BL Lac Objects and Blazars: Past, Present, and Future

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Abstract. The past 20 years have seen phenomenal progress in our understanding of BL Lac objects. They form part of the blazar class, which are radio-loud AGN whose relativistic jets are aligned along our line of sight. Several critical milestones have helped establish this picture, first proposed at the Pittsburgh BL Lac meeting 20 years ago, most recently the EGRET and TeV detections of beamed gamma-ray emission. The spectral energy distributions are double peaked and follow a self-similar sequence in luminosity, which can be explained by electron cooling on ambient photons. This simple paradigm has yet to be tested, and further questions remain, notably about physical conditions in blazar jets — the kinetic power, magnetic energy density, acceleration time scales, proton content, etc. — and how this energy is transported in the innermost regions. Some clues are available from multiwavelength monitoring campaigns although better sampling over longer periods is clearly called for.

Recent work on the host galaxies of BL Lac objects supports their unification with low-power, aligned FRI radio galaxies. Nature makes jets with a large range of kinetic powers, but the distribution of such jets — i.e., the relative number densities of low-luminosity (“blue” BL Lacs) or high-luminosity (“red” BL Lacs and FSRQ) blazars — is highly uncertain. Deeper radio-selected samples of flat-spectrum sources may resolve the degeneracy in the present demographic analyses.

Since according to unified schemes blazars are representative of all radio-loud AGN, their jet properties have broad implications. Future EUV/X-ray observations will illuminate the circumnuclear structure, especially the hot, highly ionized, high velocity gas on sub-parsec scales, which could play a role in jet dynamics and could possibly affect the formation of FRI vs. FRII type jets. The study of blazars may also help us eventually understand the difference between radio-quiet and radio-loud AGN.

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1. Legacy of the BL Lac Conferences

The Turku meeting was the third in an historic series of conferences on BL Lac objects, so it seems appropriate to begin from an historical perspective. The first BL Lac meeting was held in Pittsburgh in 1978 and the second 10 years later, in Como, Italy. Over this 20-year period, there has been enormous progress in understanding BL Lac objects, or blazars, using the collective term for BL Lac objects and flat-radio-spectrum, highly polarized quasars. This occurred despite the scarcity of sources — in 20 years the number of catalogued BL Lacs increased only by a factor of a few, roughly 1/10 the growth in catalogued quasars. (We have at least reached the point where the number of BL Lac objects is greater than the number of conference participants!)

The field has changed a great deal in 20 years. While many of the 84 Pittsburgh participants have gone on to illustrious careers in astrophysics (this is the good news, for students who wonder whether blazars are a good career move), almost none are still actively working on blazars (the bad news?). For example, only 8 people from the Pittsburgh meeting were at the 1988 Como meeting, and only 1 person came to both Como and Turku (answer at the end). This represents real turnover, as the number of blazar researchers has not increased dramatically — roughly the same number of people came to Como as Pittsburgh. In Turku the attendance was 50% higher, in large part because of the welcome influx of gamma-ray astronomers. Altogether, the demographics of these three conferences indicates considerable evolution in our understanding and renewed interest in the physics of blazars.

In his overview at Pittsburgh, Wayne Stein was reliably prescient. He suggested tongue-in-cheek that BL Lac objects might be defined as “totally uninteresting astronomical sources [to the spectroscopist] because they may exhibit neither absorption nor emission lines.” (This surely resonates with many optical observers who have trouble getting telescope time for spectroscopy!) He also pointed out, more seriously, the reason for the high level of interest in this topic, saying, “BL Lac objects are our most direct observable link with the ultimate energy source of the quasi-stellar objects.” Indeed, we now recognize that BL Lac objects and other blazars are the best probe of jet formation and evolution in AGN because, although they are rare, unification tells us they are the same as all radio-loud AGN, and at the same time, their jet emission is conveniently enhanced by relativistic beaming. Thus blazars are critical to understanding jets in all radio-loud AGN — what was discussed at Turku about BL Lac objects has near-universal relevance for AGN.

We can look back at what we have learned since Pittsburgh, what we knew then, what have been the major problems and solutions, and what are the most promising avenues for progress in the future. Over 10-year intervals, not surprisingly, real progress does happen! But it’s also humbling to recognize how much was already known in 1978. In the most quoted paper of any conference proceedings ever, Blandford and Rees (1978) already outlined a fair fraction of the underlying physics of BL Lac objects: they understood that the spectral energy distributions (SEDs) were dominated by synchrotron and probably inverse Compton emission; they realized the emission region(s) had to be relativistically expanding; and they even knew that the selection effects would favor the discovery of BL Lac objects even though they were rare objects.
It is also interesting to observe the evolution of topics under discussion at Pittsburgh, Como, and Turku:

- **Observational properties at various wavelengths** — There was the usual breakdown into wavelengths — radio, optical, X-ray — but the mix changes. In Turku there was more discussion of VLBI results, and certainly more about gamma-rays. The discovery of strong gamma-ray emission from blazars has completely changed our understanding of their energy output.

- **Multiwavelength monitoring** — The topic of multiwavelength monitoring first came up in Como and was discussed much more in Turku. Spectral variations are a very powerful tool for understanding the physics of BL Lac objects.

- **Spectroscopy: line strengths and redshifts** — In Pittsburgh, there was a great deal of interest in spectral lines and distances. These are still important, despite being less discussed today. In one of our most important BL Lac samples, the 1 Jy radio-selected sample, about 1/4 of the redshifts are still missing.

- **Models** — Theorists continue to keep up, and often to be ahead of the observations. We now understand a lot about the physics of blazars and can even speculate on the similar physics in Galactic black hole candidates and perhaps gamma-ray burst sources.

- **Surveys and population statistics** — The small number of well-defined blazar samples indicates the critical importance of surveys. In Como, the first flux-limited samples were presented; these were essential for understanding the true nature of BL Lac objects. In Pittsburgh, there was one talk on number counts (Setti 1978); in Como, there were more, plus speculation about luminosity functions, evolution, and unification. Since then, unification has been put on a firm statistical basis using the new flux-limited samples (see Padovani, this volume).

- **Gamma-rays** — Another significant advance since Como was the discovery of blazars as bright gamma-ray sources, first at GeV energies with CGRO EGRET and more recently at TeV energies with Whipple and subsequent ground-based Cerenkov detectors. A large fraction of blazar light had previously been missed. The highly variable, strong gamma-ray emission confirms that blazars are relativistically beamed and offers strong constraints on the physics of the jet.

- **Host galaxies** — There is considerable new data on host galaxies of BL Lac objects, from HST and ground-based observatories. In Pittsburgh there was speculation about whether BL Lacs sit in galaxies; it is now clear they are the active nuclei of normal, fairly luminous elliptical galaxies with intrinsically low radio powers.

In this talk I review in broad terms our current understanding of BL Lac objects, and point out where progress is being made or where it can be made. Most of these topics are discussed in more detail throughout this volume.
2. Spectral Energy Distributions

The spectral energy distributions (SEDs) of blazars have a universal two-bump structure (in $\nu F_\nu$, Fig. 1), almost certainly caused by synchrotron radiation peaking at low energies, and at gamma-ray energies, possibly inverse Compton-scattering of soft photons radiation (although there are other possibilities; see below). While I may refer to the gamma-ray component as the “Compton component” and discuss the implications of inverse Compton scattering models, bear in mind that this model is not yet established.

The characteristics of blazar SEDs, and particularly their spectral variability, offer clues to the underlying physics in blazar jets. (Here “jet” means the unresolved, inner jets of radio-loud AGN, which dominate the observed SED. The longer-wavelength radio emission comes from more extended regions of the jet, which are sometimes resolved in radio or even optical images.)

2.1. “Red” and “blue” blazars

For more than a decade, BL Lac objects have been sorted into two types according to their broad-band spectral properties (e.g., $\alpha_{ro}$ vs. $\alpha_{rx}$; Ledden & O’Dell 1985, Stocke et al. 1985); these can be described as “red” BL Lacs, technically defined as LBL (Low-frequency peaked BL Lacs) and found primarily in radio-selected samples, and “blue” BL Lacs, a.k.a. HBL (high-frequency peaked BL Lacs), found primarily in X-ray-selected samples. (Strong emission-line blazars [quasars] are very similar to red BL Lacs.) It is now becoming clear that the SEDs, luminosities, emission line and other properties of blazars form a continuous distribution, and that the original red-blue dichotomy was caused by selection biases at high flux limits (see talks by Laurent-Muehleisen, Padovani, Ghisellini, and others, this volume).

2.2. Variability

Blazars vary most at frequencies above the peak in both SED components, and intensity variations are approximately correlated between the two peaks (Fig. 2; also, Ulrich, Maraschi & Urry 1997). The lags at high energies are short — typically less than a day — and depend on wavelength. The variability amplitudes are usually larger at higher energies, increasing greatly above the SED peak frequencies. The correlated variability suggests that the same electrons could be radiating both components.

It has long been noted that blue BL Lacs are much less variable in the optical than red BL Lacs. This has been taken to mean that they are somehow less active. Instead, from an SED-based perspective, the difference is an accident of where the SED peak occurs relative to the optical band: in red BL Lacs, optical frequencies lie above the synchrotron peak, the region of maximum variability, whereas in blue BL Lacs this is well below the synchrotron peak frequency, where variability is typically small. In fact, the blue BL Lacs are at least as variable, in terms of large amplitude and short time scale, as red BL Lacs, but at the corresponding part of the SED, i.e., at X-ray energies. By the same argument, one would predict high EUV/X-ray polarization in blue BL Lacs, comparable to the optical polarization in red BL Lacs.
Figure 1. Characteristic double-peaked SEDs of blazars. The low-energy component, due to synchrotron radiation, peaks in the infrared-optical for “red” blazars (dashed line; FSRQ,LBL) and at UV-X-ray energies for “blue” blazars (dotted line; HBL). The corresponding high-energy components, which may be due to inverse Compton scattering of soft photons, peak at GeV or TeV energies, respectively.

Figure 2. Spectral energy distribution of 3C279 at multiple epochs spanning flare to faint states. Much larger amplitude variability is seen in the gamma-ray component than in the synchrotron component, and the amplitude is larger near the peak.
2.3. Synchrotron and Inverse Compton-scattering emission models

Many speakers address inverse Compton scattering (Ghisellini, Kirk, Marscher, Levinson, this volume). The various models share several basic characteristics, including a region of energetic particles moving relativistically, often in an expanding jet geometry commensurate with the unification scheme for blazars (Urry & Padovani 1995). These particles radiate synchrotron radiation and also inverse Compton scatter ambient photons to gamma-ray energies. The ambient photons can be synchrotron photons in the jet (the synchrotron self-Compton, or SSC, model), or UV/X-ray photons from the disk, or reprocessed UV (or even IR) photons from the broad-line region or obscuring region beyond. Which of these soft photon sources dominates depends on their local energy density near the electrons of interest. Because of the bulk relativistic motion of the electrons, photons impinging on the jet from the side or front are relativistically boosted in the frame of the electrons, enhancing their apparent intensity. This means strong-emission-line sources are almost certainly dominated by the inverse Compton scattering of external photons (the external Compton, or EC, mechanism), at least at GeV energies. In the weak-lined objects, the BL Lacs, probably the SSC mechanism dominates at all gamma-ray energies.

A few general points about synchrotron and Compton scattering scenarios should be noted. First, the two SED peaks reflect a characteristic electron energy, perhaps where the cooling time, which decreases with frequency, balances the time-independent escape time. Below the synchrotron peak, then, escape could be significant, which could explain the very flat infrared spectra sometimes observed, at wavelengths where the source should be optically thin. (Flat radio spectra, at longer wavelengths, are instead caused by optical depth effects.)

A second interesting point is that, roughly speaking, the ratio of peak frequencies in both red and blue blazars, $\nu_C/\nu_s$, appear similar. (Bear in mind, however, that $\nu_C$ can be affected by Klein-Nishina effects in the blue blazars, and that gamma-ray data are very sparse.) Assuming this is physically meaningful, the interpretation depends on how the gamma-rays are produced at the second peak. If SSC dominates in all blazars, then $\nu_C/\nu_s \propto \gamma_{\text{peak}}^2$ (where $\gamma_{\text{peak}}$ is the characteristic energy of electrons radiating at the synchrotron peak), and one would conclude that the peak electron energies are independent of blazar luminosity. If instead the gamma-rays are produced by the EC mechanism in all blazars, then $\nu_C/\nu_s \propto \nu_{\text{ext}}/B$, where $\nu_{\text{ext}}$ is the typical frequency of the soft seed photon and $B$ is the magnetic field. This would imply the ratio of $\nu_{\text{ext}}/B$, a sort of ratio of accretion energy to magnetic energy, is roughly constant in all blazars. More likely, SSC dominates the gamma-ray peak in low-luminosity blazars and EC the peak in high-luminosity blazars (see §2.5). In this case $\nu_{\text{ext}}/B$ in luminous blazars must approximately “match” $\gamma_{\text{peak}}^2$ in less luminous blazars. This might indicate that electron acceleration, which determines $\gamma_{\text{peak}}$ when cooling is less important, is related to the magnetic field strength and overall source (accretion) luminosity, in a kind of energy balance constraint.

2.4. General considerations for emission models

There remains the question of whether blazar jets are homogeneous or inhomogeneous. (Of course, jets are unlikely to have uniform electron densities and magnetic fields on all scales, but at high energies the dominant emission region could
be approximately homogeneous.) Perhaps surprisingly, much of the existing multiwavelength data are still consistent with a homogeneous model. For example, the lags between soft and hard X-rays can be explained by energy-dependent cooling in a homogeneous volume (see § 3). However, inhomogeneities may be needed to explain variability amplitudes even at the highest energies. For example, at X-ray energies in blue blazars, we typically see variations by factors of 2, not factors of 10 or 10%. It is natural to get very large amplitude variations from a single acceleration event — the high-energy emission should be “on” or “off” because the loss time scales are very short. At the other extreme, small amplitude variations occur naturally from the superposition of a large number of strong flares. To get the observed, intermediate amplitude variability is unnatural in the homogeneous case, and implies instead a quiescent flux, at a level comparable to the flare peak intensity. This implies that flares are on top of some quiescent level, and that the flaring region varies with large amplitude, which suggests that jets are at least partially inhomogeneous (Sikora, Madejski & Begelman 1997).

If the dominant emission region is homogeneous, there must be additional electron acceleration above the characteristic $\gamma_{\text{peak}}$, for at least two reasons. First, a sharp cutoff in electron energy should produce much larger amplitude variations than are observed. Second, the TeV spectra of Mrk 421 and Mrk 501 extend to 10 TeV, perhaps even to 30 TeV in some bright states (Krawczynski, this volume); if there were a sharp cutoff at $\gamma_{\text{peak}}$, the gamma-ray spectrum should cutoff sharply as well. Thus the acceleration process(es) must produce electrons of a characteristic energy $\gamma_{\text{peak}}$ and produce a power-law distribution of electron energies above $\gamma_{\text{peak}}$. This might occur because electrons are universally accelerated to $\gamma_{\text{peak}}$ in a blast wave or bulk acceleration process then further accelerated by shocks, or because they are injected at high energies and cool to $\gamma_{\text{peak}}$ (below $\gamma_{\text{peak}}$ cooling produces a flat electron energy distribution, flatter still if escape is important; thus electrons at $\gamma_{\text{peak}}$ dominate the emission).

More fundamental issues are how energy is extracted from the central black hole and how it is transported to the radiative zone. Much of the extracted energy is eventually manifested as kinetic energy in the jet, some fraction of which is then radiated in the observed SED (the rest feeds the extended radio lobes). Very near the black hole, the radiation and particle densities in blazars would be high enough to efficiently generate pairs, even taking relativistic beaming into account. The resulting cascades would trap high-energy radiation in an optically thick zone, contrary to observation. This means the observed emission must originate in a radiative zone a fair distance from the black hole, and the energy transport process is effectively dissipationless.

Sikora (1997) has argued that cold protons ($\gamma \sim 1$) are unlikely to carry much energy in blazar jets, assuming the energy distributions of electrons and protons are similar. This is because cold electrons, which would have an effective Lorentz factor $\sim 10$ due to the bulk relativistic outflow, should Comptonize ambient UV radiation up to $\sim 1$ keV. The absence of this so-called “bulk Compton” bump indicates there are too few cold electrons to transport much energy along the jet. Instead, there must be a dissipationless transport of energy, such as Poynting flux.
2.5. SED trends with luminosity — the current blazar paradigm

Observed blazar SEDs change shape systematically with luminosity, as noted by Rita Sambruna in her Ph.D. thesis (Sambruna et al. 1996, Sambruna 1997) and by Fossati et al. (1997). Both synchrotron and gamma-ray SED peaks decrease in frequency with increasing luminosity. At the same time, the ratio between the two SED components, $L_C/L_s$ — often called the “Compton dominance” — increases, from $\sim 1$ or even less for the blue BL Lacs to as much as 100–1000 for some luminous quasars. The luminosity in emission lines also increases with bolometric luminosity; the distinction between BL Lacs and quasars, at an equivalent width of 5 Å, is essentially an arbitrary one (Scarpa & Falomo 1997).

This is not to say that BL Lacs and emission-line blazars are identical, or even that their properties overlap strongly, simply that there is no clear gap between the populations. A possible exception is the VLBI polarization properties, which appear to differ discontinuously between BL Lacs and quasars (Gabuzda, this volume). This apparent dichotomy could be affected, however, by differences in intrinsic physical scale sampled at fixed VLBI resolution. Apart from this uncertain issue, the distinction between quasars and BL Lacs occurs at an arbitrary point (i.e., 5 Å equivalent width), spanned by a continuous distribution of physical properties. Lest this cause confusion, I repeat: Of course the average properties of quasars and BL Lacs are different, and indeed the extremes of each class are grossly different! But the point at which one defines a BL Lac is arbitrary because the properties are continuous.

The observed trends of blazar properties with luminosity, if they reflect an intrinsic physical reality, support a self-consistent picture of equilibrium between electron acceleration and cooling (Ghisellini et al. 1998; Ghisellini, this volume). The basic paradigm is that electrons are accelerated to similar high energies in all jets, in an approximate power-law distribution, and then they cool on the ambient radiation field. Because the local photon densities are higher in more luminous sources, there is more cooling, and the equilibrium values of $\gamma_{peak}$ are lower, which is reflected in lower frequencies of the synchrotron SED peaks (see also Georganopoulos & Marscher 1998; Marscher, this volume).

This is an attractive and viable paradigm but is not yet well tested. The multiwavelength data for existing samples are sparse and not uniform, particularly at gamma-ray energies. To confirm that the two SED components are produced by the same electrons requires much better multiwavelength monitoring data, to find correlated variations and to “identify” the electrons radiating at each wavelength.

Furthermore, the luminosity-dependent paradigm is based on blazars for which there are gamma-ray detections, and those samples may be biased in the direction of the observed SED trends, either through the extra beaming in EC sources (Dermer 1995) or through variability (Hartman and Wagner, this volume). That is, the gamma-ray-detected blazars may not be representative of blazars as a class, nor representative of the average state of the particular blazar.
3. Multiwavelength variability

Because they are very bright at optical/UV/X-ray wavelengths, Mrk 421, Mrk 501 and PKS 2155–304 are the best-monitored blazars. Each has been the target of multiple well-sampled, long-duration monitoring campaigns. For Mrk 421, both the high-energy synchrotron emission and the gamma-ray component have been well monitored because this blazar is consistently bright at TeV energies. Mrk 501 has more recently been well monitored, following a dramatic TeV and X-ray flare in April 1997. PKS 2155–304 has been monitored for longer and with better sampling at optical through X-ray wavelengths but without simultaneous TeV monitoring (cf. Chadwick et al. 1998).

In all three of these blue blazars, the synchrotron component dominates out to at least a few keV. In both Mrk 421 and PKS 2155–304, the hard X-rays (∼ 5 keV) lag soft X-rays (∼ 0.5 keV) by 1 hour (Takahashi et al. 1996, Urry et al. 1997; also Treves, this volume), roughly as expected for a homogeneous source, where the lag time is roughly the radiative time scale at the lower energy.

Of great interest is the correlated variability between synchrotron and Compton components at corresponding points on the SED; for these blue blazars, the spectral peaks are in the X-ray and TeV bands. Mrk 421 appears to flare roughly simultaneously in X-rays and TeV but the lag is very poorly constrained (Macomb et al. 1995, Buckley et al. 1996). More recent multiwavelength monitoring of Mrk 421 in April 1998, for a full two weeks with much denser X-ray sampling, should provide better constraints (Takahashi et al., in prep.). During a bright flare in 1997 (Catanese et al. 1997, Pian et al. 1998), Mrk 501 was easily detected at TeV energies and with the RXTE X-ray All-Sky Monitor (ASM). The cross-correlation of the two well-sampled light curves (with at least daily sampling, over several months) has a highly significant peak at zero lag, with an uncertainty of ∼ ±1 day (Krawczynski, this volume). This is the first well-measured X-ray/TeV correlation.

The close correlation of X-rays and TeV emission in blue blazars is strong evidence for a common production mechanism for both synchrotron and gamma-ray SED components. Measuring the lags accurately between the real SED peaks, a good determination of which requires detailed monitoring over a large wavelength range, should distinguish between Compton scattering models and alternatives like proton-induced cascades (PIC).

In the PIC model, protons and electrons are accelerated to extremely high energies; the primary electrons radiate the low-energy SED component via synchrotron; protons interact with ambient photons to induce pair cascades; and a subsequent (third?) generation of pairs radiates the high-energy SED component, also via synchrotron radiation. The low-energy radiation should appear first, followed by the high-energy component, and the relative amplitude of variability at the two peaks is essentially free. In contrast, the Compton scattering picture predicts true simultaneity and larger amplitude in the gamma-rays, at least for flares caused by electron acceleration.

Variability amplitudes are very informative, although the observational data at present are somewhat limited. This is because, for most GeV blazars, EGRET lacks the dynamic range to measure variations by more than a factor of 10 or so, and also because the corresponding synchrotron peaks are poorly monitored, being in the far infrared. For the TeV blazars, the synchrotron peaks can be
well observed but there are very few sources detected in gamma-rays. That said, if the multi-epoch SED of 3C279 is typical (Fig. 2), the gamma-ray component is generally much more variable than the synchrotron component. The EGRET data are near the gamma-ray SED peak in 3C279, which varies in intensity by more than a factor of 30; above the synchrotron peak, in the optical/UV, the simultaneous intensity varied by less than a factor of 2 (Wehrle et al. 1998). Indeed, the gamma-ray variation is more than the square of the apparent synchrotron variation (with the caveat that we do not actually observe the infrared peak). It should go roughly linearly in the external Compton model and roughly as the square in the SSC model, for simple electron acceleration events. Clearly additional complexity is present, such as enhanced beaming in the external Compton case (Dermer 1995) or possibly a change in the Doppler factor (Dermer & Chiang 1998).

The synchrotron peak frequencies in individual objects can change dramatically during a flare, increasing by a factor of $\sim 100$ during the strong Mrk 501 flare (Pian et al. 1998, Catanese et al. 1997; also Pian, this volume). A corresponding shift in the gamma-ray peak was not seen, probably because Klein-Nishina effects dominate at the peak. Such strong spectral hardening in blazars had not previously been observed, and it is important to look for these events now that BeppoSAX provides sufficient hard X-ray sensitivity. (It remains difficult to observe similar spectral hardening in the red blazars because their peaks are often in the far infrared spectral region, where there are few monitoring data, perhaps a handful of ISO results slowly coming out.)

4. What kind of jets does nature make?

A prerequisite for understanding jet formation is understanding the demographics of jets in radio-loud AGN. It is now recognized that blazar jets, as evidenced by their range of SEDs, encompass a range of physical states. To first order, it appears that the low luminosity, low kinetic power jets of blue blazars have systematically higher frequency synchrotron cutoffs and therefore higher electron energies, while the high luminosity, high kinetic power jets of red blazars have lower electron energies. However jets are formed, nature produces a distribution of intrinsic properties.

Selection effects are strong in blazar samples. Not only is their jet emission strongly beamed, but the principal selection bands for existing flux-limited samples, radio and X-ray, are at well separated points on the SED. Thus it is no surprise that current blazar samples are highly biased. Nonetheless, people seem surprised to learn that the extrapolation from those samples, to infer the relative numbers of low-power (blue) and high-power (red) jets, is uncertain by a factor of $\sim 100$, depending on assumptions. This is illustrated (for BL Lacs) by the comparison of integral number counts for radio and X-ray samples (Fig. 3). The left panel shows the number counts (Urry, Padovani & Stickel 1991) from five major X-ray samples (open symbols), which are primarily blue BL Lacs, and the “bivariate” X-ray counts for the 1 Jy radio sample (filled triangles) which are primarily red BL Lacs. Under the assumption that the X-ray surveys are an
unbiased probe of blazars (i.e., unaffected by their red/blue nature), one would conclude that blue BL Lacs are ten times more numerous than red BL Lacs.

However, under the assumption that the 1 Jy survey is instead unbiased, one comes to the opposite conclusion (Giommi & Padovani 1994, Padovani & Giommi 1995). The right hand panel in Figure 3 shows the integral radio counts for the 1 Jy sample, combined with the “bivariate” radio counts for the X-ray samples, i.e., the X-ray-derived surface density of blue BL Lacs at the observed radio fluxes for those samples. The solid line shows the extrapolation to lower radio fluxes for the expected counts for the best-fit unification of radio galaxies and BL Lac objects (Urry et al. 1991). If the radio survey were equally sensitive to red and blue BL Lacs, then one would conclude that the powerful red objects are 10 times more numerous than blue.

Note that the Padovani and Giommi calculation is approximately symmetric with respect to assumed SED. They assume a distribution of spectral cutoffs toward higher frequency, with the radio survey being unbiased. One could equally well assume the X-ray surveys are unbiased, and that there is a distribution of spectral cutoffs toward lower frequency. The ensuing calculation does in deed reproduce the observed radio counts (Fossati et al. 1997). Thus the relative numbers of red and blue blazars remain indeterminate at present.

Because blazar SED shapes strongly affect surveys at both radio and X-ray wavelengths, the truth probably lies somewhere in between (see Padovani, this volume). An attempt to estimate the bolometric luminosity function, thus correcting in a primitive way for the luminosity effect (but still a “bivariate” approach in the sense that missed objects are still missing), implied a much more similar space density in the region of overlapping luminosity (Urry & Padovani 1995). But the fact remains that the question of relative space density is still largely an open one, and requires deeper surveys to solve. The most promising avenue is to look at deeper flat-spectrum radio samples; the flux limit of the 1 Jy sample is so high that going even a factor of a few deeper should reveal differences between the extreme X-ray-dominant and radio-dominant scenarios.

I have described how, at present, the distribution of jets in nature, high luminosity red jets versus low power blue jets, is not well constrained. Obviously nature makes both types, and their ratio may change in cosmic time. In particular, if blazar power/luminosity decreases in cosmic time, as suggested by global evolutionary properties of AGN, there should be more blue BL Lacs locally and more red ones at high redshift, more or less consistent with the different evolutionary properties of the two types.
Figure 3. The X-ray and radio number counts for blue (open symbols) and red (filled symbols) BL Lac objects illustrate the ambiguity over which population is more numerous. Left — Observed X-ray counts for X-ray-selected samples are \(\sim 10\) times higher than the “bivariate” X-ray counts for radio-selected samples (radio-derived surface density combined with observed X-ray fluxes; Urry et al. 1991).

Right — Beaming model extrapolation (solid line) of observed radio counts for radio-selected samples (Urry & Padovani 1995) is \(\sim 10\) times higher than the “bivariate” radio counts for X-ray-selected samples (X-ray-derived surface density combined with the observed radio fluxes).

Figure 4. Simulated soft X-ray spectra for three viable models of circumnuclear absorption in blazars, at typical grating resolution. Current low-resolution CCD data have detected broad absorption clearly but cannot unambiguously determine its origin, as shown by the residuals to a simple power law fit to ASCA data (bottom panel). AXAF, XMM and/or Astro-E will clearly distinguish among the possibilities.
5. Sub-parsec structure

Very little is known about the sub-parsec structure of BL Lac objects. According to the AGN paradigm, unless structures change drastically at low luminosity (and there are few if any hallmarks of such abrupt change), the centers of BL Lacs should contain the same broad emission line regions and accretion disks as conventional quasars. Clearly at least some BL Lacs have a broad-line region (e.g., Corbett et al. 1996, Vermeulen et al. 1995, Stickel et al. 1991), as was evident already at the Pittsburgh conference (MgII lines seen in BL Lacs; Miller 1978). These properties have not been surveyed systematically, the blue bump and broad lines being hidden in large part by the relativistically boosted jet continuum, so the distribution of line or accretion disk luminosities is only poorly known. It is extremely important to survey the “thermal” properties of blazars.

One clue comes from X-ray spectroscopy. At present, the state of the art — CCD spectroscopy with resolving power of $\sim 10$ in the soft X-ray energy range — suggests there is highly ionized circumnuclear material in BL Lac objects, producing absorption near 0.6 keV (Fig. 4). At least three quite different models for the absorber — an outflowing wind, a line blend, and a so-called “warm absorber” — fit the low-resolution CCD data equally well. With the much higher spectral resolution soon available with AXAF, XMM, and Astro-E, identifying the origin of the X-ray absorbing gas in BL Lacs, and perhaps mapping it crudely via variability, should be relatively easy. Such data can be used to map the innermost structure of BL Lac objects.

6. Host galaxies

Host galaxies are easily detected in BL Lac objects, as found in our large HST survey (Falomo et al. 1997, Urry et al. 1999a,b; see also Falomo, this volume). BL Lac host galaxies are large, round, smooth ellipticals, roughly 1 mag brighter than a typical ($L^*$) elliptical (Wurtz et al. 1996; Urry et al. 1999b), fitting well the $\mu_e-\tau_e$ projection of the fundamental plane for elliptical galaxies, at the high luminosity end (Urry et al. 1999b).

According to unified schemes, the unbeamed properties of BL Lac objects, such as host galaxies, should be identical to those of their parent population, nominally FRI radio galaxies. Indeed, BL Lac host galaxies are large, round, smooth ellipticals, roughly 1 mag brighter than a typical ($L^*$) elliptical (Wurtz et al. 1996; Urry et al. 1999b), fitting well the $\mu_e-\tau_e$ projection of the fundamental plane for elliptical galaxies, at the high luminosity end (Urry et al. 1999b).

According to unified schemes, the unbeamed properties of BL Lac objects, such as host galaxies, should be identical to those of their parent population, nominally FRI radio galaxies. Indeed, BL Lac host galaxy magnitudes are typical of FRIs in the same redshift range. (N.B. Because flux-limited samples of BL Lacs usually span higher redshifts than FRIs, as do FRIIs, simple comparisons of host-galaxy magnitude distribution, ignoring redshift, can lead to incorrect conclusions. Another common mistake is to compare, in a KS sense, the observed distribution of some property of blazars and radio galaxies, such as host galaxy magnitude. Because of selection effects related to beaming and/or the redshift-luminosity correlation in flux-limited samples, the shape of the distributions will not necessarily match, even in intrinsically identical AGN; rather, the parameter values “match” if they span the same range.)

Furthermore, both the host galaxy magnitude and the extended radio power of BL Lacs must match those of the parent population, since the division between FRI and FRII galaxies appears sharp only in this two-dimensional parameter
space (Owen & Ledlow 1994). Figure 5 shows clearly that the extended radio powers and host galaxy magnitudes of BL Lac objects overlap those of FRI radio galaxies and are unlike FRIIs. The naive projection of these data in optical magnitude alone, independent of radio luminosity, has led some to the incorrect conclusion that FRIIs are a better match for the parent population. This mistake happens in part because there are no detections of BL Lac host galaxies as luminous as the very brightest FRIs, typically the central dominant galaxies in rich clusters. Indeed, BL Lacs may avoid the very richest clusters (Owen, Ledlow & Keel 1996), but as Figure 5 illustrates, this must be a second-order issue in the largely correct unification of FRIs and BL Lacs.

Figure 5. Comparison of unbeamed properties — extended radio power versus host galaxy magnitude — of BL Lac objects (filled circles and squares) and radio galaxies shows that FRIs (labeled “1”) are a much more likely parent population than FRIIs (labeled “2”). The BL Lacs were taken from complete radio- or X-ray flux limited samples and host galaxy determinations were made using HST data (Urry et al. 1999b). The FRI/II samples were from the 2 Jy sample (Wall & Peacock 1985), selected in a similar way to the BL Lac radio samples.

### 7. Radio-loud versus radio-quiet AGN

Now for some speculation about how studies of BL Lac objects might inform our larger understanding of AGN. A critical issue is the radio-loud/radio-quiet dichotomy, which essentially translates to why only some AGN appear to form relativistic jets. Blazar studies have indicated the importance of selection biases in samples flux-limited at wavelengths located in different parts of the SED. By analogy, is it possible that the distribution of $\alpha_{\text{radio}}$ is not intrinsically bimodal, i.e., that there is no sharp physical distinction between radio-strong and radio-weak AGN? The radio flux distribution for PG quasars is not so strongly bimodal (Kellermann et al. 1989); perhaps beaming effects (as yet unquantified) could...
enhance the radio relative to the optical emission in the so-called radio-loud objects. There do exist “transition” objects with intermediate values of $\alpha_{ro}$, which have been interpreted as radio-quiet quasars with significantly beamed cores (Falcke, Patnaik & Sherwood 1996). In deeper radio samples, intermediate values of $\alpha_{ro}$ should be further filled in; possibly this is seen in the FIRST radio survey (Helfand, priv. comm.)

Alternatively, sharp transitions (intrinsic bimodality) in radio-loudness could result from a critical dependence on jet kinetic power and host galaxy mass, analogous to the FRI/II transition (Bicknell 1995). At very high jet powers, one gets an FRII type source (an emission line blazar when aligned); at lower jet power, there is a sharp transition to diffuse FRI-type jets (a BL Lac object when aligned); perhaps at some still lower power, the jet cannot form or is quenched so early that one gets a radio-quiet object.

Flux-limited samples can be corrected in a straightforward way for objects that have been missed because of their lower fluxes. Thus we have confidence that they are representative. But such corrections work only when the excluded objects are intrinsically identical to the discovered objects. If the missing objects instead have a different spectral energy distribution, then their number and properties depend on assumptions about their numbers and SEDs — basically, the correction is a circular (model dependent) problem. As far as I can see, this problem has not been addressed explicitly for the radio-loud/radio-quiet issue.

8. Questions for the future

The future in blazar research is very rich. Here is a personal list of the key questions ahead:

What is the energy production and balance in blazar jets? To understand the extraction of energy from the black hole, we have first to quantify the energy distribution among particles, magnetic fields, and photons. A practical near-term issue is identifying how the gamma-rays are produced. Several years without GeV data loom ahead, so for the moment progress means detecting more TeV sources; the prospects are good, as TeV telescopes rapidly improve and extend to southern latitudes. TeV sources should be monitored also in X-rays, to look for correlated variability in the two spectral components; ditto for red objects at optical and GeV energies with GLAST, possibly sooner with AGILE-type gamma-ray satellites or ground-based gamma-ray telescopes like MAGIC. The goal is to identify the electrons radiating in each component, and to see if/how they are related. PIC models predict more independent variations than EC or SSC models.

What kind of jets does nature make? Quantifying the distribution of jet powers — the intrinsic luminosity function of jets, in a global sense — is an important constraint on jet formation scenarios. The present uncertainty in the relative numbers of blue and red jets can be resolved with deeper samples (some reported here; e.g., Perlman, Laurent-Muehleisen, this volume). Given the range of SEDs in blazars, selection effects are strong and samples flux-limited in any one band offer a necessarily biased and incomplete picture.

How do radio-loud AGN form and evolve? The study of host galaxies is a direct probe of the relative evolution of nuclei (black holes) and normal
galaxies. The high-redshift blazars turning up in deeper samples (e.g., DXRBS) are essential for studying the evolution of low-luminosity jets (which must be beamed to be seen at high redshift). The new and upcoming large telescopes with infrared sensitivity, including NGST, the VLT, Magellan, Gemini, etc., are ideally suited to these studies. Further study of blazar environments is also important. With its high spatial resolution and excellent sensitivity, AXAF will be a powerful tool for detecting clusters around BL Lac objects. This is not only easier than counting galaxies in the optical and constraining cluster membership with multi-object spectroscopy, but it probes the diffuse gas, which contains most of the mass, so classification of richness is more meaningful.

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