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Multiwavelength Emission from Blazars – Conference Summary

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Abstract. Presentations at the Guangzhou Conference on Multiwavelength Emission from Blazars confirmed our understanding of blazars as relativistic jets closely aligned with the line of sight. Powerful new studies have been enabled by the Fermi gamma-ray satellite and new ground-based TeV facilities, which are an order of magnitude more sensitive than their predecessors. Combining gamma-ray data with VLBA radio and with optical/IR photometry has shed new light on the emission mechanisms and the jet geometry. This conference summary sets the context for the 4th blazar conference and presents some of the highlights from the meeting, as well as the questions that remain outstanding.

Key words. Blazars—spectral energy distributions—gamma-ray emission—radio emission—host galaxies—blazar demographics—redshifts—polarization—Yung Wing—optical emissions—emission mechanism—black holes.

I am not the first to pale before the task of summarizing an interesting and informative 'MVB' conference. The breadth of the contributions, the depth of the different physics issues, and the sheer volume of work represented all add to the impossibility of addressing the meeting in any detail. Nonetheless, most of us try, bravely (for certain) and seriously and then steadfastly, even when the difficulty of the task surfs over us. This is my poor attempt.

The first blazar conference was held over 30 years ago, in Pittsburgh, the 1978 Conference on BL Lac Objects. Indeed, this was where the word 'blazar' was first coined, reportedly by Ed Spiegel, to reflect the mix of 'BL Lac' and 'quasar' comprising the class. This path-breaking conference was followed by the Como Conference in 1988, Turku Conference in 1998, and Guangzhou Conference in 2010. Few of us have been to all four conferences, Alan Marscher has, and Margo Aller. Looking at the Turku conference photo (Fig. 1a), you can clearly see Margo Aller, Stefan Wagner and Alan Marscher at the right; I recognized myself in the back on the left. There we are again in Guangzhou (Fig. 1b); here, Stefan is easier to pick out because he's standing. These conferences have a way of marking time, don't they? In 1978 I was a beginning graduate student, working on interpreting the X-ray spectrum of the BL Lac object PKS 2155–304 and reading the yellow Pittsburgh Conference book (Wolfe 1978) to learn about reports of synchrotron emission in the radio and optical. A proud postdoc in 1988, I knew (really?) that BL Lacs

(a)

(b)

Figure 1. Conference photos from blazar meetings in Turku in 1998 (**a**) and Guangzhou in 2010 (**b**). A few people appear in both, and some (e.g., Alan Marscher and Margo Aller) were also at Como in 1988 and/or Pittsburgh in 1978. The good news is that many young people appear for the first time at each successive conference, testifying to the excitement of the questions being addressed in blazar research.

and other blazars were relativistically beamed jets. As a tenured faculty member in 1998, I knew we had confirmed the role of beaming, identified the parent population (quantitatively!) with radio galaxies, and we were on the brink of using the gamma-ray emission to diagnose the emission mechanism and thus the physical parameters of the jet.

Today, as discussed in Guangzhou, the basic equation of blazars with aligned relativistic jets is well established; synchrotron radiation is known to dominate the radio through optical (and sometimes UV-X-ray) emission; inverse Compton scattering of synchrotron and ambient thermal photons plays a role in producing hard X-rays and gamma rays; energetic protons may also play a role in the gamma-ray emission (after all, there are likely to be hadrons in the jet); and particle acceleration and radiative losses in the jet can create a variety of observed behaviours. The physics of the acceleration sites – shocks, inhomogeneities, particle energies, magnetic field structure – is sufficiently complex that individual flares rarely repeat themselves, yet correlations among different wavebands and time scales for the rise and fall of flares provide tools to interpret the underlying processes. That is, the detailed behaviour is messy, yet if we focus on a few simple facts, then certain simple conclusions are bound to follow.

In Turku, Fossati and Georganopoulos both talked about blazar unification. FSRQ, LBL and HBL all share the following characteristics: the broad two-component SED shape; rapid variability above the SED peaks; polarized emission in the radio and optical (and likely UV and X-ray, though this has not been measured yet); and correlated variations between the two components. The general scheme Fossati introduced then, linking blazars along a luminosity sequence (Fossati *et al.* 1997, 1998) surely plays a role. The intrinsic strength of line emission is another variable (Urry & Padovani 1995). Indeed, there is likely to be a physical disk-jet connection such that more powerful jets are associated with stronger accretion flows, thus linking observable line, disk and jet emission.

By their very nature, blazars are difficult to collect in unbiased samples, as the emission is strongly beamed and there is a broad variety of SEDs. Nonetheless, by the time of Turku there were several presentations about new blazar samples, filling in the SED-shape plane (e.g., $\alpha_{\rm ro}$ *vs.* $\alpha_{\rm rx}$) which previously had shown only narrower relations. For example, although the first radio-selected samples were dominated by traditional low-frequency-peaked blazars (LBL) and X-ray-selected samples consisted of mostly high-frequency-peaked blazars (HBL), new optical surveys reported at Turku found blazars with synchrotron peaks between those of LBL and HBL (Landt *et al.* 2001; Laurent-Muehleisen *et al.* 1999). It became clear that selection effects had introduced strong SED biases into radio-selected and X-ray-selected samples – into all samples, in fact, thanks to wide variations in the underlying SED shape and to strong beaming. Obtaining these samples is a painful, hard slog, and at Guangzhou we did not see a comparable influx of new demographic information. We still need a comprehensive analysis of the selection effects operating in existing blazar samples (cf. Padovani *et al.* 2007). For example, there is an apparent difference in evolutionary behaviour between HBLs (negative evolution, i.e., more such objects in the local universe than at high red-shift) and LBLs and FSRQ (positive evolution, i.e., in the usual sense that there are more quasars at $z<1$–3 compared to $z<0$); one of my former undergraduate students, Tim Brandt, has showed that simple selection bias can lead to this result when the underlying evolution is identical. This work is not yet published but points towards a useful direction of future research which will be enabled by the many large, multiwavelength surveys under way or planned.

In the 1990s many investigators used the Hubble Space Telescope and ground-based telescopes to study the host galaxies of blazars. In general, these were found to be luminous ellipticals, similar to the brightest cluster galaxies (e.g., Urry *et al.* 2000; O'Dowd & Urry 2005; Kotilainen *et al.* 2005) and hosts of other radio-loud AGNs (e.g., McLure *et al.* 1999). Since Turku, several groups have obtained high signal-to-noise optical spectra of the host galaxy and among other things, the velocity dispersion in the stellar lines has been used to estimate black hole mass according to the M-sigma relation, or to investigate the evolution of the fundamental plane for ellipticals (Falomo *et al.* 2003; Woo *et al.* 2004, 2005).

In Turku, there was much discussion of multiwavelength variability of blazars, but only limited dynamic range was achievable in gamma-rays at GeV (with EGRET) or TeV (with ground-based Cherenkov detectors) energies. Now, the much more sensitive Fermi gamma-ray satellite and more sensitive TeV experiments (e.g., H.E.S.S., VERITAS) have led to a flood of new multiwavelength variability data, about which we heard a great deal at Guangzhou. Most remarkable in my view are the very detailed correspondences between physical features seen in VLBI radio images and flares occurring at gamma-ray (and other) wavelengths. Marscher and his group make a strong case that at least some of these events are happening pretty far out the jet (>10 pc), as outward moving plasma disturbances propagate through strong standing shocks (e.g., Marscher *et al.* 2010). Figure 2 shows Marscher's sketch of the interpretation of multiwavelength flares and radio structure changes in the FSRQ PKS1510–089.

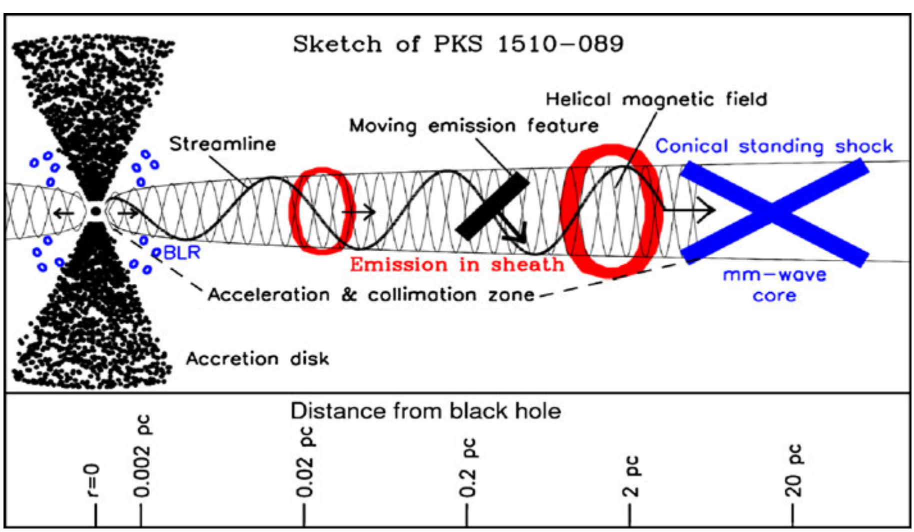

Figure 2. Model proposed by Marscher *et al.* (2010) to explain gamma-ray flares in PKS1510–089 by the passage of jet plasma, which is moving in a helical path because of the jet's magnetic field, through strong standing shocks.

This does not mean all flaring behaviour is caused the same way. Indeed, the variety of observed multiwavelength flares suggests multiple mechanisms are in play. The close correlation of gamma-ray and optical emission in several blazars (e.g., Bonning *et al.* 2009; Jorstad *et al.* 2010), with lags shorter than the temporal resolution of <1 day, supports leptonic models for gamma-ray production in FSRQ and LBL. (These are models in which the synchrotron-radiating electrons also lose energy by up-scattering ambient synchrotron, disk, or broad line photons.) Still, given the very high Lorentz factors needed, it is equally likely that energetic protons could play a role in producing some of the gamma-ray emission. Moreover, it is likely that the variability is not actually being resolved at most wavelengths, even by Fermi: TeV data for the brightest HBLs suggest there is significant variability (factors of 2 or more) on time scales of minutes. Obtaining high quality light curves at that time, resolution will require lots of planning and some luck. But it is still early days for Fermi, and some fortuitous flaring by some of our favourite blazars is likely to greatly improve our understanding of particle acceleration, jet composition, and ambient conditions in blazar jets.

In Turku, detections of HBL at TeV energies with ground-based Cherenkov detectors were very new. Now such telescopes are at least an order of magnitude more sensitive and even Fermi can detect more than the brightest couple of HBLs that were seen with EGRET. Some similar physics must be happening in these lower-luminosity, higher Lorentz-factor jets as in the GeV-bright FSRQs and LBLs, and comparison along the blazar sequence should help tease out the key variables. This was not much discussed at Guangzhou but should be considered further.

This brings us to timing analyses, which have been a highly visible part of blazar research for several decades. We heard much about this at the Guangzhou meeting. With all due respect to my colleagues, I remain a skeptic on the issue of periodicities in blazars. To be convinced, the light curve and fit would have to be comparable to what we see in X-ray binaries – and they are not. Moreover, I am curious to know why, when blazar luminosities range over maybe 4–5 orders of magnitude, do the claimed periods all have similar time scales of a few years (2–20)? If real, this is puzzling. It would be an incredible discovery to confirm measured periodicities in blazar light curves because they could be tied to an orbital period or to BH spin or perhaps, for QP0-like periods, to jet instabilities in a helical magnetic field. But we all agree that 'extraordinary claims require extraordinary proof'. To be convinced of an observed periodicity, I suggest that several levels of confidence be established: (1) There should be at least five cycles. As many authors have noted (e.g., Scargle 1982), random sampling of irregular variability often leads to 3 or fewer ups and downs that can mimic a period corresponding to roughly 1/3 of the duration of the observation. A period will be much more convincing if the light curve actually shows half a dozen repetitions of a clear periodicity. (2) Don't 'cherry pick' the data. We must consider the full time interval, not the one that conveniently shows a periodicity. (3) Most importantly, simulations of long-term blazar light curves must be carried out. Starting with a red-noise power spectrum (proportional to $1/f$ or $1/f^2$), continuous light curves can be produced, and then sampled with the window function for the actual observations. Then one can calculate all the usual statistics (e.g., Fourier transforms), tabulate how many incidences of 'QPO' are seen, the significance of any 'periods' detected, etc. When repeated many thousands of times, we would have an empirical estimate of false detections with appearance similar (or not) to the claimed periods in a given (real) light curve. This kind of careful analysis has the potential to convince us. Periods that are intrinsically transient, such that they don't last more than a few cycles, unfortunately will not (however unfair that might be).

Excellent progress has been made in understanding jet kinematics, thanks to the co-ordination between Fermi and VLBI imaging, as exemplified by the program led by Marscher and Jorstad. Their results demonstrate the link, hinted at in the EGRET era, between ejection of superluminal blobs and gamma-ray flares (see their talks, this Conference Proceedings). They argue that, in at least a few well-documented cases, the gamma-ray flare is caused by the passage of a superluminal blob (density enhancement?) through a standing shock (identified in radio parlance as the 'core' of the radio source). I find their evidence compelling but (no doubt like them) would like to see more examples with this exquisite coverage and spatial (radio) and temporal (all wavelengths) resolution. These additional data will help resolve the debate about the location of the gamma-ray emission region, whether it is within a few parsecs of the black hole, in the broad emission line region, or farther downstream. If both are strong emitting regions, we should observe different flares, one when a jet blob passes the broad line region (<0.1 pc), then another as it passes the 'core'.

Blazars are always in the news. Just before this MVB Conference, the Fermi LAT team announced the detection of a GeV flare from the FSRQ PKS 0727–11, a new gamma-ray identification (D'Ammando *et al*. 2010). This brightening could happen in any of several dozen more blazars already detected in one-year averages of Fermi integration, such that they become detectable in much shorter times. Those of us who monitor these objects at other wavelengths need to keep updating our source lists to include the new detections. (Thanks to limits on observing time, we will also have to delete sources that have become 'boring'. This is a worrying bit of observational censorship but what else can one do?) One additional worry: we cannot just select the flares we think we understand, and use them to bolster our confidence in our favourite models, while ignoring the ones that don't 'behave' properly.

We are still missing some key pieces of information, not least the red-shifts for some very famous, bright blazars, including some detected at TeV energies. Probably we have exhausted the limits of dedicated optical spectroscopy, but there are other avenues. Deep, high-resolution optical imaging can put good limits on the host galaxy luminosity, and because the observed range is small (in blazars of known red-shift), this translates into a lower limit on red-shift (i.e., the blazar must be at high red-shift or we would have detected the host galaxy). Another approach is to make a red-shift limit from intergalactic Lyman-alpha absorption lines. For $z<1$, these occur in the ultraviolet, and locally, intergalactic hydrogen absorption features are not very numerous, so the limit is not stringent – but it is robust. That is, if one detects Lyman-alpha absorption features at, say, $z<0.2$, 0.6, 0.8 and 0.85 (to take a fictional example), then the red-shift of the BL Lac object must be greater than 0.85. This technique works out to $z<2.5$ but even with the sensitivity of HST/COS, we have to wait for very strong UV flares to make the observations in fewer than a dozen orbits ($F_{1400}>10^{-14}$ ergs/cm^2/s/Å; Danforth *et al.* 2010). Finally, at higher red-shifts, $z>2$, the Lyman-alpha line is shifted into the rest-frame optical. Thus we can be pretty certain that a blazar with a featureless spectrum cannot be at $z>2$ or we would have seen the distinctive signature of Lyman-alpha absorption lines from intergalactic absorption.

Probably the most important physical quantity we want to know about a jet is its kinetic energy. Without understanding the jet energy, it is not possible to have a definite picture of jet production, collimation, and interaction with the host galaxy and intergalactic medium. At the moment, the jet energy is uncertain by several orders of magnitude, not least because we do not know the jet composition, whether light (electrons and positrons) or heavy (electrons and protons). Furthermore, using the observed radiation to estimate the jet energy requires knowing the bulk Lorentz factor accurately. There is an unresolved discrepancy between estimates from SED fitting or superluminal motion ($\delta < 10$) and from TeV variability or analogies to gamma-ray burst jets ($\delta < 100$).

From the study of blazars we have understood the role jets play in some galaxies. If we can now fill in these important missing pieces – redshifts, composition, outflow speed, particle energies – we will be able to define jet physics and thus to understand how and when jets are produced. Further study of the blazar sequence, incorporating deeper samples with less restrictive selection biases, should define the distribution of jet powers. The upcoming decade promises large surveys that could generate new and very useful blazar samples but commensurate coverage in the radio is required. Real blazars require jets, and jets produce radio emission, so radio detection is a critical piece of the puzzle. (Occasional reports of 'radio-quiet' blazars puzzle me. I think these must be galaxies with strong continuum sources polarized in some other way, but I cannot see how the defining blazar characteristics, variability and polarization, are caused by jets unless the objects are detected in the radio.) New high-energy polarization observations (such as will be performed with the upcoming GEMS or Astro-H missions) could confirm the synchrotron nature of X-rays in some sources. More and better multiwavelength monitoring will allow us to track new flares in additional blazars. Neutrino detections (or upper limits) reflecting the presence (or absence) of energetic protons in blazar jets would be definitive (or not

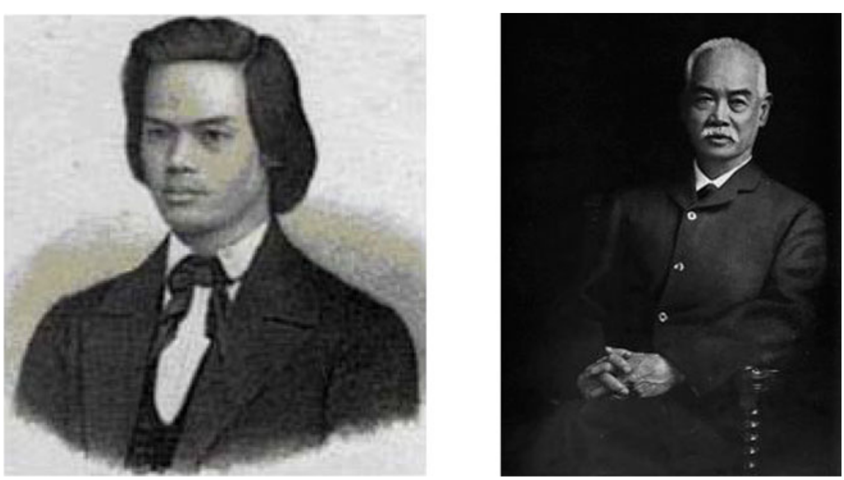

Figure 3. Portraits of Yung Wing, the first Chinese student to get a degree from a US college. Several fellowships and lectureships have been named in honor of his graduation from Yale College in 1854.

quite). There are important questions still to answer, and useful directions to look for. I look forward to hearing the answers at the next blazar conference.

It was a particular pleasure for me to give this conference summary in Guangzhou. Our hosts offered us the warmest hospitality and made this conference very enjoyable and educational. I was particularly pleased to see the large numbers of young scientists working on these interesting problems. But I am also grateful for a reason less obvious to most of you, namely, the historical ties my university has with China. The first Chinese student to get a degree from a U.S. university was Yung Wing (Fig. 3); this was at Yale in 1854. Yung Wing then worked to enable a succession of Chinese students to study in the U.S. and he and we value(d) very much the ties between our two countries. Yale University now has several programmes named in Yung Wing's honor, including lectureships and fellowships. Yale also has close ties with Beijing University, where we established a collaborative programme for undergraduates. My university greatly values collaborations with our Chinese colleagues, and this conference has reinforced the pleasure of such international ties. On behalf of the visitors to the MVB conference, I would like to offer a collective thanks to our wonderful hosts for all their efforts.

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