
Blazars – Theoretical Aspects

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Abstract

I give a brief overview of our theoretical understanding of blazars. I highlight currently unresolved problems and show how multiwavelength (X-ray and TeV) observation of TeV emitting blazars like Mkn 501 may be particularly useful in constraining emission models. I also note that intergalactic absorption of TeV gamma-rays is a process that can no longer be ignored by blazars modelers and that the standard SSC (synchrotron self-Compton) SSC models for TeV blazars cannot be made to work for certain published models of the extragalactic infrared/optical background radiation.

1. Introduction and Observational Overview

Although the notion of a “blazar” has been with us for almost thirty years (see the review of Angel & Stockman 1980 for a historical perspective), we still continue to discover new and surprising aspects of these objects – and it is very likely that there may be yet more surprises in store for us. The name blazar (a synthesis of the words “BL Lac” and “quasar”) was coined by Ed Spiegel to describe the ensemble of extragalactic objects residing in the nuclei of galaxies that exhibited strongly polarized and violently variable optical emission, contained a compact, flat spectrum radio source that often showed low frequency variability, and had an optical continuum that was smooth and featureless except for the occasional presence of strong quasar emission lines. It did not take long to posit that the radio and optical properties of these objects could be explained as synchrotron emission coming from the relativistic jet of an AGN (Active Galactic Nucleus) that was pointed towards us (Blandford & Königl 1979). In the simplest models, the relativistic motion of the fluid in these jets, spectacularly confirmed in many cases by the observation of superluminal motion of radio features, meant that the emission from such a jet should be beamed within a cone of angle $\sim 1/\Gamma_{jet}$, where Γ_{jet} is the jet’s bulk Lorentz factor. An observer looking down the jet and into the beaming cone would therefore emission that was strongly Doppler

boosted in intensity and had its variability timescale shortened by a factor of $\sim (1 - \beta_{jet})$, where $\beta_{jet} = 1/\sqrt{1 - \Gamma_{jet}^2}$. Because of special relativity, if emission features in the jet propagated with the jet velocity, $\beta_{jet}c$, he would also seem them propagating across the sky with an apparently superluminal velocity $\sim \Gamma_{jet}$. On the other hand, an observer looking outside the beam would instead see nothing, providing a natural explanation for the common phenomenon of one-sided radio jets on small scales (e.g., see Fig. 1). The strong Doppler boosting also naturally explained why the blazar continuum was so smooth. When looking down the jet beam, the synchrotron radiation from the jet appears to be so intense that it swamps out all but the very strongest emission features from the central region of the AGN. In fact, in the so-called BL Lac objects, the non-jet emission from the AGN appears to be unusually weak, in which case one sees only the featureless, approximately power law synchrotron continuum.

In subsequent years, the relativistic jet model was refined and its predictions were extensively tested and verified. In the resulting “Grand Unified Model” of AGN with jets (see Ulrich, Maraschi, & Urry 1997 for a detailed review), the main property that determines the observed properties of such AGN is orientation of their jet with respect to our line of sight. This jet viewing angle is presumably an intrinsically random parameter. Given a model for the Doppler boosting/beaming of the jet’s emission, one can then predict, for example, the distribution of values for the so-called R (core dominance) parameter, the ratio of the radio power coming from the AGN nucleus (i.e., the innermost regions of the jet where it is presumably moving most rapidly and its emission is most beamed) to the power observed from the “lobes” of seen at the end of a jet (the region where the jet decelerates to non-relativistic speeds and its emission should therefore be isotropic). One could also immediately predict the number of blazar objects which would be strongly Doppler-boosted compared to the number of objects in the larger parent population of objects, thought to be the so-called radio galaxies (e.g., see Fig. 1), whose jets would be viewed at larger angles. In the simplest unification model, where all jets have the same characteristic bulk Lorentz factor Γ_{jet} , the this ratio of non-boosted to boosted objects is $\sim \Gamma_{jet}^2$. Amazingly, this simple model predicts reasonably well the correct numbers of blazars and non-blazars as well as the R parameter distribution – provided one postulates *two* underlying parent populations of AGN with jets: low luminosity, “FR-I,” radio galaxies with weak, slow jets that move with a bulk Lorentz factor ~ 4 , and high luminosity, “FR-II,” radio galaxies with powerful jets that can propagate without disruption for up to a megaparsec in distance and move with a bulk Lorentz factor ~ 10 (see Fig. 1). Although the distinction between FR-I and FR-II radio galaxies is imprecise (there are objects that exhibit both FR-I and

FR-II traits and there are objects with intermediate luminosities), the distinction nevertheless seems to be real and is currently not understood. Still, at the time of the launch of the Compton Gamma-Ray Observatory (CGRO) in 1990, people were not overly bothered by this problem since everything else appeared to hang together so well. For example, the values of Γ_{jet} required by unification agreed quite well with those determined by observations of superluminal motion in FR-I and FR-II jets.

Fortunately or unfortunately, the launch of CGRO changed everything. The EGRET instrument on CGRO showed that blazars also happened to be extremely powerful MeV-GeV gamma-ray emitters. (See Reshmi Mukherjee’s contribution in this proceeding for a good overview of the gamma-ray observations.) In fact, if one assumes that the bulk Lorentz factor of the gamma-ray emitting regions is the same as that of the synchrotron radio emission regions (something which we will see is not entirely obvious), then the previously unknown gamma-ray luminosity of these objects can dominate the *observed* bolometric luminosity by a factor of 10-100! Although the ingredients required to predict this emission were in hand before the launch of CGRO (e.g., the previously observed synchrotron radiation implied the presence of very energetic particles with bulk relativistic motion), the lack of a clear prediction of this level of emission (see, however, Königl 1980 and Melia & Königl 1989) is considered by some to be a humbling theoretical embarrassment. In the last few years, the situation has been further complicated by the discovery of strong and rapidly variable TeV emission (extending in the case of the Mkn 501 to ~ 20 TeV!) in nearby blazars associated with the FR-I class of jet AGN. Also, the Chandra observatory has shown that radio jets shown extended radio emission, sometimes down the entire length of the jet. There is still debate on whether the X-ray emission represents synchrotron radiation by very high energy particles or Compton upscattering of ambient microwave background radiation by low energy electrons with bulk relativistic motion (both are probably happening). In either case, jets are even more extreme objects than we previously thought. If the X-ray emission is synchrotron radiation, then we must be able to accelerate particles to very high energies *in situ* (the cooling times are too short) throughout the jet, or if it is Compton upscattering, the jet must have high bulk Lorentz out to the end (higher than we inferred from radio observations). Although it is still early, the gamma-ray and X-ray observations may be calling into question the simple unified model (e.g., see §4) and may require a complicated jet structure, in particular with a very fast-moving “spine” or core that was largely missed by radio observations and that is surrounded by slower moving material with a range of bulk Lorentz factors (e.g., see Celotti & Ghisellini 2001). In other words, we still have much to learn,

and just as with some pulsars that also turned out to emit most of the power at gamma-ray energies, we may only be starting to see the tip of the iceberg.

Despite the embarrassments, theorists are agile creatures, and they quickly post-dicted several of the observed features of the EGRET gamma-ray emission. The main ingredients of this postdiction (which is still a work in progress) are the topic of this contribution. Because of space limitations and the good reviews that already exist on this topic I will concentrate here only on what I consider to be the major issues in our theoretical understanding of this gamma-ray emission. (For some of the more recent theoretical reviews on gamma-ray blazars see Sikora 2001, Sikora & Madejski 2001, Boettcher 2001, Celotti 2002 and the references contained therein. See also Blandford 2001 and Coppi 1997 for broader discussions on the problem of jets.) I will also focus mainly on the relatively recently discovered sub-class of blazars known to have strong TeV emission, because they are the main targets of interest for Cherenkov telescopes (the topic of this meeting), they appear to be more extreme than the GeV-emitting EGRET blazars in the sense that their characteristic particle energies are higher and their variability timescales are shorter, and in the short term, they may provide us with tighter model constraints than GeV blazars.

Before continuing, let me now briefly discuss the two key observational features of blazar spectra that need to be explained by theory. The first is the broad band spectrum of the blazar, summarized compactly in the νL_ν plot of Fig. 2. In a νL_ν plot, horizontal lines correspond to lines of constant luminosity per logarithmic interval of energy (e.g., constant power per decade of energy). From Fig. 2, we therefore see that the most luminous blazars are the ones whose bolometric luminosity is most strongly dominated by gamma-rays, and that this appears to be part of a systematic trend where the fraction of luminosity in gamma-rays varies with total bolometric luminosity. Moreover, the broad band spectra always show a double-peaked profile (with one peak occurring at optical to X-ray energies and the other at GeV-TeV energies) that is strongly reminiscent of what is seen in Galactic supernova remnants, and the positions of the two peaks appear correlated with each other and with the overall bolometric luminosity (lower powered blazars generically have higher peak energies). The correlation of the two peaks is important, and is not automatically predicted in some of the proposed (“hadronic”) emission models discussed below. I note that once one corrects for the intergalactic absorption of TeV gamma-rays by the diffuse background radiation, that the trends just noted may break down once one gets to the lowest power objects, the so-called BL Lac (FR-I galaxies with jets viewed head on). Just as their radio properties appear relatively distinct, it may be a mistake to merge these objects with the higher powered EGRET-detected objects

(which are predominantly FR-II galaxies). Also, one must be a little more careful in the interpretation of this diagram in that the second key observational feature of blazars is their dramatic spectral variability (e.g., see Fig. 5) and the data plotted are not always strictly simultaneous. Particularly in the TeV blazars, the timescales for variability can be extremely short, with flares of more than a factor of two occasionally occurring on timescales as short as 15 minutes (e.g., Gaidos et al. 1996).

The correlation in the (time-averaged) intensity of the two emission peaks shown in Fig. 2 appears to also be true (with a few possibly important exceptions in recent TeV blazar data) on the shortest timescales to. This argues strongly in favor of having the emission at the two peaks come from the same region. In this case, one can show that if the emission from this region is isotropic and homogeneous (the simplest emission model) and there are no relativistic time compression at work, then the emission region is so small that the density of photons in the low energy peak is so high that the gamma-rays of the MeV-GeV energy peak could not have escaped the emission region without pair producing on the low energy photons. Independent of the emission mechanism(s), this “compactness” argument (which also applies to gamma-ray bursts) implies that something is wrong with the assumptions just listed. Given that the EGRET gamma-ray detections appear to be definitely associated with blazars, the simplest explanation for this apparent contradiction is that the gamma-rays are in fact not isotropically emitted and are produced in a region that is propagating relativistically, i.e., they are produced in the same relativistic jet responsible for the previously known radio and optical blazar emission. Exactly where in the jet the gamma-ray emission occurs and how it relates to the well-studied radio emission, for example, is, as I have noted, an open question. (The short variability timescales and correspondingly small implied emission region sizes would tend to suggest, however, that the gamma-ray emission is occurring in the innermost regions of the jet where the jet is smallest in size and the jet is moving most rapidly.) One further caveat concerning spectral variability and jet structure is that in the radio through X-ray energies, it is well-established that the observed superposition of different emission components on different spatial scales (and different variability timescales). Attempting to simultaneously fit the broadband spectra of Fig. 2 at *all* energies with a one-zone emission model, as some have been tempted to do, is therefore almost certainly wrong. (For example, if the gamma-ray emitting region is indeed small, then its synchrotron emission may well be self-absorbed even up to optical frequencies.)

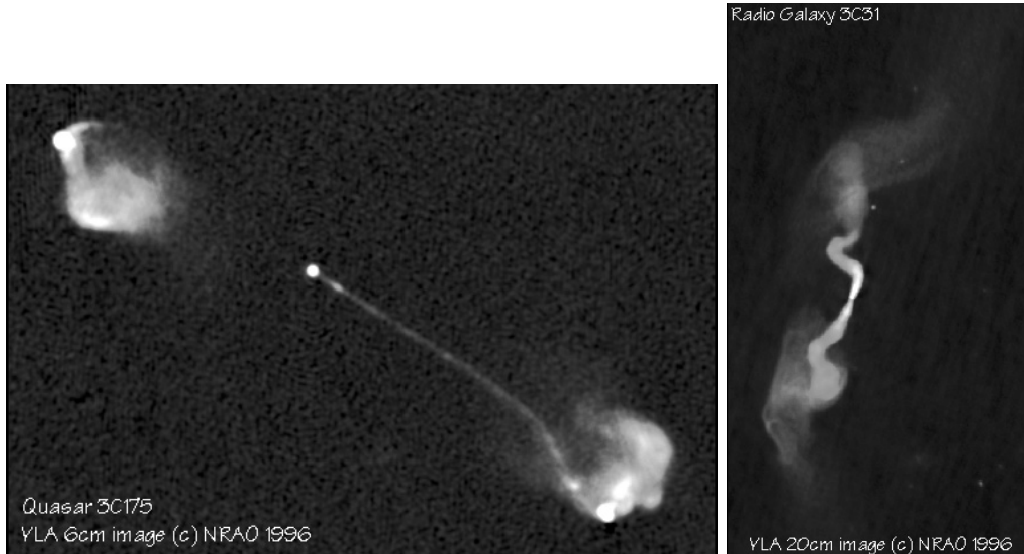


Fig. 1. The two typical jet morphologies seen for AGN radio jets. The *left panel* shows an “FR-II” jet where the bulk of the radio power is emitted at the outer radio lobes (“hotspots”), and the jet retains its well-collimated (pencil beam) appearance until the lobe. The *right panel* shows an “FR-I” jet where the bulk of the radio power is emitted near the nucleus, and the jet seems to quickly disrupt, with no well-defined lobes at its ends. In both cases, the asymmetric brightness of the jets is thought to be due to the relativistic motion of the jet material and the subsequent beaming of its emission: the beaming causes the jet moving towards us to appear much brighter and makes the receding jet appear correspondingly dim, often to the point where it becomes undetectable (e.g., as in the left panel).

2. Understanding the Data: General Theoretical Considerations and Complications

2.1. Global Energetics

An important quantity, that needs to be determined better in the case of TeV blazars, is the total amount of power lost by the jet due to its radiation. In the case of the FR-II EGRET GeV blazars, at least, the observed gamma-ray luminosity is very large, but after invoking likely beaming corrections, the power is smaller than or comparable to the accretion power inferred from observation of the broad AGN emission lines. It is also less than or comparable to the mean kinetic power inferred to be flowing into the radio lobes (e.g., see Celotti & Ghisellini 2002). This means the jet cannot be suffering catastrophic radiative losses, and rules out, for example, some of the early models that invoked radiative deceleration of the jet by bulk Comptonization to explain the fact that all radio jets seemed

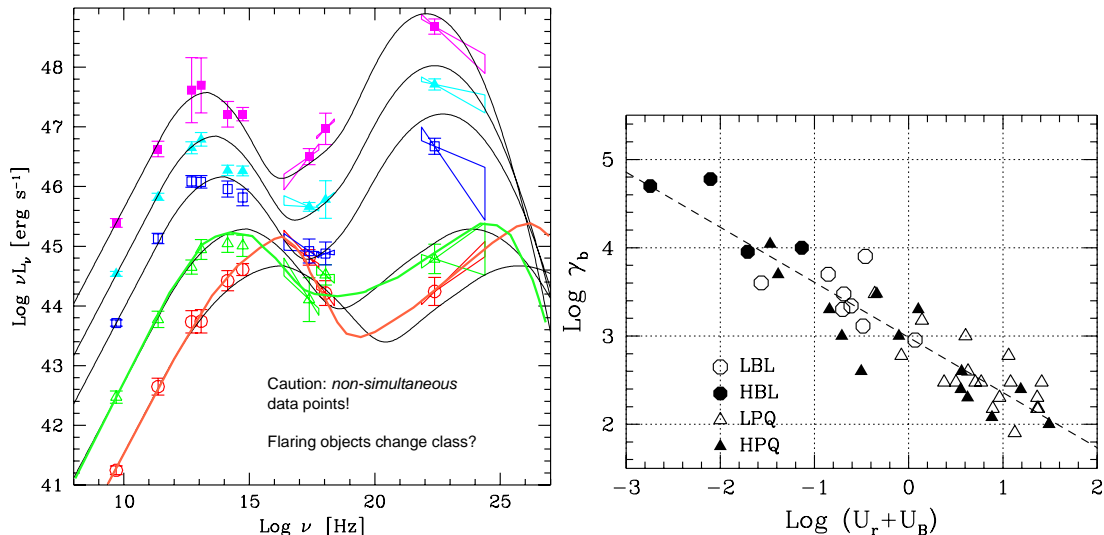


Fig. 2. The *left* panel shows a compilation of broad-band blazar spectra taken from Donato et al. (2001), based on the original work of Fossati et al. (1998) where blazar spectra are classified according to their bolometric luminosity and the spectra of objects in the same luminosity class are then averaged (and plotted as the datapoints in the figure). The *solid* lines are synchrotron-Compton models whose parameters have been scaled with bolometric luminosity (see Donato et al. 2001). The *heavy solid lines* at the bottom of the panel have been added by the author to indicate what the flaring spectra of low-powered (BL Lac) objects look like after correction for intergalactic absorption of gamma-rays. The *right* panel shows the results of Ghisellini (1997) where spectra of blazars from different classes are fit using a synchrotron-Compton model. The model parameter γ_b is the electron Lorentz factor where the slope for the energy distribution of the accelerated electrons (assumed to be a broken power law) changes. U_r and U_B are respectively the inferred energy densities for the radiation and magnetic fields in the emission region.

to have terminal Lorentz factors ~ 10 , (e.g., Melia & Königl 1989). The exact value of the jet’s radiative efficiency also is an important on the particle acceleration and radiation mechanisms. For example, in the so-called “internal shock” mechanism energy is extracted from the bulk motion of the jet when regions of the jet moving at different velocities collide with each other and shock. Since the velocity contrast between different elements of the jet are probably not that large (often a factor ~ 2 is invoked), not much energy can be extracted per event and the jet’s radiative efficiency tends to be low, which may or may not be consistent with the data. Similarly, if the emission involves hadronic processes (e.g., photo-production of pions), the interaction cross-sections for these processes are significantly smaller than ones for electromagnetic processes like Compton scatter-

ing. To produce the same amount of radiation, “hadronic” emission mechanism therefore typically require much higher particle densities than “leptonic” mechanism, i.e., they tend to have much lower radiative efficiencies (and sometimes imply prohibitively large jet energies).

2.2. Jet Origin: the Accretion Disk vs. Black Hole Spin

Two big mysteries that still confront the AGN community are why only $\sim 10\%$ of AGN show radio jets and what is the ultimate power source of the AGN jets (e.g., see Blandford 1990 for an overview of the problem). One often-discussed possibility is that the difference between “radio quiet” AGN (with no jets) and “radio loud” ones (with jets) reflects different accretion histories that impart different amounts of angular momentum to the AGNs’ black holes. The black holes with large spin (intrinsic angular momentum) could cause the jets to be produced (as opposed to diffuse winds) via their impact of their spin on the space time geometry near the black hole, e.g., in the Kerr metric around a black hole, the dragging of frames effectively imparts a preferred rotation on gas near the black hole. Moreover, the spin of a black hole represents free energy that could be extracted from the hole, e.g., by the Blandford-Znajek mechanism, and could be used to directly power the hole. Another school of thought, however, holds that it is impossible to extract energy rapidly enough from the black hole spin to explain the high luminosity EGRET blazars (e.g., see Maraschi and Tavecchio 2002). Rather the jet is powered directly by accretion onto the black hole, and the jet origin depends, for example, on the details of the magnetic field configuration near the central black hole and the initial mass loading of the magnetic field lines. A middle-of-the-road hypothesis might be that both mechanisms (spin energy extraction vs. accretion disk energy extraction) are operational, and that in FR-II galaxies, the accretion disk mechanism dominates, while in the FR-I galaxies (which have highly underluminous accretion disks) the spin extraction mechanism may dominate. The two mechanisms might be distinguishable by the nature of the particles that carry most of the jet kinetic energy (heavy protons from an accretion disk vs. light electrons and positrons that are postulated to be created in the spin extraction mechanism).

2.3. The Region of Jet Acceleration and Energy Dissipation

The intense radiation fields at the centers of FR-II objects present a significant problem for the formation and acceleration of relativistic jets in that the Compton drag on electrons and positrons is very strong there. If large scale FR-II jets are also made of electron-positron pairs yet the jets do not lose most of their

energy to radiation, this means these jets could not be both relativistic *and* pair dominated near the black hole. The only way to avoid the radiation problem is to have the jet energy initially carried in some other form that does not interact as strongly with ambient, e.g., relativistic protons or simply Poynting (magnetic field) flux, that is then gradually converted to relativistically moving pairs. (How this might occur is an open question.) As pointed out by Sikora (2001), there may also be a problem even if the jet energy is initially carried by relativistic protons. The protons are likely to drag electrons along with them, creating moderately relativistic electrons. The radiation drag of these electrons may or may not be important energetically, but if the relativistic protons and their electrons exist sufficiently close to the jet, the radiation upscattered by the electrons would be detected as a sharp spectral feature at soft X-ray energies (the so-called “Sikora bump”). Such features have not been seen, indicating that jets simply may not be relativistic at the base and are only slowly collimated and accelerated. (Indeed, high resolution VLBI observations of the base of the FR-I jet in M87 that the jet has something like a 60 degree opening angle there.)

There is one further problem caused by the strong photon fields near the base of the jet. Accretion disks are thought to be copious emitters of the UV and X-ray photons, and the density of such photons is sufficiently high near the base of the jet that any gamma-ray photons produced there would be absorbed, i.e., the radiation field near the black hole defines a “gamma-sphere” (e.g., see Blandford & Levinson 1995) within which gamma-rays cannot escape. Jets cannot produce many gamma-rays in this region or the emergent observed spectrum would be too soft (all the gamma-ray power would be reprocessed to X-ray energies resulting in a spectrum that had too much X-ray compared to gamma-ray power). The radiative dissipation of jet kinetic energy in the form of gamma-rays therefore cannot begin until quite far from the base of the jet. At the same time, the favored mechanisms for producing gamma-rays (photo-pion production and Compton upscattering) are effective only if the density of ambient photons is sufficiently high. Since the relevant interaction cross-sections are all comparable, this means that the gamma-ray dissipation probably cannot occur too far from the edge of the gamma-ray sphere. Why there such a preferred location for dissipation exists is again not understood.

FR-I objects appear to have intrinsically underluminous accretion disks, either because their mass accretion of their central black holes are low or the disks are in a radiatively inefficient (e.g., ADAF-like) state, or both. The problems caused by intense ambient radiations therefore probably do not exist for many of these objects.

2.4. Particle Acceleration

The observation of GeV and TeV photons is very strong evidence for the presence of very energetic particles. Exactly how these energetic particles are produced is an open question. In the more standard “bottom-up” scenarios like particle acceleration in shocks, particles are accelerated from low to high energy until, for example, the particle radiation losses balance the acceleration force. (Such a scenario could explain the anti-correlation of the synchrotron and gamma-ray peak energies with the bolometric luminosity of the blazar, e.g., see Fig. 2 and Ghisellini 1997.) On the other hand, the radiative losses may simply be too strong for direct particle acceleration, in particular electron acceleration. In this case, “top-down” scenarios have been invoked where particles are created at the required energies and then cool. A popular example of such a model is the proton-initiated cascade (e.g., see Mannheim 1993) where the jet power is initially in very relativistic protons, which are much easier to accelerate by virtue of the smaller radiation losses. These protons produce pions on ambient photons, and these pions in turn decay producing energetic photons and electrons which may then undergo one or more cycles of cascading. In sum, the controversy here is very similar to that we see in this meeting concerning supernova remnants. Do the gamma-rays represent Compton upscattering by primary electrons that are accelerated along with protons, or are they secondary particles, created as a result of pion production?

2.5. The Gamma-Ray Emission Mechanism

The controversy over particle acceleration carries over to the nature of the particles responsible for gamma-ray emission. In so-called “leptonic models,” primary energetic electrons are responsible for the gamma-rays (which would be produced by Compton scattering), and in the so-called hadronic models, the observed gamma-rays are some combination of direct synchrotron radiation by protons (for sufficiently high magnetic fields), secondary gamma-rays produced in π_0 decay, and photons Compton upscattered by secondary electrons. Right now I think Occam’s razor favors the leptonic models as there is currently no need to invoke hadronic processes to explain spectra, and perhaps more importantly, hadronic processes tend to be slow and inefficient and have a difficult time matching the very rapid variability timescales observed in blazars without resorting to extreme parameters. However, one should keep an open. Detailed time multi-wavelength variability observations combined with realistic simulations of emission from leptonic and hadronic models may be the key to unraveling the two alternatives. The discovery of strong neutron emission from blazars would be a smoking gun

for the importance of hadronic processes in these objects.

2.6. Target Photons from External vs. Internal Radiation Fields

As was quickly realized after the discovery of EGRET blazars, even a relatively weak ambient, isotropic radiation field can appear strongly boosted in the jet frame and can easily dominate the Compton losses of energetic electrons. That this is occurring definitely appears to be the case in the case of the EGRET blazars because it is impossible to explain the observed spectra using a standard synchrotron-self Compton (SSC) model where electrons Compton upscatter primarily their own synchrotron radiation. The detection of upscattered external radiation in blazars potentially provides a useful diagnostic for location of the jet dissipation region. However, as can be seen in Fig. 4, it also tremendously complicates the interpretation of observed spectra as they may be the sum of several Compton upscattered components.

3. The Special Case of TeV Blazars

As we have just seen, the presence of strong radiation fields external to the jet introduces considerable uncertainty for the models of the powerful GeV blazars typically seen EGRET. Observationally, there are further difficulties in constraining the theoretical models. These objects are extremely variable (EGRET saw flares as short as hours) and until the arrival of GLAST (and even then for weaker objects), it is difficult to measure the gamma-ray spectra of these objects on timescales comparable to or shorter than their variability timescales. In addition, in some models, the electrons responsible for the GeV gamma-rays emit their synchrotron radiation in the UV band, which is inaccessible because of intergalactic and interstellar absorption. To get the best model constraints, ideally we would therefore like to find objects with no strong ambient radiation fields and synchrotron/Compton peaks in the right energy bands to be monitored simultaneously and on the relevant variability timescales.

TeV blazars like Mkn 501 appear to be quite promising in this regard. The accretion disks and the broad line regions in objects like Mkn 501 appear to be unusually underluminous, and a simple SSC model may actually apply. Moreover, the large collecting area of ground-based Cherenkov detectors means one can obtain reasonable gamma-ray spectral information on the source variability timescale (as HEGRA did for Mkn 501). Finally, the part of synchrotron emission peak corresponding to the TeV peak occurs in the 10-100 keV X-ray range, which can also be monitored on similar timescales using an instrument with BeppoSax-like capabilities. I would therefore argue that simultaneous X-ray/TeV monitor-

ing of TeV blazars will be especially fruitful: the simultaneous monitoring of the synchrotron and Compton emission components provides two very constraining handles on the electron distribution responsible for both of them.

As an example of what one can learn, we (Krawczynski, Coppi, & Aharonian 2002) tried to fit a one zone, time-dependent model SSC model to the relatively good X-ray/TeV lightcurve one has for the April-May 1997 data for Mkn 501. This might at first seem a strange thing to do since the flaring episode lasted two months and a single emitting region (“blob”) moving relativistically would be at $\sim 2\Gamma_{jet}^2$ lightmonths from the nucleus in distance, and it would hard to be believe that source parameters would not changed have with propagation over such a large distance. Indeed, a one-zone SSC model cannot fit the entire data train unless all particle cooling and escape times (in the observer frame) are less than the typical flare timescale of ~ 12 hours, i.e., all flares involve different populations of energetic particles and are essentially independent. On the other hand, the hard X-ray flux showed a remarkably good correlation with the TeV flux (Fig. 6, right panel). This is hard to understand if the flares are completely independent since the X-ray to TeV ratio depends sensitively on source parameters like the source size and magnetic field. (It is worth exploring whether a realistic internal shock model for the flares can produce a sufficiently narrow correlation.) If one goes ahead and assumes that the different flare events do have the same physical parameters, e.g., because the flares always occur in a fixed physical jet region such as a recollimation shock (determined by external pressure gradients), then one *can* fit the entire data train very well, particularly if one invokes a non-variable soft X-ray component due to some other region of the jet. (In fact, one can even explain all the flares with simply a variable Doppler factor, e.g., due to wiggling of the jet.) It is very curious to note that Mkn 421 and Mkn 501, despite their very variable gamma-ray emission, do *not* appear to show any superluminally moving features, which could be consistent with a stationary emission region in the jet.

Given enough time and spectral resolution, which should be possible with next generation instruments, it should also possible to probe in detail the microphysics, ie., detect time lags between various bands due to slow particle cooling or acceleration, or the inevitable light crossing-time delay between Compton gamma-rays and synchrotron photons that must occur due to the finite time it takes to build up the target (synchrotron) photon distribution. Note that lag/lead based constraints such as these are *independent* of the amount of intergalactic gamma-ray absorption discussed in the next section. That section also presents an example of important auxiliary science that can be done *if* multi-wavelength monitoring campaigns show that the SSC model can describe the observations.

I conclude by noting that while I personally strongly favor “leptonic” (synchrotron-Compton) models, it is by no means clear yet that they actually are correct. Every TeV blazar flare observed in detail thus far has been different in detail from the others, e.g., the time structure of Mkn 421 flares to be quite different and complex compared to Mkn 501 flares, and a very recent campaign on 1ES 1959 has found a TeV flare with *no* apparent X-ray counterpart (Krawczynski, private comm.)... (At this conference, Dieter Horns also presented possible evidence for an occasionally poor X-ray/TeV correlation in Mkn 421.)

4. TeV Blazars and the Infrared/Optical Background: A Blazar Modeler’s Perspective

This topic has been already extensively discussed by Dwek (this proceedings; see also the review of Hauser & Dwek 2000, and also Aharonian 2001), but I will nonetheless touch on the topic briefly because I think blazar modelers have something to contribute to and to learn from the discussion on the absorption TeV gamma-rays by the low-energy diffuse extragalactic background radiation (DEBRA).

Perhaps the most important piece of information for modelers to take away from recent observational and theoretical attempts to model the DEBRA (e.g., see Fig 9.) is that the indicated background levels are much higher than were commonly discussed even 5 years ago. The gamma-ray absorption correction, even for objects as close as Mkn 501 (at redshift $z = 0.034$) therefore can no longer be ignored. Some might still argue that for a moderate background level and at energies in the few TeV range, the absorption is “only” a factor of \sim two, and so is not very important. In fact, the correction is significantly more important than that. The reason, for synchrotron-Compton models at least, is that the peak of the gamma-ray energies now shifts by a factor 2-3 to higher energies, and the inferred total TeV luminosity of the object increases by a comparable factor or more. To increase the TeV flux and shift the TeV peak energy by this amount is non-trivial when the Compton upscattering electrons are interacting with most of the ambient radiation in the Klein-Nishina limit. In this case, the energy of upscattered electrons goes as γ , the Lorentz factor of the scattering electron, and not as the usual factor of γ^2 . The ratio of the Compton to synchrotron peak energies therefore goes as $(\delta/B)^{1/2}$, where δ is the Doppler boost factor and B is the magnetic field in the region. A factor \sim 3 increase in the TeV peak energy therefore implies a factor \sim 10 increase in δ/B , the jet is even more relativistic (with Doppler factors $\delta \sim 30+$) or has a magnetic field strength even more out of equipartition than implied by the analysis, for example, of Kino & Takahara

(2001). In SSC models, the increased amount of TeV flux also tends to push the magnetic field strength to low values since the more the Klein-Nishina correction is important, the more inefficient is the Compton upscattering (e.g., see the right panel of Fig. 8).

Now the equipartition value of the magnetic field in an SSC model is the value that minimizes the total energy off the emitting region contained in the form of particles and magnetic field. Moving the field out of equipartition therefore significantly increases the total kinetic luminosity inferred for the emitting region of the jet (e.g., see the fits in Krawczynski, Coppi, and Aharonian 2002) to the point where it becomes uncomfortably large, $\sim 10^{43}$ erg/sec in just relativistic electrons and positrons. If one were to require every electron to be associated with a proton, then the required kinetic luminosity would jump to 10^{46} erg/sec, implying that FR-I jets are incredibly radiatively inefficient and essentially just as powerful as FR-II jets. This is not impossible (especially given that central black holes in FR-I galaxies may be as massive as those in FR-II galaxies), but it would certainly imply a major revision in our understanding FR-I vs. FR-II galaxies. I note that proton-synchrotron models for TeV gamma-ray emission (Aharonian 2000, Mücke and Protheroe 2000) require comparably jet energetics. Moreover, such large amounts of jet energy may simply be ruled out since they presumably could produce an observably large perturbation on their surroundings. (FR-I galaxies have no strong radio lobes at the ends of their jets, so where is the jet’s “beam dump” in this case?) Alternatively, the large energetics when the proton and electron numbers are comparable could be used as an argument to argue that the jets must be dominated (in number not necessarily energy) by electrons and positrons, which would also be an interesting piece of information. The high minimum Doppler factors ($\sim 20 - 30+$) that seem to come out when one tries detailed SSC model fits including moderate DEBRA absorption (e.g., see Tables I&II; Coppi, Krawczynski, & Aharonian, in preparation) also wreaks havoc with the unified model since TeV blazars are in FR-I/BL Lac objects that supposedly have systematically lower jet Lorentz ($\Gamma_{jet} \sim 4$.) In other words, especially when one corrects for DEBRA absorption, something appears to be wrong with our current understanding, at least of TeV blazars. As one further example, in Fig. 11, we see that it is basically impossible to fit the (non-simultaneous) BeppoSax X-ray spectrum and the HEGRA TeV using an SSC model with no external photons. This conclusion is not true if one ignores DEBRA absorption.

Finally, those interested in using TeV blazar spectra to actually measure or constrain the DEBRA level need to pay attention to theoretical modeling because it is impossible to derive any meaningful constraints without having some idea of what the intrinsic spectrum looks like. For example, if a standard SSC model

explains the Mkn 501 spectrum then the sharp upturn seen at $\sim 10 - 20$ TeV seen in several of the absorption-corrected spectrum in Fig. 9 (right panel) is highly unlikely and this in turn places strong constraints on the DEBRA at 60μ . However, if something more extreme is happening in the jet, e.g., the jet contains a beam of very energetic particles that Compton upscatter in the strong Klein-Nishina limit, then such an upturn is not impossible (although the jet energetics become even more embarrassing in this case). Conversely, if one simply assumes that the TeV spectrum of all blazars is a strict power law one will infer strong absorption, when in fact there could be no absorption at all. (In Table II, the model fits with no absorption are either acceptable or only ruled out at the 2-3 σ level.) This is because a blazar SSC spectrum is likely intrinsically curved.

A further complication is that the curvature of these spectra is observationally known to vary with time. Ideally, one would like to be able to somehow theoretically predict this curvature. Fig. 10 shows that this may be possible *if* an SSC or synchrotron-Compton model applies. This is because the X-ray coverage of current and planned instruments (like Astro E-2) appears sufficient to cover the synchrotron emission of the electrons responsible for the bulk of the observed TeV spectrum. One then waits for a dramatic flare like that which occurred in Mkn 501 on April 16, 1997. That flare was so strong and so rapid that it is unlikely that it was caused by the superposition of several randomly flaring regions, i.e., we are probably seeing a single emission region. In this case, a single zone SSC model may well be appropriate and one can invert the observed synchrotron distribution to determine the shape of the underlying electron distribution (Fig.5). Given this constraint and specific values of the Doppler beaming factor, the source radius, and the source magnetic field, one can make fairly robust predictions for the intrinsic gamma-ray spectrum during the flare. One can then scan over all the source parameters and, assuming a specific DEBRA absorption, determine the best possible SSC fit to the observed gamma-ray spectrum. In Fig. 10, 11 and Table I+II (from Coppi, Krawczynski, & Aharonian, in preparation), we have attempted this exercise using simultaneous (BeppoSax-CAT) data and time-averaged (RXTE-HEGRA) data with very conservative systematic errors. As can be seen, no good fits are possible for the higher DEBRA levels, which if correct, has interesting implications for DEBRA/galaxy formation models. Our ability to carry out such studies will improve tremendously with the arrival of the next generation Cherenkov instruments. In a 5 hour observation time (which was shorter than the typical variability time seen during the April 1997 Mkn 501 flare), an instrument like HESS (e.g., see Fig. 11, right panel for a simulated HESS spectrum of 1ES 1426-42) can get sufficient statistics over a broad enough energy range to span both the strongly absorbed and weakly absorbed portions

Table 1. Joint RXTE-HEGRA Fits for Various DEBRA Models

Assumed DEBRA	χ^2/dof	Chance Probability	$\delta_R^{\text{min}}/\delta_B^{\text{min}}$	$B_{\delta_{\text{min}}}$	$R_{\delta_{\text{min}}}^{15}$
High, no shift	76/20	1.7×10^{-8}	25/86	0.0124	1.57
High, shift	47/20	5.2×10^{-4}	21/48	0.015	3.56
Kennicutt, no shift	58/20	1.4×10^{-5}	37/220	0.0089	0.54
Kennicutt, shift	30/20	0.069	26/78	0.0125	2.3
Salpeter, no shift	33/20	0.035	28/78	0.0125	2.8
Salpeter, shift	21/20	0.41	24/47	0.015	5.9
TT02, no shift	12/20	0.91	19/22	0.019	17
TT02, shift	18/20	0.60	16/13	0.028	20
No Background	39/20	6.8×10^{-3}	9.0/2.3	0.16	12

Table 2. Joint BeppoSAX-CAT (April 16, 1997) Fits for Various DEBRA Models

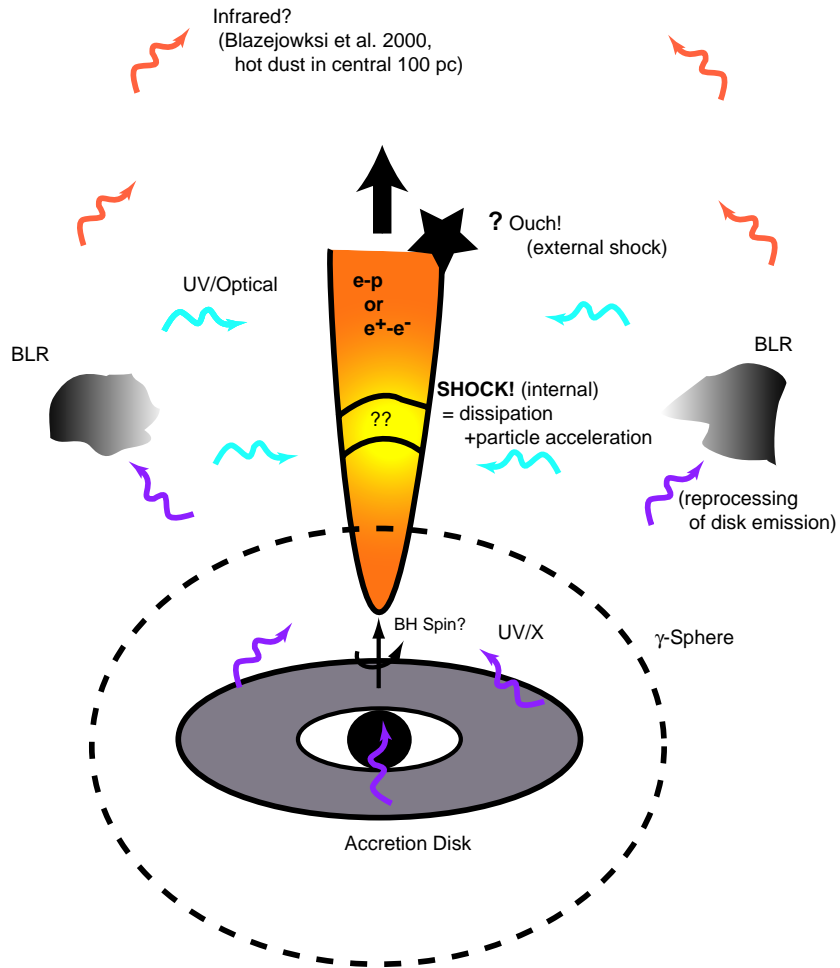
Assumed DEBRA	χ^2/dof	Chance Probability	$\delta_R^{\text{min}}/\delta_B^{\text{min}}$	$B_{\delta_{\text{min}}}$	$R_{\delta_{\text{min}}}^{15}$
High, no shift	43/5	3.3×10^{-8}	12/7.7	0.043	16
High, shift	53/5	4.4×10^{-10}	44/690	0.0062	0.059
Kennicutt, no shift	11/5	0.044	24/78	0.012	1.5
Kennicutt, shift	14/5	0.014	17/27	0.018	6.8
Salpeter, no shift	3.4/5	0.64	13/10	0.032	17
Salpeter, shift	4.3/5	0.51	5.8/11	0.056	14
TT02, no shift	3.7/5	0.59	12/7.7	0.043	16
TT02, shift	3.7/5	0.59	10/4.6	0.073	13
No Background	2.8/5	0.73	8.5/2.3	0.15	11

of the spectrum. If one can combine this with a simultaneous X-ray spectrum of the quality of the Mkn 501 spectrum, one obtain quite tight constraints on the DEBRA.

5. References

1. Aharonian, F.A., 2001, astro-ph/0112314
2. Angel, J.R.P. & Stockman, H.S., 1980, Ann. Revs. (ARAA), 18, 321
3. Blandford, R.D. & Königl, A., 1979, 232, 34
4. Blandford, R.D., 1990, Saas Fe Lecture, 20, 132
5. Blandford, R.D. & Levinson, A., 1995, 441, 71
6. Blandford, R.D., 2001, ASP. Conf. Proc, 224, 499
7. Blazejowski, M., Sikora, M, Moderski, R., & Madejski, G., 2000
8. Boettcher, M., 2001, astro-ph/0105554

9. Celotti, A., *Lecture Notes in Physics*, 589, 88
10. Coppi, 1997, *astro-ph/9903162*
11. Coppi, P.S. & Aharonian, F.A., 1999, *A&A*, 11, 35
12. Costamante L., Ghisellini G., Giommi P., et al., 2001, *A&A*, 371, 512
13. Donato D., Ghisellini G., Tagliaferri G., Fossati G., 2001, *A&A*, 375, 739
14. Fossati G., Maraschi L., Celotti A., Comastri A., Ghisellini G., 1998, *MNRAS*, 299, 433
15. Gaidos, J.A., et al., 1996. *Nature*, 383, 319
16. Ghisellini, G, 1997, *astro-ph/9706216*
17. Ghisellini, G., & Celotti, A., *A&A* L
18. Inoue, S. & Takahara, F.,
19. Kino, M., Takahara, F., Kusunose, M., 2002, *ApJ*, 97
20. Königl, A., *ApJ*, 1981, *ApJ*, 243, 700
21. Krawczynski H., Coppi P. S., Aharonian F., 2002, *MNRAS*, 336, 721
22. Mannheim, K., 1993, *A&A*, 269, 67
23. Maraschi, L., & Tavecchio, F., 2002, *ApJ*, in press. (*astro-ph/0205252*)
24. Melia, F. & Königl, A., 1989, 340, 162
25. Pian E., Vacanti G., Tagliaferri G., et al., 1998, *ApJL*, 492, 17
26. Primack J.R. et al., 1999, *Astropart. Physics*, 11, 93
27. Sikora, M., 2001, *astro-ph/0101381*
28. Sikora, M., & Madejski, G., 2001, *AIP Conf. Proc.*, 558, 275 (*astro-ph/0101382*)
29. Totani, T. & Takeuchi, T., *ApJ*, 570, 470.
30. Ulrich, M.H., Mararschi, L., & Urry, C.M, 1997, *Ann. Revs. (ARAA)*, 35, 445



The central engine of a generic gamma-ray blazar is a MESSY place!

Fig. 3. A summary of the various ingredients considered in current jet models for blazar emission.

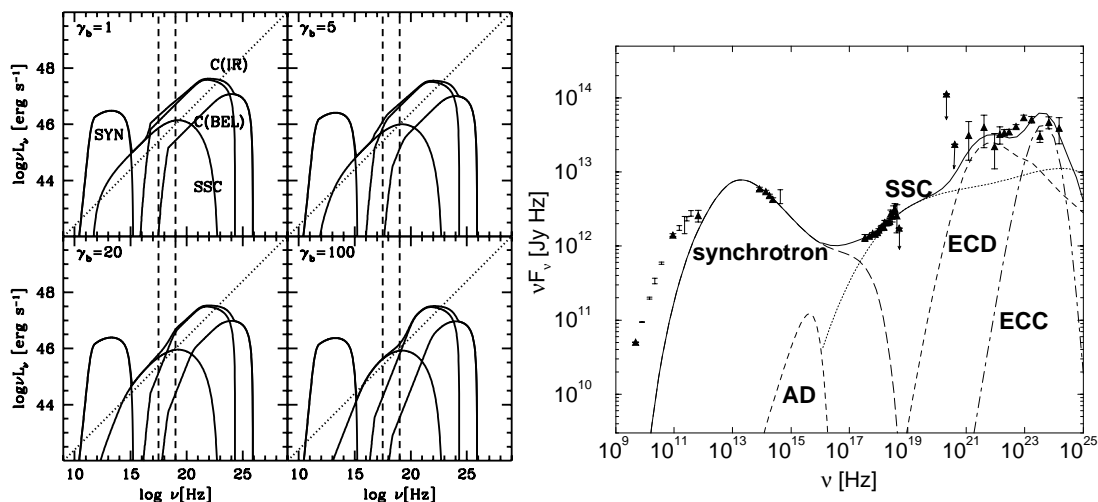


Fig. 4. The importance of external radiation fields in determining the blazar emission spectrum. The *left* panel is taken from Blazejowski et al. (2000), which points out the possible importance of ambient infrared radiation, e.g., from molecular gas often inferred to be near the central region of (powerful) AGN. The labeled curves respectively show the contributions to the total spectrum from electron synchrotron emission (“SYN”), the Compton upscattering by the synchrotron-emitting electrons of their own synchrotron emission (“SSC”), the Compton upscattering by the same electrons of ambient optical and UV radiation from the blazar’s broad emission line region (“C(BEL)”), and their Compton upscattering of ambient infrared radiation (“C(IR)”). The *right* panel is taken from Boettcher (2001) shows an alternative fit to the broad-band spectrum of 3C279 using a synchrotron emission component (“synchrotron”), a Compton-upscattered synchrotron component (“SSC”), direct UV emission from the accretion disk (“AD”), Compton-upscattering of these accretion disk photons (“ECD”), and Compton-upscattering of ambient broad emission line optical/UV photons (“ECC”).

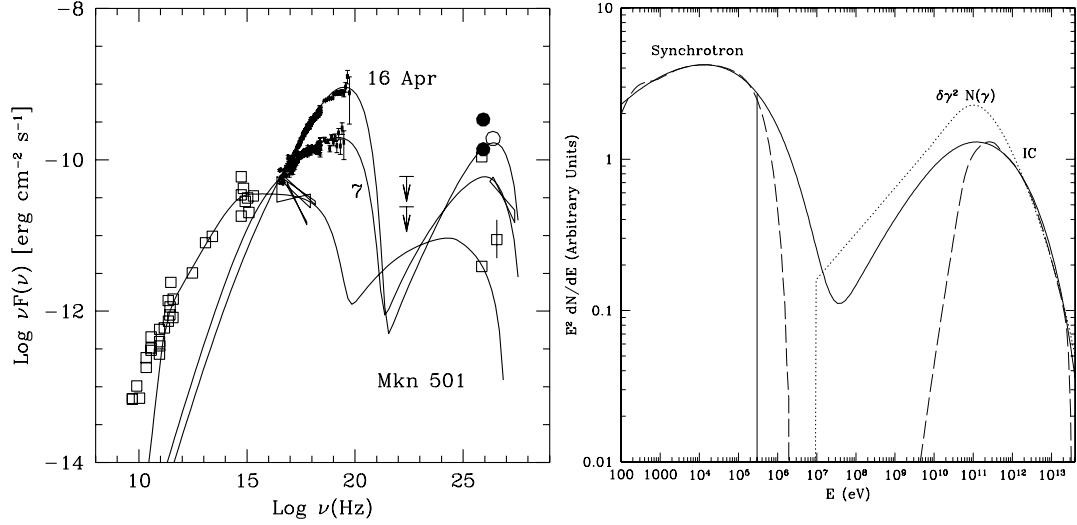


Fig. 5. The *left* panel from Pian et al. (1998) shows broad-band X-ray and gamma-ray data from the dramatic flare of Mkn 501 during April-May 1997 (see also Fig. 6). The curves labeled “7” and “16” show approximately simultaneous flare data for the nights of April 7 and 16. Note the dramatic shift of the peak energy of the X-ray emission (presumably synchrotron radiation) compared to its typical position during the “low” state of Mkn 501. (Non-simultaneous spectral data from the non-flare periods is shown by the *open squares*.) The curves show synchrotron-Compton model fits computed by the authors. The *right* panel from Coppi & Aharonian (1999) shows a generic one zone, synchrotron-self Compton (SSC) model of the type which appears to be able to fit the Mkn 501 data (see Fig. 7). The *long-dashed* lines show the synchrotron and inverse Compton (IC) emission from the electron distribution obtained by inverting the 0.5-300 keV X-ray spectrum given by the *solid* (SSC model) curve. The *dotted* curve shows the underlying electron energy distribution assumed in the SSC model. Klein-Nishina effects are important in computing the gamma-ray spectrum of this model.

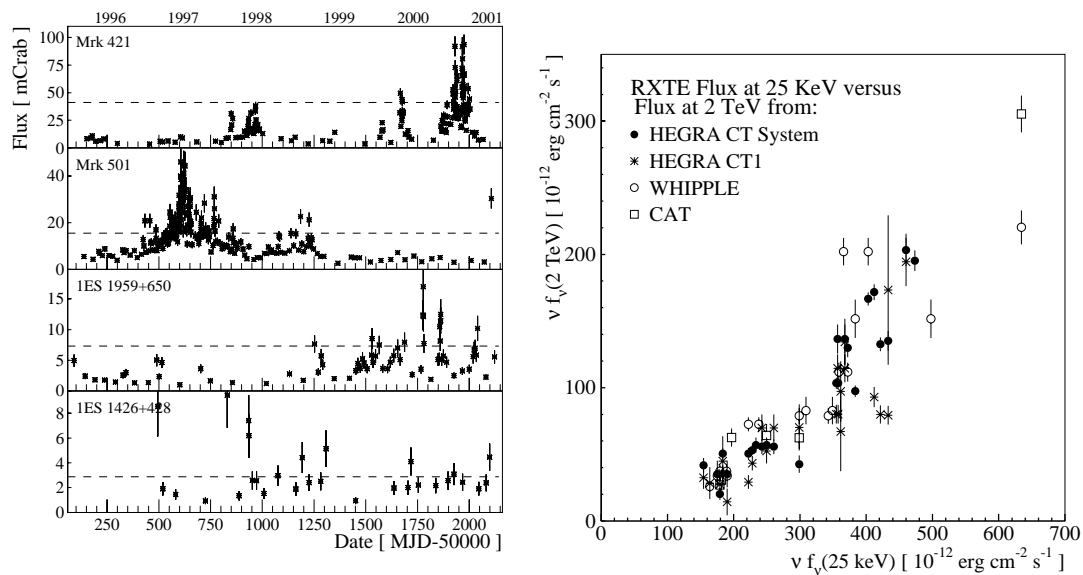


Fig. 6. The *left* panel shows a compilation by H. Krawczynski of RXTE ASM (2-10) keV lightcurves for the confirmed TeV blazars. The *right panel* from Krawczynski et al. (2002) shows the 25 keV X-ray flux of Mkn 501 obtained from RXTE plotted against the quasi-simultaneous gamma-ray flux at 2 TeV obtained by various ground-based Cherenkov telescopes. The data cover the time period March-June 1997 during which Mkn 501 showed several strong flares.

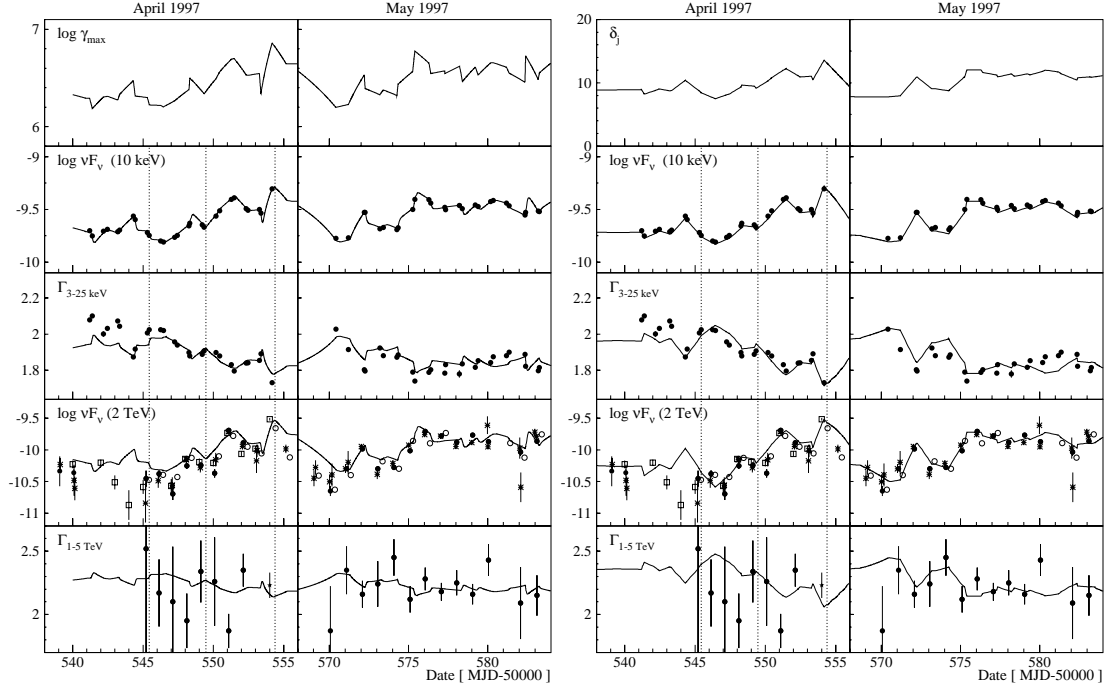


Fig. 7. Detailed time-dependent SSC model fits for the April 1997 Mkn 501 flare taken from Krawczynski et al. (2002). The *left* panel shows a fit where the luminosity (l_e) and maximum energy (γ_{max}) of the accelerated electrons are varied together ($\gamma_{max} \propto l_e^2$) to match the observed RXTE flux at 10 keV (second panel from top). The remaining model parameters are then searched to find the best fits to the data in the lower panels (respectively from top to bottom, the spectral index between 3-25 keV, the flux at 2 TeV, and the spectral index from 1-5 TeV). The *right* panel shows an equally good, if not better, fit to the same data using an alternative model where the low energy X-ray emission is explained by a steady, low-intensity component (presumably from the outer regions of the blazar jet) and the *only* SSC model parameter which varies is the Doppler boost factor (δ_j) of the emission region (e.g., due to changes in the spatial orientation of the shock region responsible for accelerating the electrons).

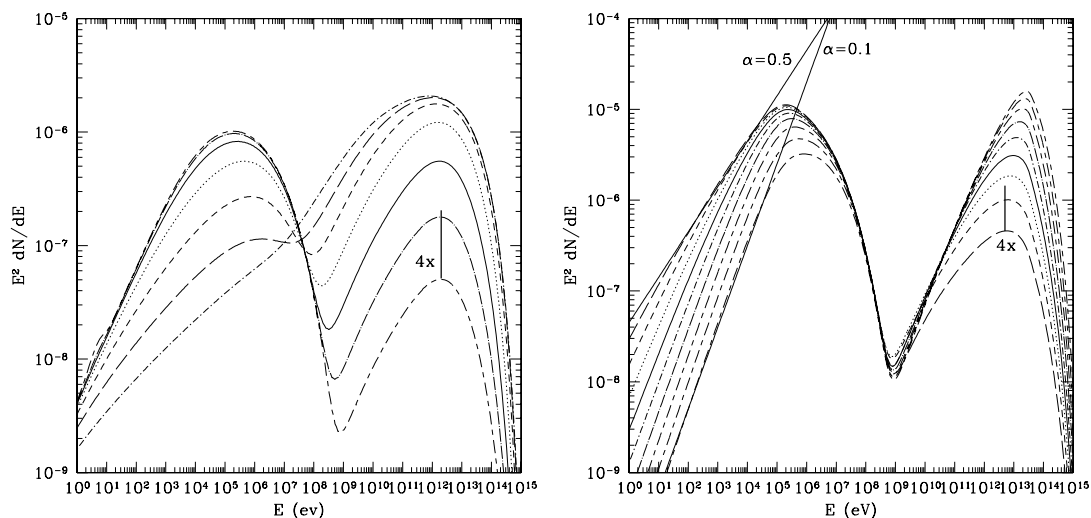


Fig. 8. The response of an SSC model where Klein-Nishina corrections are important to changes in the electron injection rate. In the *left* panel, the peak energy of the synchrotron emission (and the corresponding break in the electron energy distribution) is determined by the condition that the electrons emitting at that energy cool radiatively in a time comparable to the time it takes them to cool adiabatically or escape from the emitting region. In the *right* panel, all electrons are assumed to cool radiatively on a timescale much shorter than any escape or adiabatic cooling timescale. The X-ray spectral peak in this case is determined by the minimum Lorentz factor of the accelerated electrons ($> 10^5$ in this model). From top to bottom (at X-ray energies), the curves are obtained by successively increasing the accelerated electron luminosity by a factor two and rescaling the SSC spectrum obtained by the electron luminosity, i.e., if the SSC spectrum did not change shape, the curves would lie on top of one another. The standard lore for SSC models is that a factor two increase in electron luminosity produces a factor four increase in gamma-ray (inverse Compton) luminosity (shown by the vertical line labeled “4x”). Note the very different responses. The *right* panel seems to fit the 1997 Mkn 501 flare data best.

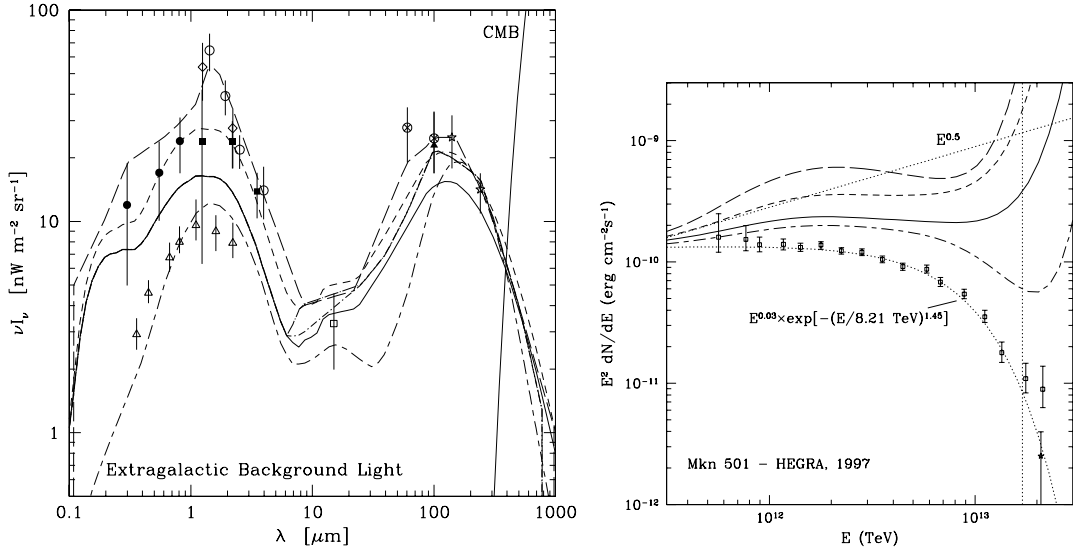


Fig. 9. The *left* panel shows a compilation of data on the extragalactic background light (EBL) taken from Aharonian (2001). The long-dashed curve (the “High” model in Table 1& 2) is an arbitrary curve constructed to pass through the upper ends of most error bars. The *dashed* and *solid* curves are the “Kennicut” and “Salpeter” models of Primack et al. (1999), and the lowest (*long-short dashed*) curve is the model of Totani & Takeuchi (2002). In the *right* panel, the *dotted* curve shows a model spectrum which fits well the time-averaged 1997 TeV data from the HEGRA Cherenkov instrument. The other curves show the inferred intrinsic source spectrum after correcting the observed model spectrum for the gamma-ray absorption produced by the EBL models of the left panel. The data points below ~ 18 TeV (*vertical dashed line*) are thought to be quite reliable.

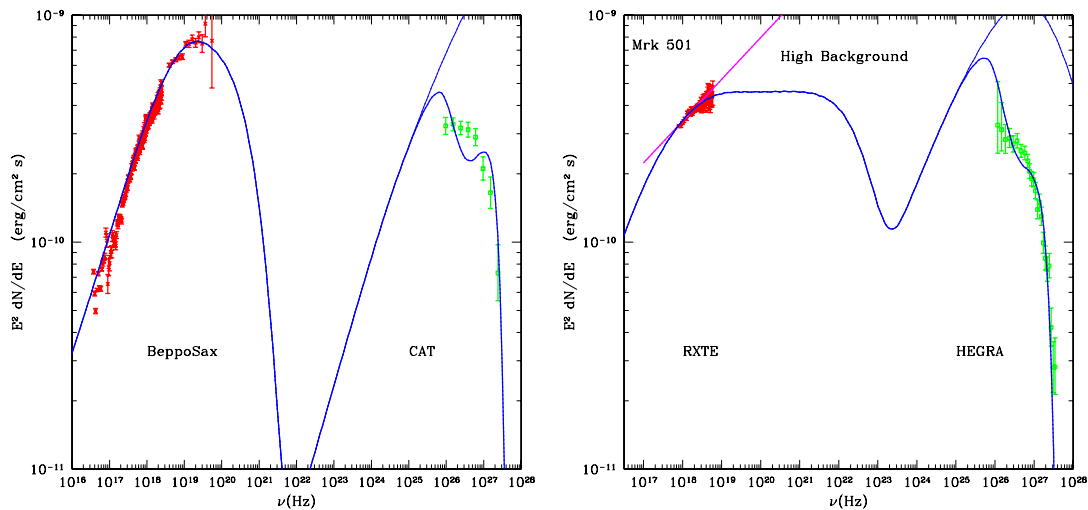


Fig. 10. *Left panel:* Best-fit SSC model for simultaneous April 16, 1997 Mkn 501 BeppoSax and CAT. *Right panel:* Best fit model for the time-averaged April-May time-averaged RXTE and HEGRA data. In both models, the shape of the electron distribution is determined by matching the observation synchrotron X-ray distribution. The source radius, magnetic field, and Doppler boost factor are then adjusted to obtain the best match to the observed gamma-ray flux. In both fits, absorption by the “High” EBL is assumed. (The upper gamma-ray curves show the intrinsic spectrum before absorption.) As seen by comparing the two panels, the fit results are insensitive to the maximum energy of the electron distribution, which is poorly constrained by observations.

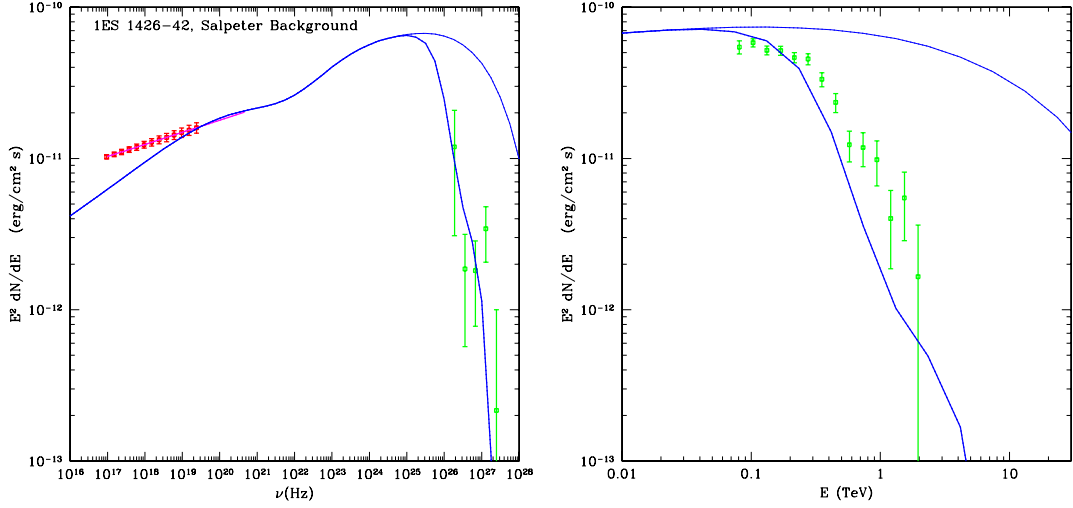


Fig. 11. *Left panel:* An attempt to fit broad-band data for 1ES 1426-42 using the procedure of Fig. 10. Without invoking external photons, there appears to be no way to match the X-ray spectral slope claimed in Costamante et al. (2001). Note also that after correcting for absorption, the gamma-ray luminosity of the source is significantly higher than the typical X-ray luminosity of this source, in apparent contradiction to the trend shown in Fig. 2. *Right panel:* The data points are fake ones generated using the expected response matrix for the HESS instrument and assuming the same source intrinsic spectrum and absorption as in the left panel. The model shown is the best-fit SSC model obtained by (incorrectly) assuming that absorption is instead given by the “Kennicut” EBL model.