PROCEEDINGS OF SCIENCE

Parsec-Scale Jets of γ-ray AGNs

Matthew L. Lister[∗†]
Dept. of Physics, Purdue University, USA
E-mail: `mlister@purdue.edu`

The *Fermi* γ-ray telescope has created important new opportunities for exploring the demographics of blazar jets associated with active galactic nuclei. Here we discuss a study of the *Fermi* LAT γ-ray and 15 GHz VLBA radio properties of a joint γ-ray- and radio-selected sample of AGNs obtained during the first 11 months of the *Fermi* mission (2008 Aug 4 - 2009 Jul 5). This sample contains the brightest 173 AGNs in these bands above declination -30° during this period, and thus probes the full range of γ-ray loudness (γ-ray to radio band luminosity ratio) in the bright blazar population. The latter quantity spans at least four orders of magnitude, reflecting a wide range of spectral energy distribution (SED) parameters. The BL Lac objects, however, display a strong correlation of increasing γ-ray loudness with synchrotron SED peak frequency, suggesting a universal SED shape for objects of this class. The synchrotron self-Compton model is favored for the γ-ray emission in these BL Lacs over external seed photon models, since the latter predict a dependence of Compton dominance on Doppler factor that would destroy any observed synchrotron SED peak - γ-ray loudness correlation. The high-synchrotron peaked (HSP) BL Lac objects are distinguished by lower than average radio core brightness temperatures, and none display large radio modulation indices or high linear core polarization levels. No equivalent trends are seen for the flat-spectrum radio quasars (FSRQ). Given the association of such properties with relativistic beaming, we suggest that among the bright blazar population, the HSP BL Lacs have generally lower Doppler factors than the lower-synchrotron peaked BL Lacs or FSRQs.

AGN Physics in the CTA Era - AGN2011,
May 16-17, 2011
Toulouse, France

[∗]Speaker.
[†]This work is a joint effort of the MOJAVE and *Fermi*-LAT collaborations

PoS(AGN 2011)010

1. INTRODUCTION

The successful launch of the *Fermi Gamma-Ray Space Telescope* in 2008 has brought about a new era for understanding the physics of blazars, which dominate the extragalactic sky at high energies. Because of their highly variable fluxes and spectral energy distributions (SEDs), blazar samples are typically subject to large biases, making it difficult to study their demographics. With the nearly continuous all-sky monitoring capabilities of *Fermi's* Large Area Telescope (LAT), however, it is now possible to construct well-defined samples that can be used to investigate the wide range of jet properties in these powerful AGNs [4, 21].

One of these properties that has been of considerable interest since the era of the *Compton* Observatory (CGRO) in the 1990s is γ-ray loudness, or in other words, why only a particular small subset of known AGNs (~ 100) were detected by the CGRO's EGRET telescope [14]. Considerable evidence has been presented by many researchers [11, 20, 22, 18, 39] supporting the idea that relativistic Doppler boosting has a large impact on AGN γ-ray emission, but lingering questions regarding the roles of the flaring duty cycle and the AGN spectral energy distribution remain. The superior sensitivity and full-time survey operation mode of *Fermi* has provided substantial insight into these issues. With the release of the 1FGL catalog [3], the strong impact of SED characteristics on the fainter γ-ray AGN population was realized, as the sky at these levels becomes dominated by high-synchrotron peaked BL Lac objects. At the same time, the predominant association of *Fermi* LAT sources with flat-spectrum radio quasars (FSRQ) and BL Lacs (blazars) has established Doppler boosting as the primary factor in determining γ-ray loudness in the brightest AGNs.

Initial studies of bright blazars based on the 3 month LAT data [1] established several important radio/γ-ray connections using quasi-simultaneous VLBA observations. These included the fact that the γ-ray photon flux correlates with the parsec scale radio flux density [23], and that the jets of the LAT-detected blazars have higher-than-average apparent speeds [27], larger apparent opening angles [35], more compact radio cores [23], strong polarization near the base of the jet [25], and higher variability Doppler factors [37]. AGN jets have also been found to be in a more active radio state within several months of the LAT-detection of their strong γ-ray emission [23, 34].

With the release of the 1st LAT AGN catalog (1LAC; [4]) based on the initial 11 months of *Fermi* data, it is possible to investigate the impact of Doppler beaming and SED characteristics on AGN γ-ray loudness with much better statistics. We have carried out a joint analysis of *Fermi* and VLBA 15 GHz radio properties of the brightest radio and γ-ray AGN in the northern sky, based on data from the LAT instrument, flux density measurements from the OVRO and UMRAO radio observatories, and the MOJAVE VLBA program [28]. In particular we examine the differences in the SED and γ-ray properties of BL Lac objects with respect to FSRQs, and the role of relativistic beaming on their γ-ray loudness. The full details of our study have been published elsewhere[29].

2. THE MOJAVE-LAT BLAZAR SAMPLE

In assembling a suitable γ-ray AGN sample, our main considerations were that the sources be suitably bright at γ-ray energies, and have sufficiently strong compact radio emission for imaging with the VLBA. We also required the sample to be of reasonable size (~ 100 sources) to ensure good statistics, yet small enough so that it could still be fully monitored by the MOJAVE VLBA

PoS(AGN 2011)010

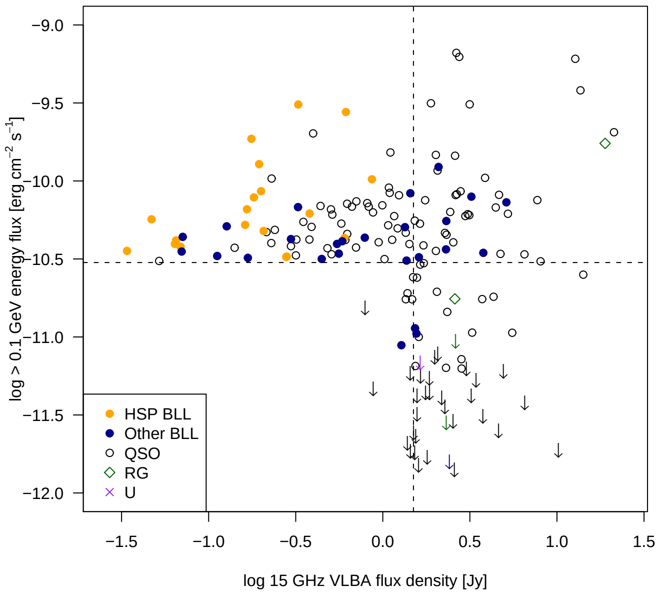

Figure 1: Plot of 11 month *Fermi* average > 0.1 GeV energy flux versus 15 GHz VLBA flux density for our joint AGN sample. Upper limits on the γ-ray fluxes are indicated by arrows. The vertical dashed line indicates the radio sample limit of 1.5 Jy, and the horizontal dashed line indicates the γ-ray limit of 3×10^{-11} erg cm^{-2} s^{-1}. Some AGNs in the bottom left quadrant have flux densities below 1.5 Jy since the VLBA radio measurements don't necessarily coincide with the epoch of maximum flux density.

program. We first eliminated from the LAT 1FGL catalog [3] all of the γ-ray sources known to be associated with non-extragalactic objects, and one gravitationally lensed AGN. We also excluded five millisecond γ-ray pulsars that were recognized after the publication of the 1LAC [4] and 1FGL [3] papers. We then kept all AGNs that had an average integrated > 0.1 GeV energy flux $\geq 3 \times 10^{-11}$ erg cm^{-2} s^{-1}, declination $> -30^\circ$, and Galactic latitude $|b| > 10^\circ$. These criteria yielded a total of 118 candidate AGNs in our 1FGL-MOJAVE (hereafter 1FM) list. Of these, only two had no clear radio source association. Subsequent radio observations at OVRO showed no strong radio counterparts within the LAT error circles, so we dropped these two LAT sources from the 1FM sample.

For our matching radio-selected sample, we used the same sky region criteria as the 1FM, choosing all AGNs known to have exceeded $S_{\rm VLBA}$ = 1.5 Jy at 15 GHz during the initial *Fermi* 11 month period, without regards to γ-ray flux (Figure 1). There are 105 AGNs in our final 1FM matching radio-selected sample, 48 of which are also in the 1FM γ-ray-selected sample.

Selection Biases: Our two complete samples consist of the brightest AGNs in the northern γ-ray and radio sky, as seen during the first 11 months of the *Fermi* mission. Unlike blazar surveys in the optical or soft X-ray regimes, the radio emission from the brightest radio-loud blazars is not substantially obscured by or blended with emission from the host galaxy. Furthermore, the use of a long-spacing interferometer at relatively short radio wavelength guarantees little contamination of the flux densities by large kpc-scale lobe emission. Our VLBA-selected sample thus provides a relatively clean blazar sample, namely, one selected solely on the basis of beamed synchrotron emission from the relativistic jets. Likewise, at γ-ray energies, the brightest AGNs are highly jet-dominated, with very few extended kpc-scale lobes having being detected to date (e.g., Centaurus A [2]).

Although our γ-ray and radio selections are both made on the basis of compact beamed jet emission, there is only a 28% overlap in the two samples. This is perhaps lower than might be expected, given the strong correlations previously seen between the 1LAC catalog and flat-spectrum radio sources [4]. As we will discuss in §3, this is mainly a consequence of the wide range of γ-ray loudness in the bright blazar population. The nature of our γ-ray sample selection differs from that of our radio sample, since it spans a wide energy band compared to the radio. It is thus more sensitive to the shapes of the AGN SEDs, which can have curvature and breaks within the LAT detector band. The spectral response function of the LAT detector and its favoritism towards harder sources causes some selection bias towards faint high-synchrotron peaked AGNs [3]. We note, however, that the sources in our 1FM sample are selected well above the instrument sensitivity level of the LAT detector, and should be devoid of biases related to threshold effects.

Observational Data: The 15 GHz radio VLBA data were obtained as part of the MOJAVE observing program [28], and consist of linear polarization and total intensity images with a typical image FWHM restoring beam of approximately 1 milliarcsecond. This corresponds to a scale of a few parsecs at the typical redshifts ($z \simeq 1$) of our sample AGNs. Our chosen statistic for describing γ-ray loudness is the ratio of average γ-ray luminosity during the first 11 months of the *Fermi* mission to the median 15 GHz VLBA radio luminosity. We have compiled this ratio G_r for all the AGNs in our sample using the 1FGL > 0.1 GeV γ-ray energy flux measurements of [3] and our VLBA and single-dish radio data. For those AGNs not in the 1FGL catalog, we derived $\sim 2\sigma$ γ-ray upper limits directly from the LAT data.

3. DISCUSSION

Redshift Distributions: The redshift data for our AGN samples are incomplete, with missing values for 4 sources in the radio-selected sample, and 22 sources in the γ-ray-selected sample (two are common to both samples). The redshifts range from $z = 0.00436$ to $z = 3.396$, and the distributions are generally peaked between $z = 0.5$ and $z = 1$. The overall redshift distribution of the γ-ray-selected sample has an additional peak at low redshift, due to the presence of at least 9 high synchrotron peaked (HSP) BL Lacs that are not in the radio selected sample (8 additional HSP BL Lacs lack redshift information). These objects also bring the overall fraction of BL Lacs up to 35% in the γ-ray-selected sample, as compared to only 13% for the radio-selected sample. Considering the overlap of the two samples and similar overall redshift distributions, we will combine them throughout the balance of our discussion.

γ-ray Loudness and Synchrotron Peak Frequency: In Figure 2 we show a plot γ-ray loudness versus synchrotron SED peak frequency, which shows several interesting trends. First, there is a significant difference in the G_r distributions of the quasars and the BL Lacs, with the former peaking at $G_r \simeq 10^3$ and the latter peaking above $10^{3.5}$. There is a substantial population of quasars with G_r values below 100, while all of the BL Lacs (with the exception of J0006−0623) have *Fermi* associations and $G_r > 60$. None of the 4 radio galaxies in our sample are significantly

PoS(AGN 2011)010

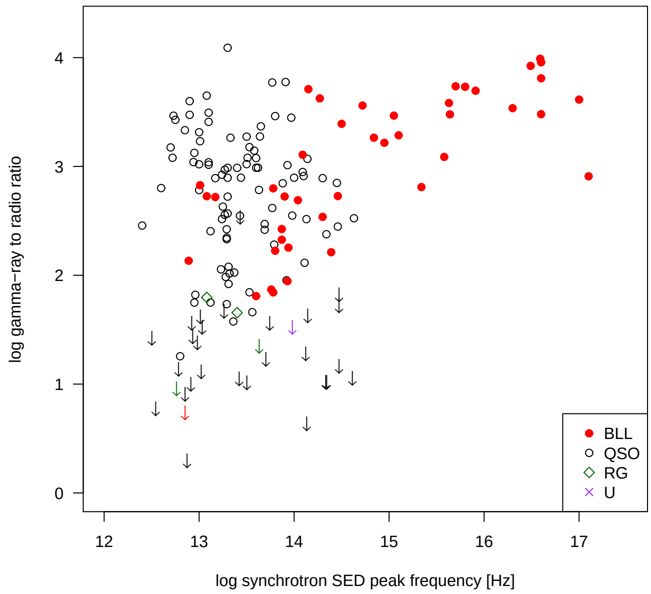

Figure 2: γ-ray to radio luminosity ratio G_r versus synchrotron SED peak frequency.

γ-ray-loud, with ratios all below 65. The large range in G_r – over 4 orders of magnitude – reflects the wide diversity in SED shapes among bright blazars, in terms of their synchrotron peak location and Compton dominance.

Second, the BL Lacs show a good log-log correlation with a scatter of 0.5 dex, while the quasars show no trend. It is apparent that the BL Lacs have a higher mean γ-ray loudness value because many of them have synchrotron peaks above $\sim 10^{15}$ Hz. Since the fixed radio bandpass is always located below the synchrotron peak, if we compare two BL Lacs with identical SED shapes but different synchrotron peak locations, the high synchrotron peaked BL Lac will have a lower radio flux density, and thus a higher γ-ray loudness value.

A similar spectral index effect also occurs as the high energy SED peak moves in tandem through the *Fermi* LAT band as the synchrotron peak frequency increases. This is manifested in the strong correlation between the γ-ray photon index and synchrotron peak frequency for the 1FGL blazars[4]. In Figure 3 we plot γ-ray loudness against photon spectral index. Again we see a good (even tighter) correlation for the BL Lac objects, and no trend for the quasars.

The continuous trend from LSP to HSP BL Lacs in Figures 2 and 3 is noteworthy, since it implies a relatively narrow intrinsic range of variation in the SED shapes of the brightest BL Lac objects. Broadly speaking, there are three aspects of a SED that can affect its measured γ-ray loudness parameter. These are the relative positions of the synchrotron and high energy peaks with respect to the fixed γ-ray and radio bands, their relative luminosities (often referred to as the Compton dominance), and the width and shape of each peak. In the simplest scenario of both peaks having equal luminosity, constant spacing and parabolic forms in $\nu F_\nu - \nu$ space [29], then we would expect expect to find a relation of the form $\log G_r = \alpha \log \nu_s$, exactly as in Figure 2.

From compilations of observed blazar SEDs[5, 8] we know, however, there is a range of SED parameters and shapes among the population. These factors would tend to distort any trend from the simple linear one described here. Furthermore, an intrinsic range of Compton dominance parameter would likely destroy any linear relation completely. The fact that we see a scatter of only 0.5 dex for the BL Lac objects therefore implies that the SEDs of the brightest AGNs of this class must have relatively similar shapes, at least much more so than the quasars, which show no ν_s-G_r correlation. Our results are corroborated by a recent study of the 1LAC[13], which defined a "Compton efficiency" parameter as the ratio of the high-energy (inverse Compton) SED peak luminosity to 8 GHz radio VLA core luminosity. They found a similar trend of higher Compton efficiency with increasing synchrotron peak frequency for BL Lac objects, but no trend for FSRQs.

So far in this discussion we have neglected the possible effects of relativistic beaming on the SED. For the simple case of the same Doppler factor in both the radio and γ-ray-emitting regions, the entire SED should be blue-shifted by the Doppler factor, and the apparent luminosity of both peaks will be Doppler boosted. Models which attribute the high energy peak to inverse Compton scattering of external seed photons by relativistic electrons in the jet predict a higher Doppler boost in γ-rays, because of the additional Lorentz transformation between the seed photon and jet rest frames [10]. In this case, when considering a jet at smaller viewing angle, the resulting increase in Doppler factor boosts the luminosity of the high energy peak to a level much higher than the synchrotron peak, thereby increasing the observed Compton dominance and γ-ray loudness. If the seed photons are internal to the jet, for a single-zone synchrotron self-Compton (SSC) model relatively equal boosting is expected in both regimes; thus G_r in this case is much less sensitive to Doppler boosting. The good G_r-ν_s correlation for the BL Lacs therefore favors the SSC process as the dominant emission mechanism in this class of blazars. This is in general agreement with the conclusions of recent studies which have modeled the SEDs of *Fermi*-detected blazars with detailed synchrotron and inverse-Compton emission models [5]. It will be possible to investigate this issue in much greater depth, using measured Compton dominance values, when more detailed information on the SED parameters of our full sample are available.

Core Brightness Temperature: Nearly all of the AGNs in our sample have a parsec-scale radio jet morphology that is dominated by a bright, flat-spectrum core, which is often unresolved or barely resolved in our mas-scale VLBA images. At our observing frequency of 15 GHz, this core typically represents the region where the jet becomes optically thick, with the true jet nozzle being located upstream. The brightness temperature of the core component in our VLBA images measures the compactness of the radio jet emission, which has been previously shown to be well-correlated with indicators of relativistic beaming, such as superluminal apparent speed [16] and radio flux density variability [40, 17]. In Figure 4 we plot core brightness temperature against synchrotron SED peak frequency. The main visible trend is that the HSP BL Lac radio cores tend to be less compact than those of the other AGNs in the sample. This has possible ramifications on beaming and jet velocity stratification models for HSP BL Lacs, as we will discuss below.

Other Radio Properties: The intense flux variability seen in blazars is also believed to be closely related to Doppler beaming [6, 24, 17] since it can significantly heighten the magnitudes of flaring events and shorten their apparent timescales. AGN jets have also been found to be in a more active radio state within several months from LAT-detection of their strong γ-ray emission [23, 34]. We have examined the radio modulation indices at 15 GHz, as measured by the OVRO

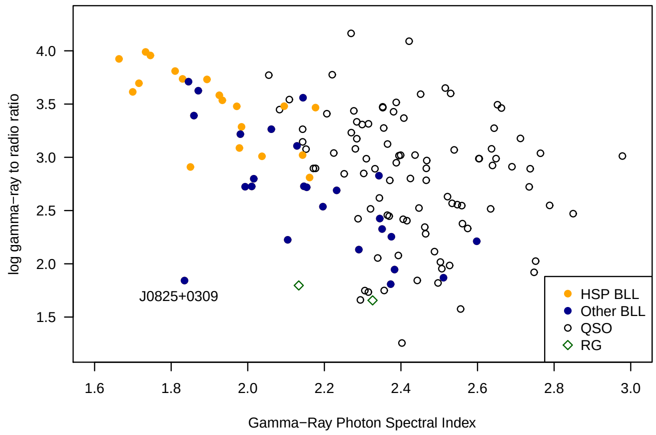

Figure 3: Plot of γ-ray to radio luminosity ratio G_r versus γ-ray photon spectral index.

40m telescope [36], and find that the AGNs in our sample are indeed highly variable, with 51 of 144 sources having standard deviations greater than 15% of their mean flux density level over an 11 month period. In their full OVRO sample of over 1000 sources, [36] found the FSRQs to have significantly higher variability amplitudes than the BL Lacs. We do not see this distinction in our sample, however, most likely because ours contains a smaller proportion of high-synchrotron peaked BL Lacs. The latter tend to have moderately low radio modulation indexes. These high-peaked objects also have low core polarization levels in our VLBA images.

In a previous study of the MOJAVE sample using the initial 3 months of *Fermi* data, [35] found a tendency for the γ-ray-detected blazars to have wider apparent opening angles than the non-detected ones. Since the calculated intrinsic opening angles of the two groups were similar, they concluded that the γ-ray-detected jets were viewed more closely to the line of sight. We have analyzed the apparent jet opening angles of our sample, and find that they range from 5 to 68 degrees, with a mean of 24 degrees. There is an extended tail to the distribution, with 19 jets having opening angles greater than 40 degrees. With the exception of the quasar J0654+4514, none of the high opening angle jets have very strong variability (radio modulation indices all less than 0.26). We find no statistically discernible differences in the opening angle distributions of the different optical or SED classes. In terms of γ-ray properties, all of the AGNs in the high-opening angle tail ($>$ 40 deg.) of the distribution are significantly γ-ray-loud ($G_r > 100$). The apparent opening angle of a jet is related to the viewing angle and intrinsic opening angle, with smaller intrinsic angles expected for high Lorentz factor jets based on hydrodynamical considerations [19]. The high opening angle jets in our sample are a mixture of BL Lac objects and FSRQ, with a range of synchrotron SED peak frequencies. Recently acquired jet kinematic information from the MOJAVE program will aid in distinguishing whether these particular jets are viewed unusually close to the line of sight, or have atypically large intrinsic opening angles.

High Synchrotron Peaked AGN Jets and the BL Lac Blazar Class: Previous studies of the full 1LAC catalog[4, 5] have established that HSP BL Lacs have fundamentally different γ-ray properties than the γ-ray-loud FSRQs. In our study we have found that the HSP BL Lacs are char-

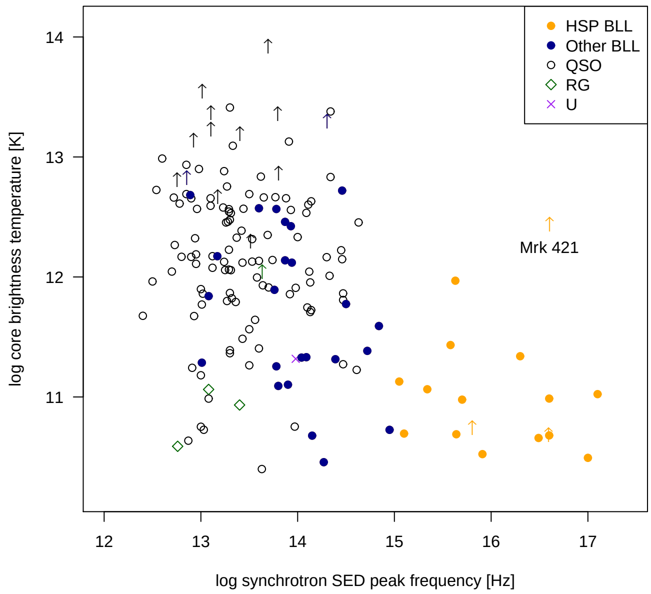

Figure 4: Radio core brightness temperature at 15 GHz versus synchrotron SED peak frequency. The arrows denote lower limits. Not plotted is the unusually low-brightness temperature quasar J0957+5522 (4C +55.17) at $\nu_s = 10^{13.77}$ Hz, $T_b = 10^{8.46}$ K.

acterized by high γ-ray to radio luminosity ratios and lower than average radio core compactness. Given these differences seen in both the radio and γ-ray regimes, a fundamental question remains as to whether the lower synchrotron-peaked BL Lacs also form a jet population distinct from the FSRQs. The continuity of the trend between SED peak frequency and γ-ray loudness (Figure 2) would suggest that their SED shapes are similar to the HSP BL Lacs, and thus they should be unified with them. They are also more similar to the HSPs in terms of their radio luminosity, as compared to the generally more luminous FSRQs.

If we directly compare the radio properties of the LSP BL Lacs and LSP FRSQs in our sample, we find that the LSP BL Lacs have higher mean fractional linear polarization according to a Welch Two Sample t-test, although both classes span roughly the same range of extreme values. It is possible that beam depolarization effects may lower the mean value for the FSRQs, since they are typically at higher redshift than the BL Lacs and are thus imaged with poorer spatial resolution. However, if we compare the LSP and HSP BL Lacs, which have similar redshift ranges, we find the latter have consistently low core polarization and modulation indices, as well as lower than average radio core brightness temperatures. Since high radio variability, core polarization, and brightness temperature are generally associated with high Doppler boosted-jets [26, 40, 17], the trends we find in our sample support the following scenario for the brightest γ-ray and radio blazars in the sky: Because of their higher intrinsic γ-ray loudness ratios and low redshifts, the HSP BL Lacs do not need to be as highly beamed to enter into flux-limited γ-ray and radio samples, thus they tend to have lower Doppler boosting factors than other blazar classes. The LSP BL Lacs are less intrinsically luminous than the FSRQs, but their moderately high intrinsic γ-ray loudness ratios and

Doppler boosting factors combine to give them apparent γ-ray and radio luminosities comparable to the fainter end of the FSRQ distribution.

The above scenario is supported by another study[31] which found a general trend of decreasing Doppler factor with increasing synchrotron SED peak frequency. That sample only included blazars of the LSP and ISP class, however. A potential test can be made with parsec-scale superluminal motion measurements, which set an upper limit on the viewing angle and a lower limit on the bulk jet Lorentz factor [41]. One of the main unresolved problems for HSP BL Lacs has been the relatively slow apparent jet speeds detected for these objects [32, 33], despite the need for large Doppler factors to account for rapid variability seen in γ-rays and to accurately model their SEDs [15]. Several models have been put forward to address this "Doppler factor crisis", including decelerating flows [12], and stratified spine-sheath models [7, 38], in which the γ-rays originate in a high-velocity jet spine, while the radio emission (and moving blobs) are associated with a lower-Lorentz factor sheath. In this manner the radio and γ-ray emission can have independent Doppler factors. However, uncorrelated beaming factors for the synchrotron and high-energy peaks would likely destroy any linear relation between SED synchrotron peak and γ-ray loudness, in contrast to what we see for the BL Lacs in our survey (Figure 2). A more recent model put forward by [30] involving non-steady magnetized outflows suggests the existence of different, yet correlated Doppler factors for the two SED peak regions, which can potentially preserve the G_r versus synchrotron SED peak relation. With the MOJAVE program we are currently obtaining multi-epoch VLBA measurements of all the γ-ray-selected radio jets in our sample. Together with more complete SED information, light curves and deep EVLA images, we aim to gain a fuller understanding of the connections between synchrotron SED peak frequency, Compton dominance, apparent jet speed, and Doppler factor in bright blazars.

Acknowledgments

The author wishes to acknowledge the collaborative efforts of the MOJAVE and Fermi-LAT teams in carrying out this study.

The MOJAVE project is supported under NSF grant AST-0807860 and NASA *Fermi* grant NNX08AV67G.

References

[1] Abdo, A. A., et al. 2009, ApJ, 700, 597

[2] —, 2010, Science, 328, 725

[3] —. 2010a, ApJS, 188, 405

[4] —. 2010b, ApJ, 715, 429

[5] —. 2010c, ApJ, 716, 30

[6] Aller, M. F., Aller, H. D., & Hughes, P. A. 1992, ApJ, 399, 16

[7] Celotti, A., Ghisellini, G., & Chiaberge, M. 2001, MNRAS, 321, L1

[8] Chang, C. 2010, PhD thesis, Max-Planck-Institut für Radioastronomie

[9] Deller, A. T., et al. 2011, PASP, 123, 275

[10] Dermer, C. D. 1995, ApJL, 446, L63

[11] Dondi, L., & Ghisellini, G. 1995, MNRAS, 273, 583

[12] Georganopoulos, M., & Kazanas, D. 2003, ApJL, 594, L27

[13] Gupta, J. A., Browne, I. W. A., & Peel, M. W. 2011, ArXiv e-prints, 1106.5172

[14] Hartman, R. C., et al. 1999, ApJS, 123, 79

[15] Henri, G., & Saugé, L. 2006, ApJ, 640, 185

[16] Homan, D. C., et al. 2006, ApJL, 642, L115

[17] Hovatta, T., Valtaoja, E., Tornikoski, M., & Lähteenmäki, A. 2009, A&A, 498, 723

[18] Jorstad, S. G.,et al., 2001, ApJS, 134, 181

[19] Jorstad, S. G., et al. 2005, AJ, 130, 1418

[20] Kellermann, K. I., et al. 2004, ApJ, 609, 539

[21] Kovalev, Y. Y. 2009, ApJL, 707, L56

[22] Kovalev, Y. Y., et al. 2005, AJ, 130, 2473

[23] —. 2009, ApJL, 696, L17

[24] Lähteenmäki, A., Valtaoja, E., & Wiik, K. 1999, ApJ, 511, 112

[25] Linford, J. D., et al. 2011, ApJ, 726, 16

[26] Lister, M. L. 2001a, ApJ, 562, 208

[27] Lister, M. L., et al., 2009a, ApJL, 696, L22

[28] Lister, M. L., et al. 2009b, AJ, 137, 3718

[29] Lister, M. L., et al. 2011, ApJ, 742, 27

[30] Lyutikov, M., & Lister, M. 2010, ApJ, 722, 197

[31] Nieppola, E., Valtaoja, E., Tornikoski, M., Hovatta, T., & Kotiranta, M. 2008, A&A, 488, 867

[32] Piner, B. G., & Edwards, P. G. 2004, ApJ, 600, 115

[33] Piner, B. G., Pant, N., & Edwards, P. G. 2010, ApJ, 723, 1150

[34] Pushkarev, A. B., Kovalev, Y. Y., & Lister, M. L. 2010, ApJL, 722, L7

[35] Pushkarev, A. B., Kovalev, Y. Y., Lister, M. L., & Savolainen, T. 2009, A&A, 507, L33

[36] Richards, J. L., et al. 2011, ApJS, 194, 29

[37] Savolainen, T., Homan, D. C., Hovatta, T., Kadler, M., Kovalev, Y. Y., Lister, M. L., Ros, E., & Zensus, J. A. 2010, A&A, 512, A24

[38] Tavecchio, F., & Ghisellini, G. 2008, MNRAS, 385, L98

[39] Taylor, G. B., et al. 2007, ApJ, 671, 1355

[40] Tingay, S. J., et al. 2001, ApJL, 549, L55

[41] Urry, C. M., & Padovani, P. 1995, PASP, 107, 803