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Gamma-Ray and Multiwavelength Emission from Blazars

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Abstract. Blazars are now well understood as approaching relativistic jets aligned with the line of sight. The long-time uncertainty about the demographics of blazars is starting to become clearer: since the Fermi blazar sample includes a larger fraction of high-frequency peaked blazars (like the typical X-ray-selected blazars in, say, the Einstein Slew Survey sample) than did the higher-flux-limit EGRET blazar sample, these low-luminosity sources must be more common than their higher luminosity, low-frequency-peaked cousins. Blazar spectral energy distributions have a characteristic two-component form, with synchrotron radiation at radio through optical (UV, X-ray) frequencies and gamma-rays from X-ray through GeV (TeV) energies. Multiwavelength monitoring has suggested that gamma-ray flares can result from acceleration of electrons at shocks in the jet, and there appears to be an association between the creation of outflowing superluminal radio components in VLBI maps and the gamma-ray flares. In many cases, the gamma-ray emission is produced by inverse Compton upscattering of ambient optical-UV photons, although the contribution from energetic hadrons cannot be ruled out. The next few years of coordinated gamma-ray, X-ray, UV, optical, infrared and radio monitoring of blazars will be important for characterizing jet content, structure, and total power.

Key words. Blazars—demographics—spectral energy distributions—gamma-ray emission—multiwavelength monitoring.

1. Background

We have learned a lot about blazars over the past three decades, since the first meeting on BL Lac objects in Pittsburgh in 1978. It is clear that observed blazar spectral energy distributions (SEDs) are dominated by emission from relativistic jets oriented towards us (Urry & Padovani 1995). The parent population is radio galaxies (all radio galaxies have jets), with lower luminosity FRIs being the parent population of nearby BL Lac objects (especially HBLs), weak-lined FRIIs corresponding to more luminous BL Lacs (especially LBLs), and classical FRIIs giving rise to flat-spectrum radio-loud quasars (FSRQ). These blazar jets have a range of intrinsic power, almost certainly linked to the SED shape (Fossati *et al.* 1997, 1998). Particles in the jet are accelerated at shocks (Marscher & Gear 1985) and emit synchrotron radiation

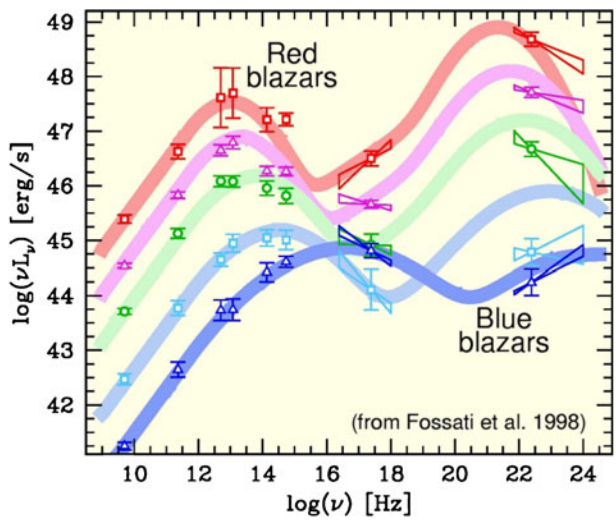

Figure 1. Spectral energy distributions of blazars are characterized by two peaks, between the infrared and soft X-ray for low-energy synchrotron component and at GeV to TeV gamma rays for high-energy component. The peak frequency is roughly inversely correlated with source luminosity (figure from Fossati *et al.* 1998). The Fermi telescope has enlarged the sample of gamma-ray bright blazars, and its greater sensitivity means more blazars are observed across a larger range in intrinsic luminosity, so an update to this study is in order.

as they are accelerated by the local magnetic field; Compton scattering is probably important in producing the gamma-ray emission in blazars with luminous broad-line emission (Tavecchio *et al.* 2000 and references therein) (Fig. 1).

Blazars tell us about jet physics. Relativistic aberration magnifies the jet emission so that it dominates everything but the accretion disk (most visible in faint jet states). So we have spent 20 years monitoring SED variations with CGRO/EGRET, Fermi/LAT, AGILE, Whipple, HEGRA, H.E.S.S., VERITAS, CANGAROO, and a plethora of other instruments, modelling the multiwavelength variability of blazars in hopes of deducing the physical state of the jet plasma. Unfortunately, this is not an easy problem. The observed characteristics depend on the combination of intrinsic physical parameters and Doppler beaming. This means that physical parameters are uncertain. In addition, the particle composition of the jet is uncertain – are jets heavy or light? – which means an uncertainty factor of roughly 2000 (the ratio of the mass of the proton to the mass of the electron). Another serious complication is that the number density of jets has been hotly debated since the 1990s (e.g., Maraschi *et al.* 1986; Giommi & Padovani 1994).

2. Blazar demographics

New results are illuminating some of these issues. The fact that the Fermi LAT is now detecting many HBLs means that the ratio of HBL:LBL is increasing to lower flux levels. This is consistent with HBLs being more numerous than LBLs. This is perhaps not surprising, since they are lower luminosity and most luminosity functions

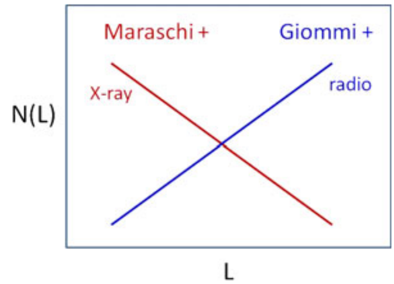

Figure 2. Schematic representation of the uncertainty in blazar demographics. If X-ray surveys are an unbiased probe of blazars, then high frequency-peaked blazars (HBLs) are roughly ten times more numerous than low frequency-peaked blazars (LBLs; Maraschi *et al.* 1986). If instead, radio surveys are unbiased, then LBLs are 10 times more numerous than HBLs (Giommi & Padovani 1994). The detection of many HBLs with the Fermi satellite argues for the former condition (i.e., the red line is favored over the blue line).

are decreasing power-laws, but Giommi and others have argued strongly that the LBLs are the more numerous. Careful analysis by my former undergraduate student Tim Brandt (unpublished) before the launch of Fermi shows that (a) the connection between luminosity and SED shape is required to explain the content of radio and X-ray surveys for blazars; (b) the underlying luminosity function is a traditional power-law rising towards lower luminosity (and thus towards HBLs); and (c) the negative (positive) evolution observed in the first samples of HBL (LBL) is a likely consequence of the blazar sequence.

If this is correct, then there are many relatively low-luminosity (intrinsically) BL Lacs, and a family of blazars with characteristics changing continuously with luminosity (Fig. 2).

Previously, different evolution has been seen for HBL and LBL/FSRQ populations, as assessed by the $\langle V/V_{\rm m}\rangle$ (Schmidt 1968; Avni & Bahcall 1980): HBLs appear to have negative evolution ($\langle V/V_{\rm m}\rangle$ <0.5; Perlman *et al.* 1996; Padovani *et al.* 2003) while FSRQs have positive evolution ($\langle V/V_{\rm m}\rangle$ <0.6; Stickel and other references). This led people to suggest that populations were quite distinct or that FSRQs could evolve into HBLs (Cavaliere & D'Elia 2002). But it is also possible that 'negative evolution' for HBL is a selection effect: they fall out of samples at high red-shift because of a negative K correction (Brandt & Urry, unpublished). Thus it is not clear if the data require FSRQ to evolve into BL Lac objects, although equally it does not mean these ideas could not be right either.

3. High energy emission

The discovery of gamma-rays from blazars with EGRET should have been expected. Although some models had clearly predicted gamma-rays from blazars (e.g., Königl 1981), many of us were not imagining that their radiative output would be dominated by the high-energy emission (although I learned after this talk that Alan Marscher had specifically predicted that a large number of blazars would be detected with EGRET). So not everyone was surprised. Certainly the EGRET-enabled study of gamma-ray emission from blazars constituted a giant step forward, as did the detection of HBLs with TeV (Cerenkov and air shower) facilities. Now with the greater sensitivity of Fermi, H.E.S.S., VERITAS, etc., we can measure larger samples, resolve variability, explore variability amplitudes and duty cycles, and probe multiwavelength correlations.

We know that gamma rays come from the jet because of the correlation between ejection of radio blobs and flaring at gamma-ray energies. The same is true for optical emission: besides simultaneous variability with the gamma rays, there are clear flips in polarization associated with gamma-ray flaring.

The SED shape seems connected with variability in a systematic way in that there is more variability above spectral peaks than below. For HBLs, that means at X-ray and TeV energies, whereas their optical and GeV light curves show little variability; for FSRQ, it means IR/optical and GeV variability but little action in the X-rays (the low energy part of the high-energy component). This is natural in the synchrotron regime, where the radiative time scales depend on the inverse square of the energy and cooling electrons naturally generate a stable power-law below a spectral break. Above the break, synchrotron radiation can be modelled successfully by optically thin, homogeneous regions filled with relativistic electrons and magnetic field.

4. A laboratory for multiwavelength variability: 3C 454.3

At the launch of Fermi, the superluminal quasar 3C 454.3 was the brightest blazar in the sky, perhaps unexpectedly, as it had never been a particularly notable gamma-ray source. Our group immediately targeted it with SMARTS, the Small and Moderate Aperture Research Telescope System, located in Cerro Tololo, Chile, which is a set of five telescopes, each with unique optical and/or near-infrared instrumentation (ANDICAM; Depoy *et al.* 2003). We used the SMARTS 1.3 m + ANDICAM to obtain simultaneous 0.4–2.2 m images of 3C 454.3 and other southern blazars in BVRJK every 1–3 days. We also obtained optical spectra of bright blazars about once per month per object. In general, we can schedule new targets with <1 day response time for flaring sources. For the first two years of Fermi operations, our target list consisted of southern blazars from the Fermi public blazar list with a few new sources added during that time. In the 3rd year we included some of the newly bright sources from the first Fermi catalogues. Yale SMARTS blazar photometry is online in near-real time at http://www.astro.yale.edu/smarts/fermi/.

With 3C 454.3, a very striking result was the very clear correlation between gamma rays and IR/optical emission (Bonning *et al.* 2009). Effectively, this meant a close correlation for high Lorentz factor electrons radiating at the peak of the synchrotron emission at near-IR/optical wavelengths and near the peak of the gamma-ray emission at a few GeV. At the same time, the X-rays, produced by low Lorentz factor electrons, varied little if at all. This kind of spectral variability strongly favours leptonic models for the gamma-ray emission; otherwise, the close temporal correlation seems arbitrary. However, there may be arguments for hadronic emission as well, at the very highest energies, since TeV emission from FSRQ is otherwise difficult to explain (e.g., in the case of 3C 279, Boettcher 2009).

The largest amplitude variations in the 3C 454.3 light curves were seen in the J band, the smallest in the B band. This was somewhat unexpected since the jet emission should have the opposite wavelength dependence (since higher energy electrons lose energy faster). We quickly realized that the shorter wavelength light included an increasing disk component. Correlating the optical and gamma-ray light, and assuming that the gamma rays come only from the jet, we extrapolated back to zero gamma-ray flux to get the optical disk contribution. Doing this in each optical band, we derived a disk spectrum that looked very reasonable, i.e., increasing to the blue. Subtracting this component from the total optical/IR spectrum, we do indeed find that the fractional variability in the jet increases towards the blue (Bonning *et al.* 2009).

3C 454.3 has been very active, flaring again in the second year of Fermi observations, with very large amplitude. Whereas the first flare showed relatively similar amplitude in optical and gamma-rays, the second was much stronger in gamma-rays. With these additional data, a detailed physical interpretation becomes possible. For example, some brightness changes and/or polarization flips could be due to a changing Doppler factor for a 'blob' moving along helical magnetic fields in the jet. In this case, the emission comes from relatively large scales and is probably intrinsically stable.

5. Blazars as a class

The rapid variability of blazars, especially at TeV energies, implies very high Lorentz factors, very compact emission regions, or both. For example, PKS 2155–304 has doubled in brightness in minutes, which is difficult to explain without Lorentz factors well above 10 (Aharonian *et al*. 2009). The relation of spectral index to brightness does not (in most cases) have simple, repeatable structure. That is, each flare can be different from the next, and indeed different regions of the jet might dominate at any one time (Bonning *et al.* 2011). The magnetic fields in these components can be different, which can explain some of the polarization variability (e.g., Bjornsson 1982a, 1982b). We can look forward to the opportunity to measure X-ray polarization with the upcoming NASA Explorer, GEMS, and with the Japanese-led Astro-H mission. Blazars will be the most important initial target of both missions.

The field of neutrino astrophysics enters a new phase with the Ice Cube observatory. If neutrinos are detected from blazars, this is a sure sign that there are energetic hadrons in the jet. Otherwise, the composition of the jet has remained elusive (Celotti *et al*. 1997; Sikora 1997), even though leptonic models certainly seem to fit the multiwavelength variability naturally. A lot (perhaps too much) of the debate has centered on plausibility rather than actuality: we note that hadronic jets are too inefficient and they require huge kinetic powers, and apart from the neutrino signature, they have indistinct tell-tale signs. At the same time, we worry that leptonic models have their own implausibilities: they require very relativistic electrons and it is unclear how they get accelerated to such high Lorentz factors when radiative time scales are so short. Regardless, we need to know the composition of the jet or else we cannot understand the energetics. In the next decade, this debate should change from a philosophical argument to definitive measurements.

Even if jets are 'light' (leptonic), it is likely that the jet's kinetic energy dominates its radiation by large factors in luminous blazars. Some very interesting work has been done on disk luminosity relative to jet luminosity (for likely Doppler factors; Maraschi & Tavecchio 2007). In low-luminosity blazars, the jet's kinetic power is comparable to the radiative output, hence it is not surprising that the jets die out rapidly, whereas in luminous blazars, the kinetic energy far outstrips the observed radiation.

6. Summary and final thoughts

In some respects, we understand blazars well. They have well-collimated relativistic outflows with bulk Lorentz factors in the range of a few to over 100. The electrons in the jet have a relativistic energy distribution with Lorentz factors as high as 10^6 or even 10^8 (we think). Their spectral energy distributions show two broad peaks, the lower one clearly from synchrotron radiation from a relativistic distribution of electrons. The high-energy peak is variously attributed to inverse Compton scattering of ambient soft photons by the synchrotron-emitting electrons, or to synchrotron radiation from energetic protons (which then generate secondary electrons that radiate the synchrotron radiation). Efforts to distinguish between the two have not been completely decisive to date: the multiwavelength variability is well explained by the leptonic models but this does not rule out hadronic processes. Detection of neutrinos from blazar jets would point definitively to energetic protons in the jet.

The numbers, luminosities and superluminal velocities of blazars are well understood in this picture (Urry & Shafer 1984; Urry & Padovani 1995), with the parent population being radio galaxies, both low-(FRI) and high-(FRII) luminosity. Probably the range in observed line strengths, from BL Lac objects (which are weak-lined or lineless) to flat-spectrum radio quasars, can be understood as a variation in the intrinsic luminosity of the line emission. The bulk velocities observed with VLBA radio imaging are commensurate with Doppler factors near 10.

Lots of details are missing, however. How do we reconcile the superluminal expansion and SED analysis, which point to moderate Doppler factors, with the extremely rapid flares seen at TeV energies in a few BL Lacs, which suggest Doppler factors of 100 or more (similar to gamma-ray bursts)? Furthermore, the details of shock structure, particle acceleration and the evolution of the particle energy distribution along the jet are not well constrained.

The Fermi satellite data have allowed us to firm up multiwavelength correlations and to associate radio structures with gamma-ray flares (see Marscher & Jorstad talks, this conference). However, given the small number of gamma-ray-bright blazars (even with Fermi), constraints on visibility from ground-based optical/IR telescopes, and the rarity of strong gamma-ray activity, it is clear we will have to monitor several dozen blazars for another half a dozen years in order to obtain high quality multiwavelength data to further test physical models.

So far, the good multiwavelength correlations seen in 3C 454.3, 3C 279, PKS 1510–089, and other blazars, support leptonic models. Observed lags are shorter than one day (the typical resolution for both optical and gamma-ray data). We and others have carried out optical monitoring on faster time scales (within one night) but even if variability is seen, the amplitude is typically small, even though gamma-ray amplitudes on those time scales can be large. So it is not clear we can follow the jet structure to smaller and smaller cells. Furthermore, there is evidence that the accretion disk contributes an observable fraction of the flux, which complicates the analysis. The disk variability in the optical/IR is expected to be on much longer time scales than the jet variability, but at X-ray energies, disk and jet variability could be comparable.

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