Blazars in Context in the Fermi Era

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Blazars are the most plentiful γ-ray source at GeV energies, and despite detailed study, there is much that is not known about these sources. In this review I explore some recent results on blazars, including the controversy of the “blazar sequence”, the curvature in the LAT spectra, and the location along the jet of the γ-ray emitting region. I conclude with a discussion of alternative modeling possibilities.

1. Introduction

The second Fermi Large Area Telescope (LAT) catalog [Nolan et al. 2012] contains 1,298 identified or associated sources, of which 84% are Active Galactic Nuclei (AGN) of some flavor or another, mostly blazars. Of the 575 unidentified sources in this catalog, 27% have since been associated with blazars based on analysis of their infrared (IR) colors, as observed by the Wide Field Infrared Survey Explorer (WISE) [Massaro et al. 2012]. Blazars dominate the γ-ray sky in terms of sheer number of sources.

1.1. Basic Blazar Physics

Blazars are thought to be powered by accretion onto supermassive (M ∼ 10^6 − 10^9 M☉) black holes at the center of what seem to be almost entirely elliptical galaxies [e.g., Bahcall et al. 1997, Bové et al. 1998, Urry et al. 2000]. Jets are produced perpendicular to the accretion disk probably through magnetic fields wound up by the spin of the black hole [Blandford & Znajek 1977]. The jets are closely aligned to our line of sight, the defining property of blazars. The jets move at speeds close to the speed of light, c, with Lorentz factors Γ = (1 − β^2)^{-1/2} ∼ 10, where the jet speed v = βc. These high jet speeds can be inferred from several pieces of evidence: their extreme radio surface brightnesses, from GHz radio frequencies to TeV γ-rays, implies emission from a compact region. If a compact region of plasma (the “blob”) is assumed to be a sphere with radius R′ in the frame co-moving with the blob, then the variability timescale (t_v; the approximate time it takes the flux to double) and light travel-time arguments give the constraint

\[ R' \lesssim \frac{\delta c t_v}{(1 + z)} = 3 \times 10^{15} \frac{A_{\gamma}}{10^3 M_{\odot}} \frac{\delta t_v}{(1 + z)^{-1}} \text{ cm} . \]  

Here and everywhere, primed quantities refer to the co-moving frame. I have used the notation that A_{γ} = 10^3 M_{\odot} and all variables are in Gaussian/cgs units unless otherwise stated. The VLBI imaging of blazars and jets often reveal individual knots [e.g., Lister et al. 2009, Piner & Edwards 2004], further evidence that jets consist of discrete components.

Electrons are accelerated, probably by shocks internal to the jet, to form power-law distributions, N(γ) ∝ γ^{-p}. In a magnetic field these electrons emit synchrotron radiation, which almost certainly is responsible for the low-energy emission in blazars, peaking in the infrared through X-ray. The γ-ray emission from blazars is less clear but probably originates from Compton scattering either of the synchrotron radiation (synchrotron self-Compton or SSC) or some external radiation field (external Compton or EC). The external radiation field could be from a thermal accretion disk, a broad line region (BLR), or a dust torus. It is also possible there could be a γ-ray component from emission by protons accelerated in the jet as well. Both leptonic and hadronic emission models in blazars are reviewed by Böttcher [2007, 2012].

1.2. Classification

Blazars are sub-divided as Flat Spectrum Radio Quasars (FSRQs) and BL Lacertae objects based on their optical spectrum, with sources with weak or absent broad emission lines being BL Lacs, and...
those with stronger broad emission lines being FSRQs. Blazars are further classified based on $\nu_{pk}^y$, the frequency of their synchrotron peak in a $nu_{ph}$ representation. Most recently, they were classified as low synchrotron peaked (LSP) if $\nu_{pk}^y < 10^{14}$ Hz, intermediate synchrotron peaked (ISP) if $10^{14}$ Hz < $\nu_{pk}^y$ < $10^{15}$ Hz, or high synchrotron peaked (HSP) if $10^{15}$ < $\nu_{pk}^y$ by Abdo et al. [2010c]. Almost all FSRQs are LSPs [Ackermann et al. 2011]. BL Lacs are generally thought to be the aligned counterpart to FR Is, while FSRQs are generally thought to be the aligned counterpart to FR IIs [e.g., Urry & Padovani 1995], although some exceptions exist [e.g., Landt et al. 2004].

2. Blazar Sequence

2.1. The Origin of the Sequence

One of the great accomplishments of twentieth century astrophysics is the understanding of stars. We now understand their power source, how much radiation they produce and the spectra, how this depends on their mass and chemical composition, and how it evolves with time. It is worth taking the time to think about the question: How is it that we understand stars so well, yet we understand blazars so poorly? Why do we not have a good understanding of how blazars’ emission and spectra depend on fundamental parameters (black hole mass, black hole spin, or other parameters), how they evolve with time, and so forth.

Stars are isotropic emitters, and appear mostly the same no matter which direction one is looking at them. For blazars, this is obviously not the case. Stars tend to have relatively constant emission on human timescales, or, if they are variable, the variability is predictable (e.g., Cepheid variables or RR Lyrae stars). Blazars are highly variable at all wavelengths across the electromagnetic spectrum on time scales as short as hours or even minutes [e.g., Aharonian et al. 2007], and the variability is apparently stochastic. Globular clusters played an important role in the understanding of stars, since one can safely assume that all of the stars in the cluster have been created at about the same time. There is no such similar method for figuring out the relative ages of blazars. Finally, one can determine the composition, temperature, and density of stellar photospheres from their optical spectra; as the jets of blazars are fully-ionized, spectral lines are not expected, and they have no similar diagnostic.

One of the most useful tools in stellar astrophysics is the Hertzsprung-Russell diagram, which describes the luminosity to the optical spectral type (related to temperature and color) of stars and includes the very prominent main sequence, on which stars spend a large fraction of their lifetimes. This diagram has led to enormous success in the understanding of stars, so that one is greatly tempted to find a similar diagram for blazars. The possible discovery of a “blazar main sequence” or “blazar sequence” was made by Fossati et al. [1998], combining three samples of blazars: a sample of FSRQs [from the 2 Jy sample of Wall & Peacock 1985], a radio-selected sample of BL Lacs [from the 1 Jy sample of Kuehr et al. 1981], and an X-ray selected sample of BL Lacs [from the Einstein Slew Survey; Elvis et al. 1992]. They found three parameters that appeared to be well-correlated with the peak of the blazar synchrotron component: the 5 GHz radio luminosity, the luminosity at the peak of the synchrotron component, and the “$\gamma$-ray dominance”, i.e., the ratio of the $\gamma$-ray luminosity (as measured by EGRET) and the peak luminosity of the synchrotron component. Could one or all of these sequences hold the same place in blazar phenomenology?

Ghisellini et al. [1998] provided a physical explanation for the correlations, or sequence, found by Fossati et al. [1998]. For nonthermal electrons accelerated as power-laws and allowed to escape a region of size $R$ and cool through synchrotron and Compton losses, a “cooling break” will be found in the electron distribution at electron Lorentz factor given by

$$\gamma' = \frac{3m_e c^2}{4e\sigma_T u_{tot} t_{esc}}$$

where $m_e = 9.1 \times 10^{-28}$ g is the electron mass, $\sigma_T = 6.65 \times 10^{-25}$ cm is the Thomson cross section, $t_{esc} \equiv R/c$ is the escape timescale, and $u_{tot}$ is the total energy density is the frame of the relativistic blob, given by the sum of the Poynting flux ($u'_p$), synchrotron ($u'_y$), and external radiation field ($u'_{ext} \equiv \Gamma^2 u_{ext}$) energy densities. Note that all primed quantities are in the frame co-moving with the jet blob. The cooling Lorentz factor $\gamma'_c$ will be associated with a peak in the synchrotron spectrum of the source in a $nu_{ph}$ representation observed at frequency

$$\nu_{pk}^y = 3.7 \times 10^6 \frac{r_e^2}{G} \frac{B}{\delta (1+z)}$$

[e.g., Tavecchio et al. 1998] where $B$ is the magnetic field in the blob. For objects that have weak external radiation fields so that $u'_p \gg u'_{ext}$, and neglecting $u'_{sy}$, then Equations (2) and (3) give

$$\nu_{pk}^y \simeq 2.2 \times 10^{15} B_0^{-3} \delta_1^{-1} (1+z)^{-1} R_{15.5}^{z/2} \text{ Hz}$$

where I have chosen fiducial values for all quantities. These objects will be HSPs. Objects with a strong external radiation fields from the broad line region (BLR) which dominate over $u'_p$ and $u'_{sy}$, will have peak synchrotron frequencies given by

$$\nu_{pk}^y \simeq 3.2 \times 10^{12} B_0 \delta_1^{-3} (1+z)^{-1} R_{15.5}^{-2} u_{ext}^{-2} \text{ Hz(5)}$$
where I assumed that $\delta = \Gamma$. These objects will be LSPs. It turns out that so far all blazars with high synchrotron peaks are BL Lacs (without strong broad emission lines by definition), while FSRQs with strong emission lines are almost entirely LSPs. Note however, that there are a significant number of BL Lacs which are LSPs. Objects with stronger line emission would also be expected to have greater $\gamma$-ray dominances, due to scattering of the external radiation field. Ghisellini et al. [1998] thus predicted a sequence of blazars, from low power, high peaked, low $\gamma$-ray dominance, lineless objects, and as the external radiation field increases, to low peaked, high $\gamma$-ray dominance objects with strong broad emission lines. Böttcher & Dermer [2002] suggested the “blazar sequence” is evolutionary, with FSRQs being young objects, and as the circum-nuclear material accretes, the the broad emission lines decrease, and the accretion rate decreases, and the sources become older BL Lac objects.

However, the correlations found by Fossati et al. [1998] have not always been found in subsequent studies [Nieppola et al. 2006, Padovani et al. 2003] although they have in others [e.g., Chen & Bai 2011, Finke 2013]. Furthermore, an alternative explanation was provided by Giommi et al. [2002, 2012, 2005]. In their scenario, the sequence is a result of a selection effect: luminous blazars with high synchrotron peaks will have their spectral lines totally swamped by the nonthermal continuum, making a redshift measurement impossible. Without a redshift, it is not possible to determine their luminosities, and so they are not included in statistical tests between luminosity and $\nu_{pk}$.

What is the explanation for the blazar sequence? Is it a physical effect [Ghisellini et al. 1998] or a selection effect [Giommi et al. 2002]?

### 2.2. More Recent Work

Rau et al. [2012] have constrained the redshifts of a number of high $z$ BL Lacs. Four of these do seem to have high $\nu_{pk}$ and are very luminous [see Fig. 1]. Padovani et al. [2012]. This would seem to support the argument that the blazar sequence is the result of a selection, rather than physical, effect. In the Fermi era, however, it is possible to look at not just the synchrotron component, but also the $\gamma$-ray component, presumably the result of Compton scattering. Both Meyer et al. [2012] and Ghisellini et al. [2012] pointed out that these four sources are not out of the ordinary on a $\gamma$-ray “blazar sequence,” where one plots the LAT spectral index, $\Gamma$ (a proxy for the peak of the $\gamma$-ray component) and the LAT $\gamma$-ray luminosity, and they are perfectly consistent with other LAT $\gamma$-ray sources (see Fig. 2). However, it is certainly possible that in the future, as more redshifts are measured and constrained, sources with high $L_\gamma$ and low $\Gamma_\gamma$ will be found.

An often overlooked part of the blazar sequence as found by Fossati et al. [1998] is the $\gamma$-ray dominance, i.e., the ratio of the $L_\gamma$ to the peak synchrotron luminosity ($L_{pk}^{\nu}$). This and a similar quantity, the Compton dominance, $A_C \equiv L_C^{\nu}/L_{pk}^{\nu}$ (where $L_C^{\nu}$ is the luminosity at the Compton peak) are redshift-independent. Also, $\nu_{pk}^{\nu}$ is only weakly dependent on redshift, by a factor $(1+z)$, i.e., a factor of a few.

![Figure 1: LAT $\gamma$-ray luminosity versus LAT spectral energy index ($\alpha = \Gamma_\gamma - 1$) for a number of blazars. RAU et al. [2012] found the redshifts for the four luminous, high-peaked, high $z$ objects shown in red.](image1)

![Figure 2: The LAT $\gamma$-ray luminosity versus LAT spectral energy index ($\alpha = \Gamma_\gamma - 1$) for a number of blazars. RAU et al. [2012] found the redshifts for the four luminous, high-peaked, high $z$ objects shown in red.](image2)
A plot of $A_C$ versus $v_{pk}^{\nu_y}$ is shown in Fig. 3 from a subset of sources in the second LAT AGN catalog [Ackermann et al. 2011], including sources which do not have known redshifts. It is clear that there is a correlation, and this is confirmed with the Spearman and Kendall tests [Finke 2013]. It seems that this aspect of the blazar sequence has a physical origin, and not the result of a selection effect. In the future, the luminosity-peak frequency relations could be improved with new redshift measurements and constraints [e.g., Shaw et al. 2013]. Then it should be possible to determine if these aspects of the sequence are physical as well.

As an alternative to the physical scenario described by Ghisellini et al. [1998] and in § 2.4 [Meyer et al. 2011] proposed another physical scenario, based on updated data from a number of sources. In their scenario, the difference between BL Lacs and FSRQs is the former have jet structure with velocity (or Lorentz factor) gradients, either perpendicular or parallel to the direction of motion. FSRQs, according to [Meyer et al. 2011], do not have these gradients; they have a single Lorentz factor for the entire jet, or at least the radiatively important parts. There is indeed ample evidence for different Lorentz factors in BL Lacs and FRIs [e.g., Abdo et al. 2010a, Chiaberge et al. 2001, 2000]. The lack of $\gamma$-ray detected FRIIs hints that FRIIs/FSRQs do not share this jet structure [Grandi et al. 2012], however, see Böttcher & Principe [2009] for evidence of jet deceleration in an FSRQ.

3. Curvature in LAT Spectra

After the launch of Fermi, while the spacecraft was still in its post-launch commissioning and checkout phase, the FSRQ 3C 454.3 was detected by the LAT in an extreme bright state [Tosti et al. 2008]. The source reached a flux of $F(\gamma > 100$ MeV) $> 10^{-5}$ ph cm$^{-2}$ s$^{-1}$ and its spectrum showed an obvious curvature (i.e., a deviation from a single power-law), which was best-fit by a broken power-law [Abdo et al. 2009], with break energy $\sim 2$ GeV. This source flared on several more occasions [Abdo et al. 2011, Ackermann et al. 2010], always exhibiting a spectral break during bright states. The energy of the break varied by no more than a factor of $\sim 3$, while the flux varied by as much as a factor of 10 [Abdo et al. 2011]. This spectral curvature has been found in other blazars as well, although a broken power-law is not always preferred over a log-parabola fit, which has one less free parameter [Abdo et al. 2010]. The cause of the break is not clear but there are several possible explanations.

A combination of several scattering components, Finke & Dermer [2011] noted that, based on the shape of the optical and $\gamma$-ray spectra, the Compton scattering of more than one seed photon source was needed to explain the overall spectral energy distribution (SED) of 3C 454.3. The particularly soft spectra above the break requires that this scattering be done in the Klein-Nishina (KN) regime. This model requires that scattering occur within the BLR, and a wind model for the BLR in order to explain the relative stability of the break energy.

Photorecombination of $\gamma$-rays with BLR photons, Poutanen & Stern [2010] [see also Stern & Poutanen 2011] pointed out that He II Ly$\alpha$ and recombination photons are at the right energy (54.4 eV and 40.8 eV, respectively) to absorb $\gamma$-ray photons at $\sim 5$ GeV, about the same energy as the spectral breaks observed. This model would also require the $\gamma$-ray emitting region to be within the BLR.

Compton scattering of BLR Ly$\alpha$ photons. For the scattering of Ly$\alpha$ photons ($E_\alpha = 10.2$ eV), the KN regime will emerge at energies above

$$E_{KN} \approx 1.2 \left( E_\alpha / 10.2 \text{ eV} \right)^{-1} \text{ GeV},$$

approximately in agreement with the observed break energy [Ackermann et al. 2010]. Fits with this model using power-law electron distributions failed to reproduce the observed LAT spectra [Ackermann et al. 2010]; however, fits using a log-parabola electron distribution were able to reproduce the $\gamma$-rays [Cerruti 2012]. Naturally, this model would also require the $\gamma$-ray emitting region to be within the BLR.

Curvature in the electron distribution. This is the explanation originally favored by Abdo et al. [2009]. If there is curvature in the electron distribution that
produces the $\gamma$-rays, presumably from Compton scattering, this would naturally be reflected in the LAT spectrum as well. In this scenario, one would expect the curvature in the electron distribution to cause a curvature in the synchrotron emission from the same electrons, which would appear in the IR/optical. Indeed, observations of PKS 0537–441 do show this curvature [D’Ammando et al. 2013, see Fig. 4]. This explanation would not require scattering to take place in the BLR, as dust torus photons could be the seed photon source for scattering. This scenario begs the question: what is the cause of the break in the electron distribution?

### 4. Location of the $\gamma$-ray Emitting Region

Many of the scenarios described in §3 require the $\gamma$-rays to be produced within the BLR. However, it is not clear that this is the case. Optical and $\gamma$-ray flares are often associated with the rotation of polarization angles, the slow increase in radio flux, and the ejection of superluminal components from the core as seen at 43 GHz [e.g., Marscher et al. 2008, 2010]. According to Marscher et al. 2012, 2/3 of $\gamma$-ray flares are associated with the ejection of a superluminal component, indicating the $\gamma$-ray flares are coincident with the 43 GHz core. There are two arguments that the 43 GHz core is located at, and the $\gamma$-ray flares originate from, > a few pc, outside the BLR. (1) Using the observed radius of the 43 GHz core ($R_{\text{core}}$), and assuming a conical jet with a half opening angle $\alpha$ [measured, e.g., by Jorstad et al. 2005], one can determine the distance of the core from the base of the jet, $r = R_{\text{core}}/\alpha$ [Agudo et al. 2011]. (2) The $\gamma$-ray flares occur in the same region as the much slower radio outbursts and/or polarization angle swings lasting 10s of days [Marscher et al. 2010, Orienti et al. 2013]. The distance associated with the light travel time of these radio outbursts or polarization swings assuming $\theta \ll 1$

$$r \geq 1.0 \Delta t_6 \delta_1 \Gamma_1 (1+z)^{-1} \text{ pc}.$$  

On the other hand, the rapid $\gamma$-ray variability observed in blazars such as 3C 454.3 [~ 3 hours; Tavecchio et al. 2010, PKS 1510–089 [~ 1 hour; Brown 2013, Saito et al. 2013, 4C 21.35 [~ 10 minutes; source also known as PKS 1222+21; Aleksic et al. 2011, and PKS 2155–304 [~ 5 minutes; Aharonian et al. 2007] limits the size of the emitting region by Equation (1). If the emitting region takes up the entire cross section of a conical jet, then it should be at a distance

$$r \leq 0.1 \delta_1 t_{v,4} \alpha_{-1}^{-1} (1+z)^{-1} \text{ pc}$$

from the base of the jet. Based on scaling relations found from reverberation mapping, the typical BLR region for FSRQs is $r_{BLR} \sim 0.1$ pc [e.g., Bentz et al. 2006].

4C 21.35 was detected to have flux-doubling timescales of ~ 10 minutes, as measured by MAGIC, out to 400 GeV. The $\gamma\gamma$ optical depth is

$$\tau_{\gamma\gamma} = \int_{\text{max}[r,r_{BLR}]}^{\infty} d\ell \, \sigma_{\gamma\gamma} \frac{u_{BLR}}{E_*}.$$  

We can estimate the $\gamma\gamma$ cross section $\sigma_{\gamma\gamma} \approx \sigma_T/3$, and $u_{BLR} \approx$ constant for $r < r_{BLR}$ . I will use $E_* = 10.2$ eV, i.e., for Lya. If $r < r_{BLR}$ then

$$\tau_{\gamma\gamma} \approx 40 u_{BLR, -2} r_{BLR, 17.5} (E_*/10.2 \text{ eV})^{-1},$$

so $\gamma$-rays with energies above the threshold energy, about 50 GeV ($E_*/10.2 \text{ eV})^{-1}$ will clearly not be able to escape the BLR.

Several ways to avoid $\gamma\gamma$ attenuation have been suggested, such as energy transport through neutron beams [Dermer et al. 2012], or $\gamma$-ray conversion to axions [Tavecchio et al. 2012]. Otherwise, the $\gamma$-rays from this source must be produced by a small fraction of the jet cross section at $\geq 4$ pc from the black hole, outside the BLR.

If the $\gamma$-ray emitting region is within the BLR, the seed photons for Compton scattering are likely to be at higher energies than they would be if they emitting region was outside the BLR, where lower-energy dust torus photons would serve as the seed photon source. Due to KN effects, the Compton cooling will be different in these different cases. Dotson et al. 2012 suggest that because of this effect, detailed study of the $\gamma$-ray light curves could distinguish the seed photon source energy, and hence, the location of the emitting region.
5. The End of the One-Zone Leptonic Model?

One-zone leptonic models (1ZLMs), where the lower energy emission is produced by synchrotron radiation, and the higher energy emission is produced by Compton scattering with the same electron population (SSC or EC) has been the standard for fitting multiwavelength blazar SEDs. However, lately the multiwavelength coverage has become complete enough that in many cases these models do not provide sufficient fits to blazar SEDs. These include 3C 279 that in many cases these models do not provide sufficient fits to blazar SEDs. However, lately the multiscattering cosmic microwave background (CMB) photons in the kpc-scale jet. Several models have been motivated by the contradictory clues for the location of the γ-ray emitting region, as described in §4. These typically include a smaller region at a large distance from the black hole, with one or more other regions accounting for the slower radio emission [e.g., Marscher & Jorstad 2010; Nalewajko et al. 2012; Tavecchio et al. 2011a,b]. Inhomogeneous jets have also been explored by Graff et al. 2008 and Joshi & Böttcher 2011.

Hadronic models. Blazars have long been a candidate for the production of ultra-high energy cosmic rays (UHECRs), a hypothesis that was recently strengthened by the correlation of UHECRs observed by the Auger observatory with local AGN [e.g., Abraham et al. 2007]. This has motivated blazar emission models where the γ-rays come from processes originating from protons and cosmic rays accelerated in the jet [e.g., Mücke et al. 2003]. Variability in hadronic models is difficult to model, although progress has been made recently by Böttcher 2012. A neutral beam model was recently proposed by Dermer et al. 2012 to explain the rapidly varying very-high energy (VHE) emission from 4C 21.35 (see §4).

Intergalactic cascade models. If blazars are sources of UHECRs, the particles that escape the jet could interact with the extragalactic background light (EBL) from stars, dust, and the CMB, to produce cascade VHE γ-rays Essey et al. 2010, Essey & Kusenko 2010. In this case the VHE emission would not be variable, and would be expected to be disconnected from the rest of the SED. This is a simple prediction that could be used to test this hypothesis. VHE γ-rays could also be produced from VHE γ-rays which interact with the EBL to produce e+/e− pairs. These pairs could then in turn Compton-scatter CMB photons, producing γ-rays in the LAT bandpass. This creates another component that needs to be taken into account in spectral modeling of blazars D’Avezac et al. 2007; Tavecchio et al. 2011a.

The problem with alternatives to the 1ZLM is that the addition of free parameters means that no matter what model is used, one will almost certainly be able to adjust the parameters to fit the data. Both theoretical and observational advances are needed to advance our understanding of these sources.

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Log \( \nu L^S_{\text{peak}} \) + \( \nu L^i_{\text{C,peak}} \) erg/s

Log(\( \nu_{\text{S,peak}} \) (rest-frame), Hz)

FSRQs
BL Lacs
Uncertain type