**Abstract**

High synchrotron peak (HSP; $\nu_{\text{pk}} > 10^{15}$ Hz) BL Lac objects are some of the most extreme accelerators in the universe. Those found at high redshifts ($z > 1$) challenge our understanding of blazar evolution models and are crucial for cosmological measurements of the extragalactic background light. In this paper, we study a high-$z$ BL Lac object, 4FGL J2146.5-1344, detected to be at $z = 1.34$ using the photometric dropout technique. We collected multiwavelength data for this source from optical up to $\gamma$-rays, in order to study its spectral energy distribution (SED). In particular, this source was observed for the first time with the Nuclear Spectroscopic Telescope Array, which accurately measures the synchrotron emission of this blazar up to 50 keV. Despite being classified as an HSP BL Lac object, the modeling of the SED reveals that this source likely belongs to the “masquerading BL Lac” class, which comprises flat spectrum radio quasars appearing as disguised BL Lac objects.

**Unified Astronomy Thesaurus concepts:** Active galactic nuclei (16); Blazars (164); Active galaxies (17); Astronomy data modeling (1859); BL Lacertae objects (158); High-redshift galaxies (734)

1. Introduction

Blazars form the largest class of active galactic nuclei (AGN) detected in the Fourth Fermi-Large Area Telescope (Fermi-LAT) source catalog (4FGL; The Fermi-LAT Collaboration 2019), making up about 97% of the total AGN population in the 50 MeV–1 TeV range. Displaying highly variable non-thermal emission credited to relativistic jets aligned very close to our line of sight (Blandford & Rees 1978), blazar spectral energy distribution (SED) is typically characterized by two broad bumps, one at lower energies (infrared to X-rays), attributed to synchrotron emission and inverse Compton scattering at higher energies (X-rays to $\gamma$-rays; Maraschi et al. 1994; Abdo et al. 2011). The two subclasses of blazars are BL Lacertae objects and flat spectrum radio quasars (FSRQs), mainly distinguished by their optical spectroscopic characteristics. BL Lac objects have been observed to have either no or very weak (equivalent width < 5 Å) emission lines (Urry & Padovani 1995), whereas FSRQs exhibit broad emission lines. The characteristic of BL Lac objects indicates either an especially strong nonthermal continuum or atypically weak thermal disk/broad-line emission which is mainly attributed to low accretion activity, jet dilution, or possibly both (Giommi et al. 2012a). Based on the frequency of synchrotron peak ($\nu_{\text{pk}}$), blazars are further classified into three categories (Abdo et al. 2010a), namely, low-synchrotron peak blazars (LSP; $\nu_{\text{pk}} \lesssim 10^{14}$ Hz), intermediate-synchrotron peak blazars (ISP; $10^{14}$ Hz $< \nu_{\text{pk}} < 10^{15}$ Hz), and high-synchrotron peak blazars (HSP; $\nu_{\text{pk}} > 10^{15}$ Hz). A sizable population of BL Lac objects lies within the ISP and HSP categories (Ackermann et al. 2015), exhibiting $\nu_{\text{pk}}$ up to $10^{17}$ Hz. BL Lac objects with such large $\nu_{\text{pk}}$ are able to accelerate electrons to beyond 100 TeV (Costamante et al. 2001; Tavecchio et al. 2011), making them some of the most powerful accelerators in the universe.

These BL Lac objects are extremely crucial for the studies of extragalactic background light (EBL; Ackermann et al. 2012; Abdollahi et al. 2018), which constitutes the emission of all stars and accreting compact objects in the observable universe since the reionization epoch. Presence of the zodiacal light and Galactic emission (Hauser & Dwek 2001) make direct studies of the EBL a challenging task. An indirect approach employed in measuring EBL intensity involves using $\gamma$-ray photons emitted by highly energetic sources (blazars). The interaction between these photons and the EBL ones causes an attenuation in the spectra (Stecker et al. 1992; Ackermann et al. 2012) of these $\gamma$-ray sources through the production of electron–positron pairs. This signature allows us to constrain EBL and study its evolution with redshift (Aharonian et al. 2006). Stronger attenuation is achieved when the $\gamma$-ray source is present at higher redshifts ($z$), which leads to better EBL constraints. Therefore, on account of being bright $\gamma$-ray sources with significant emission $>10$ GeV, high-redshift (high-$z$) BL Lac objects represent the perfect probes in indirect studies of the EBL.

Years of follow-up observations utilizing a range of techniques (Rau et al. 2012; Ajello et al. 2013; Shaw et al. 2014, 2013; Kaur et al. 2017) has allowed us to gather redshift constraints for the ∼200 brightest Fermi BL Lac objects. This approach yielded the discovery of a sizable number of BL Lac objects at redshifts up to $z \approx 2$, some of which possess hard GeV spectra (photon index $< 2$) and surprisingly belong to the HSP BL Lac object class.

Ghisellini et al. (2012) and Padovani et al. (2012) have proposed these candidates to be “blue FSRQs” (alternatively also called masquerading BL Lac objects), i.e., sources whose relativistic jet aimed at us swamps any broad emission lines and thus are hidden by a bright synchrotron emission. Recent evidence for TXS 0506+056 (originally classified as a BL Lac object), the first plausible cosmic nonstellar neutrino source detected by the IceCube Collaboration (2018), suggests it could...
belong to the masquerading BL Lac object class (Padovani et al. 2019). Although still very uncertain, this class may harbor cosmic neutrino emitters similar to TXS 0506+056. However, identifying such objects is challenging.

In this work, we focus on the high-$z$ source 4FGL J2146.5-1344, found by Kaur et al. (2017) to be at $z = 1.34$ using the photometric redshift technique. With the goal of identifying the nature of this source, we collected data from optical, UV, and X-ray facilities. Indeed, the synchrotron emission from the jet peaks in these energy bands, hence the best approach to precisely characterize their jet properties is to accurately sample these wavelengths. To this end, we have obtained as a part of an approved Cycle 4 program,\footnote{Proposal number: 4231, PI: M. Ajello.} data from the Nuclear Spectroscopic Telescope Array (\textit{NuSTAR}; Harrison et al. 2013). Launched in 2012 June, \textit{NuSTAR} has been a critical instrument for HSP BL Lac object studies. Spanning an energy range from 3 to 79 keV, \textit{NuSTAR}'s capabilities enable us to sample the falling part of the synchrotron emission, allowing us to solidly constrain the shape of the underlying electron distribution as well as the jet properties such as the bulk Lorentz factor, magnetic field strength, and jet power (Ghisellini et al. 2012).

Furthermore, quasi-simultaneous optical data from the Southeastern Association for Research in Astronomy (\textit{SARA}; Keel et al. 2017) consortiums 0.65 m telescope in Chile and UV/Optical data from Neil Gehrels \textit{Swift} Observatory’s UV/Optical Telescope (\textit{Swift}-UVOT; Gehrels et al. 2004) were utilized along with X-ray and \textit{\gamma}-ray data obtained from \textit{XMM-Newton} (Jansen et al. 2001) and \textit{Fermi-LAT} (Acero et al. 2015), respectively, in order to construct a multiband SED of the source.

The order of the paper is as follows: Section 2 describes the details about the source selection. Section 3 elaborates on the observations and data analysis methods and Section 4 elaborates on the X-ray analysis method. Section 5 describes the modeling procedure while Section 6 discusses the results and conclusions. We use a flat $\Lambda$CDM cosmological model with $H_0 = 67.8$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.30$, and $\Omega_{\Lambda} = 0.69$.

2. Target Selection

4FGL J2146.5-1344 (J2146 from here on) is an HSP BL Lac object first detected in the 1FGL catalog (Abdo et al. 2010b) and then subsequently reported in all \textit{Fermi}-LAT catalogs (Nolan et al. 2012; Acero et al. 2015; The Fermi-LAT Collaboration 2019). Found to be a high-$z$ source ($z = 1.34$) by Kaur et al. (2017) as part of the photometric campaign for BL Lac objects begun by Rau et al. (2012), J2146 exhibits a synchrotron peak frequency of $\sim 10^{16}$ Hz, a luminosity in excess of $\sim 10^{47}$ erg s$^{-1}$, and a very hard \textit{\gamma}-ray spectrum with photon index $\sim 1.6$. The considerable emission at 100 GeV (Abdo et al. 2017) also makes it a powerful tool to probe EBL, since at $z = 1.34$ the universe is already opaque to the propagation of $E \sim 100$ GeV photons (optical depth, $\tau > 1.3$; Domínguez et al. 2011). This implies that these high-$z$ HSP sources can help constrain the cosmic \textit{\gamma}-ray horizon, which is defined by the energy at which the optical depth ($\tau$) is 1, as a function of redshift.

3. Observations and Data Analysis

3.1. \textit{Fermi-LAT}

Data at \textit{\gamma}-ray energies for J2146 is provided in the fourth \textit{Fermi}-LAT source catalog (The Fermi-LAT Collaboration 2019), which includes all the sources detected at energies between 50 MeV and 1 TeV. \textit{\gamma}-ray flux from 1 to 100 GeV and the uncertainty associated is shown in Table 1. Both 3FGL and 4FGL catalogs report the source as nonvariable and since the source is absent from the 2FAV catalog (Abdollahi et al. 2017), we are able to use the data from the 4FGL catalog for the SED construction of this source.

3.2. \textit{NuSTAR}

J2146 was observed by \textit{NuSTAR} on 2018 May 18 for 42.3 ks. Data was processed for both the instrument Focal Plane Modules A (FPMA) and B (FPMB) using the \textit{NuSTAR} Data Analysis Software, \textit{NUSTARDAS}, integrated in the HEASoft v.6.21\footnote{https://heasarc.nasa.gov/lheasoft/} software package. Calibrations were performed using the \textit{nupipeline} task (response file obtained from the latest CALDB database, v.20180419). For the source extraction, a circular region of radius 30" was centered on the coordinates of the target and a background circular region of $\sim 30^\circ$ radius was placed in the same frame, avoiding possible contamination from source photons to provide a good signal-to-noise ratio. These events were operated on by the task \textit{nuproducts} in order to generate the spectra and matrix files. The spectra obtained were rebinned to have 15 counts per bin.

3.3. X-Ray Multi-Mirror Mission Spacecraft (\textit{XMM-Newton})

The \textit{XMM-Newton}, launched by the European Space Agency, consists of three X-ray telescopes equipped at their foci with a set of three X-ray CCD cameras: MOS1, MOS2 (Metal Oxide Semi-conductor), and the European Photon Imaging Camera (EPIC) pn CCD. In the energy range from 0.2 to 12 keV, \textit{XMM-Newton} allows us to observe sources with extreme sensitivities over the telescope’s field of view. J2146 was observed by \textit{XMM-Newton} on 2018 May 18 for 17 ks. Observations for the source were obtained and processed for all three CCD arrays. The \textit{XMM-Newton} Science Analysis Software v16.0.0. was employed for data reduction and tasks \textit{emproc} and \textit{epproc} were used for generating event files for MOS and pn respectively. Source and background spectra were generated using \textit{evselect} after extracting source and background regions of 10" and 20" respectively. The spectra obtained were rebinned to have 15 counts per bin.

3.4. \textit{Swift} and \textit{SARA}

The X-ray data were supplemented by optical observations from the \textit{SARA} consortium’s 0.65 m telescope at Cerro Tololo, Chile (\textit{SARA}-CT), and UV/Optical observations from the \textit{Swift} satellite (Gehrels et al. 2004). Data was gathered with \textit{SARA}-CT on 2018 August 27 sequentially in four filters ($g', r', i', z'$) and \textit{Swift}-UVOT (The Ultraviolet and Optical Telescope; Roming et al. 2005) conducted observations of the source in six filters (\textit{uvw2}, \textit{uvw1}, \textit{u}, \textit{b}, \textit{v}) on 2018 June 23, obtaining data for $\sim 2000$ s. Optical data was reduced using the photometry technique with the help of the software package, \textit{IRAF} (v2.16; Tody 1986). Standard star calibrations were
performed using the SDSS Data Release 13 (Albareti et al. 2017) and Galactic foreground extinction corrections were made using Schlafly & Finkbeiner (2011).

\textit{Swift}-UVOT data reduction employed the use of the standard UVOT pipeline procedure (Poole et al. 2008) to obtain the magnitudes of the source in each filter. This was achieved using HEASoft v.6.218 software and the tasks therein. The task \textit{uvotimsum} was used to combine image snapshots obtained from multiple observations and task \textit{uvotsource} was used to obtain the magnitudes and errors. A source region of radius 5\arcsec and a background region of 25\arcsec was selected in order to maximize the signal-to-noise ratio and subtract the background. The obtained magnitudes were corrected for Galactic foreground extinction using Table 5 presented in Kataoka et al. (2008) and converted to the AB system.

### 4. X-Ray Spectral Analysis

The X-ray spectral analysis for \textit{XMM-Newton} and \textit{NuSTAR} spectra was carried out using the \textit{XSPEC} tool (also provided in the HEASoft package). We obtained the Galactic column density ($N_H$) for the source using Kalberla et al. (2005) and employed a $\chi^2$-fitting procedure which used a simple power-law model with a multiplicative constant factor to fit the source. The constant was fixed at unity for EPIC pn and left free for all other instruments in order to calibrate them against each other. The flux of FPMA was found to be $\sim$20% of FPMB. Upon investigation, it was established that the source falls in a chip gap between the two focal planes accounting for the loss of photons. In order to account for this discrepancy, we separately fitted with \textit{XSPEC} both \textit{NuSTAR} focal modules using a simple power law. The resulting fluxes and indices are consistent for both FPMA and FPMB considering the errors so the gap does not influence our X-ray analysis. Furthermore, we tested for a possible curvature in the spectrum of the source. We jointly fitted \textit{XMM-Newton} and \textit{NuSTAR} with a log-parabolic model ($\text{logpar}$ in \textit{XSPEC}) and a broken power-law one ($\text{bknpo}$ in \textit{XSPEC}), always keeping the galactic $N_H$ fixed. The outcomes of the spectral fits did not provide any significant improvement with respect to the simple power law. Results using the F-test returned p-values $\sim$10$^{-1}$, hence, any curvature in the X-ray spectrum of our source can be excluded. The parameters obtained from the model fit are shown in Table 1 and the model fit is depicted in Figure 1.

### 5. Modeling

To explain the SED of J2146, a single-zone leptonic emission model is adopted. In this section, we highlight its general outline (see Ghisellini & Tavecchio 2009 for more details). The radiation is assumed to be produced by relativistic electrons enclosed in a spherical region distant $R_{\text{diss}}$ from the black hole. This region encompasses the total jet cross-section and moves with a bulk Lorentz factor, $\Gamma$. The electrons are distributed in energy according to a broken power-law shape of the type:

$$N(\gamma) \propto \frac{(\gamma/\gamma_{\text{break}})^p}{(\gamma/\gamma_{\text{break}})^p + (\gamma/\gamma_{\text{break}})^q},$$

where $\gamma_{\text{break}}$ is the energy break and $p$ and $q$ are the slopes before and after the break.

The particles are embedded in a uniform and randomly oriented magnetic field ($B$). As a consequence, they accelerate and thereafter radiate via the synchrotron process. In the presence of an external radiation field they also lose energy via the inverse Compton process. In the model, both synchrotron self Compton (SSC) and external Compton (EC) are taken into account. In the SSC case, photons produced by synchrotron emission are up-scattered to higher energies by the same electron population. For the EC, the electrons instead interact with photons external to the jet, up-scattering them to high
energies. The following are considered as reservoirs of low-energy photons:

1. The accretion disk. It is modeled as a standard Shakura & Sunyaev (1973) disk and its SED is reproduced by a multicolor blackbody (Frank et al. 2002).

2. The X-ray corona above the disk. Its spectrum is considered to be a power-law with exponential cutoff reprocessing 30% of disk emission.

3. The broad-line region (BLR) clouds. Modeled as a spherical shell at the distance, \( R_{\text{BLR}} = 10^{17} L_{\text{disk,45}}^{1/2} \) cm, where \( L_{\text{disk,45}} \) is the accretion disk luminosity in units of \( 10^{45} \text{ erg s}^{-1} \), from the black hole, it reprocesses 10% of the disk emission. Its spectrum is a blackbody peaking at the \( L_\gamma \) frequency.

4. The infrared torus. Similarly to the BLR, it is considered a spherical shell at \( R_{\text{TORUS}} = 10^{18} L_{\text{disk,45}}^{1/2} \) cm, reradiating 50% of the disk emission. Its blackbody spectrum peaks at the typical torus temperature of 300 K.

The energy densities of all components depend on \( R_{\text{disk}} \) and are evaluated by the model.

As for the black hole mass, we found that the source optical spectrum is reported in Shaw et al. (2013), along with a redshift lower limit of 0.71 and an upper limit of 1.64, consistent with its measured photometric one (Kaur et al. 2017). Although no bright emission lines are detected, the authors estimate the black hole mass of the studied BL Lac objects from the \( M-\lambda \) relationship with the host galaxy, and found an average of \( \sim 5.6 \times 10^8 M_\odot \) (with large dispersion).\(^9\) Similarly, Sbarrato et al. (2012) found an average mass for LAT detected FSRQs of \( 5 \times 10^8 M_\odot \) and Paliya et al. (2017) derived an average mass of \( 8 \times 10^8 M_\odot \) for radio-loud (i.e., jetted) CGRabs (Healey et al. 2008) quasars using a model dependent approach. We therefore use these ranges for our assumptions on the black hole mass of J2146. Moreover, since the disk emission is overwhelmed by the nonthermal synchrotron one, if detected, it would result in a visible hump in the optical part of the SED. Further constraints on the disk luminosity come from empirical relations (see Ghisellini et al. 2012; Sbarrato et al. 2012).

\(^9\) In the same work, authors report masses found spectroscopically for Fermi FSRQs that have \( M \sim 1.3 \times 10^9 M_\odot \).
The source J2146 is one of the soft X-ray brightest ($L_{\nu,0.3-10\text{ keV}} \gtrsim 5 \times 10^{46} \text{ erg s}^{-1}$) and high-$\zeta$ blazars detected by the Fermi-LAT. With $\nu_{\text{pk}}^p \approx 6 \times 10^{15} \text{ Hz}$, it is among the few high-power HSP blazars so far discovered (although Masetti et al. 2013 reclassified this source as an ISP BL Lac object instead of an HSP one). Only a handful of similar objects have been found (see Ghisellini et al. 2012; Padovani et al. 2012) and, together with our source, they challenge our understanding of the blazar population and the physical processes powering them. In fact, according to the so-called “blazar sequence” (see, e.g., Fossati et al. 1998; Ghisellini & Tavecchio 2008; Ghisellini et al. 2017) these kinds of high-power HSP blazars should not exist. In the works of Padovani et al. (2012) and Ghisellini et al. (2012), the authors have established that these blazars are more likely “blue FSRQs” (or “masquerading BL Lac objects,” i.e., FSRQs with emission lines saturated by the nonthermal synchrotron emission) rather than BL Lac object–type sources. Indeed, their high radio power ($P_{\nu,\text{1 GHz}} > 10^{27} \text{ WHz}^{-1}$), high synchrotron peak luminosity ($L_{\text{syn,peak}} > 10^{46} \text{ erg s}^{-1}$) and $\nu_{\text{pk}}^p > 3 \times 10^{15} \text{ Hz}$ are all factors that make them resemble more FSRQs than BL Lac objects (see Giommi et al. 2012a, 2012b). Unveiling the nature of J2146 (i.e., whether it is a “masquerading BL Lac object” or an HSP BL Lac object) is important in the context of the blazar sequence and to test the cosmological models of the EBL. Moreover, J2146 is among the most luminous accelerators in our universe and its emission up to 100 GeV makes it an excellent probe to test cosmological models of the EBL.

Lacking absorption lines in the optical spectra (Shaw et al. 2013), in order to understand the nature of this blazar and to constrain the jet properties, it is necessary to obtain a multwavelength coverage of the source, from radio up to $\gamma$-rays. Availability of quasi-simultaneous optical and X-ray data enables us to accurately constrain the position of the $\nu_{\text{pk}}^p$ as well as the shape of the underlying electron distribution, which in turn provides us with good estimates for the jet power. In particular, the capabilities of NuSTAR allow us to sample the falling part of the synchrotron spectrum up to 50 keV. The source shows a very soft spectral index in this regime ($\Gamma_{\text{X}} = 2.48 \pm 0.02$), which is reflective of the shape of the underlying electron emitting population. Moreover, if present, a curvature in the hard X-ray spectra would have hinted toward an intrinsic curvature in the particle spectrum and would have been reflected in the falling part of the $\gamma$-ray spectrum. The lack of such a feature in the X-ray continuum (see Section 4) indicates that any curvature above 10 GeV is likely due to EBL absorption.10

From a modeling perspective, both the EC and SSC appear to return equally good fits. The parameters obtained for the two models (see Table 2) and the jet power components are in agreement with what was found by Ghisellini et al. (2012). We note that to explain the FSRQ-like emission (i.e., EC model), we need to impose the location of the emission region beyond the BLR clouds (and within the torus), conforming to what is reported in Ghisellini et al. (2012). Hence, the main photon energy density contributing to the EC is the torus one. This is in agreement with the recent results of Costamante et al. (2018) and Meyer et al. (2019), who found the emission region location outside the BLR while studying the emission of Fermi-LAT broad-line blazars. However, if this source is an FSRQ, it would need to support a very high radiative power, even larger than the kinetic one. Therefore, the jet would be radiatively and magnetically dominated in contrast with what is usually expected for FSRQs. In the SSC scenario, we point out that in order to explain the SED, we require a steeper index of the electron distribution below the break ($p$) which does not provide a very good fit to the optical and archival data. Comparing the BLR and $\gamma$-ray luminosity of J2146 with other Fermi-detected blazars analyzed by Ghisellini et al. (2011), we can see in Figure 4 how our source falls in the region typically occupied by FSRQs. Nonetheless, since we do not have strong constraints on the black hole mass of the object from either spectroscopy or photometric data, we tested how the position of the source would change for a higher black hole mass of $M_h > 10^9 M_\odot$. From Figure 4, it can be seen how the source will still fall above the BL Lac/FSRQ divide. Also, since the synchrotron peak luminosity is $\sim 6 \times 10^{46} \text{ erg s}^{-1}$ and the radio power of our source is $P_{\nu,\text{1 GHz}} = 2.59 \times 10^{36} \text{ WHz}^{-1}$ (Condon et al. 1998), these values are more consistent with FSRQs than BL Lac objects. Overall, even though a firm conclusion on the nature of J2146 cannot be made, comparing it with the other similar objects studied in the works of Padovani et al. (2012) and Ghisellini et al. (2012), it could likely belong to the class of “masquerading BL Lac objects.”

Finally, using the model from Finke et al. (2010) we are able to model the curvature in the $\gamma$-ray spectrum. BL Lac object–like sources with emission beyond $>10$ GeV are of incredible value for studies of the EBL. Indeed, the absorption due to the annihilation of the source $\gamma$-rays with EBL photons is a tracer for the EBL intensity and it is effective beyond $>10$ GeV. However, a lack of redshift measurements for half of the BL Lac object population has hindered accurate measurements of the EBL so far. The new photometric redshift measurements of BL Lac objects (Rau et al. 2012; Kaur et al. 2017) represent a new avenue to use BL Lac objects as EBL probes. As can be seen from Figures 2 and 3, the $\gamma$-ray part of J2146 SED shows a very steep fall off which is perfectly explained by EBL.

10 Our model does not include the Klein–Nishina effect which would produce a steeper high-energy IC spectrum (Georganopoulos et al. 2001; Ackermann et al. 2010; Dermer & Lott 2012). However, this effect should also be visible in the X-ray part of synchrotron spectrum, and therefore already constrained by our found $q$. The sharp cutoff in the $\gamma$-ray band could not be explained by this effect alone.
absorption at the redshift of the source. This points to the fact that sources such as J2146 would represent perfect probes for constraining and testing EBL models. In fact, prediction of many such models diverges as redshift increases, and the uncertainties associated get larger. Therefore, a systematic multwavelength study of more such blazars would allow for tighter constraints on the EBL measurements.

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**ORCID iDs**

M. Rajagopal https://orcid.org/0000-0002-8979-5254
L. Marcotulli https://orcid.org/0000-0002-8472-3649
M. Ajello https://orcid.org/0000-0002-6584-1703
A. Kaur https://orcid.org/0000-0002-0878-1193
V. Paliya https://orcid.org/0000-0001-7774-5308
D. Hartmann https://orcid.org/0000-0002-8028-0991
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