution for two degrees of freedom corresponding to the null hypothesis of no source, that is, random fluctuations. Right: significance profile of a simulated $\gamma$-ray point object with a hard and faint $\gamma$-ray spectrum. Note the bright and soft background emission is clearly distinguishable from the point-source signal. We have masked the negative TS values to highlight the positive signal. See the text for details.

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17 http://www.astropy.org
Stacking Analysis from 100 MeV

In Section 5.1, we presented the results derived from the stacking analysis with the minimum energy set as $E_{\min} = 300$ MeV. Here we explain the reasons behind the adopted choice of $E_{\min}$ instead of considering 100 MeV, which is conventionally used in the standard Fermi-LAT data analysis.

The left panel of Figure 13 shows the combined significance profile of 133 Fermi-LAT undetected blazars when the analysis was carried out using $E_{\min} = 100$ MeV. A bright and extremely soft $\gamma$-ray emission can be noticed. However, this emission may not have originated from the high-redshift blazars. This is due to three reasons: (1) none of the known $\gamma$-ray blazars, including the high-redshift ones, exhibit such a steep $\gamma$-ray spectrum in the 0.1–300 GeV energy range; (2) a comparison with the Fermi-LAT sensitivity limit for the period covered in this work suggests that individual objects with such a soft spectrum should have already been detected (see Figure 13, left panel); and (3) even after assuming that all 133 sources have the same photon flux and index, the combined TS cannot reach a value as large as $TS = 2250$. This is demonstrated in the middle panel of Figure 13, where we show the TS distributions for the considered high-redshift blazars and compare with a $\chi^2$ distribution with two degrees of freedom representing the null hypothesis. This plot also explains that the derived $\gamma$-ray signal (Figure 2) is not due to random background fluctuations and belongs to the real blazar population. Therefore, we conclude that the soft and bright emission observed in the stacked profile is most likely due to the isotropic background embedded in the Fermi-LAT data. This is further confirmed with the simulation of a hard spectrum blazar assuming it has 0.1–300 GeV photon index $\Gamma_{0.1–300 \text{ GeV}} = 1.7$, a photon flux $F_{0.1–300 \text{ GeV}} = 10^{-10}$ ph cm$^{-2}$ s$^{-1}$, and a faint signal $TS = 8$. The significance profile for this simulated blazar can be seen in the right panel of Figure 13. Due to the input assumption of the hard spectrum, we are able to disentangle the soft background emission, as can be seen in this plot.

To remove the observed background emission from the stacking, we carried out a number of tests and simulations, such as by changing the $z_{\max}$ or $E_{\min}$ thresholds. It was noticed that only after increasing the minimum energy from 100 MeV to 300 MeV are we able to get rid of the background. This is expected since a soft emission is brightest at the lowest energies. As can be seen in the right panel of Figure 2, when considering $E_{\min} = 300$ MeV, the background is completely removed from the stacking. Therefore, we repeated the whole exercise with $E_{\min} = 300$ MeV.

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