Bottom-up modelling of gamma-ray blazars

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Abstract. I discuss blazar modelling from the point of view of the radiating particles and emphasise the role of low-energy emission in high-energy variability studies. I address problems that can arise from focusing on the high-energy spectrum and variability without taking into account the low-frequency behaviour and data – especially if the low-frequency emission is the most direct signature of the particles producing the gamma flares (shock-in-jet models). I use recent Planck observations combined with long-term monitoring of AGNs as examples and for motivation for the “bottom-up” direction – starting from the particles and the low-energy emission – in modelling gamma-ray blazars.

1. Introduction
The last decade or so has seen a rapid development in blazar observations across the electromagnetic spectrum with Cherenkov telescopes and X- and gamma-ray satellites at one end, and VLBI and now the Planck satellite at the other. The observational leaps have also enabled advances in theoretical modelling, although these possibilities are still often neglected. Power-distributions in radiating particle energy have already replaced the initial attempts that assume a monoenergetic or thermal distribution, and broken power laws are adding more physics into the models, but still few models go beyond the next step and really pay attention to the origin and evolution of the particle energy during a flaring event.

There are several ways in which we can update our models to meet the standards our new observations deserve. In this paper I call attention to one of these, accurate modelling of the emitting matter and the primary emission. Synchrotron emission is the first and the most straightforward (meaning: requiring least additional assumptions) observable signature of the particles and the environment that produce the high-energy spectra and variability, but only a part of the observations are typically used to constrain models, and especially the low-frequency radio data are often completely neglected.

2. Open questions and why the low energies matter
In the co-moving frame of the radiating region the relativistic electrons do two things: they emit synchrotron radiation and up-scatter photons to very high energies. The big questions are the location of the gamma-ray flares and the origin of the up-scattered photons (whether they are the synchrotron photons or whether they originate from somewhere else, e.g. from the accretion disk or the dust torus). In the following I limit the discussion to leptonic models, as they are the most popular ones, although the possibility of hadronic emission is still somewhat open (see Anita Reimer’s review elsewhere in this volume for hadronic and lepto-hadronic models, and [1] for a more general review of spectral models in blazars).
2.1. Location of gamma flaring

The origin of the up-scattered seed photons tells us about the properties of the particles and the jet as well as the ambient radiation field. Generally speaking, external Compton emission (hereafter EC\(^1\)) requires intense radiation field and works best near the central engine and the broad line region (BLR), whereas farther away the synchrotron self-Compton (SSC) is more likely to be the dominating mechanism.

Traditionally, the innermost jet has been the strongest candidate for the origin of high-energy photons, and the violent, extreme conditions near the black hole are the likely culprits for the extreme radiation. Also rapid variability and the inferred small size-scales (of the order of light-minutes or light-hours) have been argued to imply a central origin. Similarly, observed high-energy cutoffs in some blazars have been suggested to be evidence of absorption due to photon-photon interactions within the BLR [2, and Poutanen, elsewhere in this volume], or otherwise near the central engine [3].

Then again, the size scale of the emission region needs not always be linked to its distance from the central engine, as a shock front can be light-minutes in size even if it is light-years away down the jet. Shock waves can create violent and extreme conditions far away from the central engine, and statistical studies have found strong gamma-ray flares often happening after the onset of radio flares [4; 5; 6], as well as after the ejection of new VLBI components [7; 8, and Agudo, this volume]. This makes the shocks in the jet and in the radio core (parsec away from the black hole) a viable source for some gamma-ray flares [9; 10; 11]. Even the high-energy cutoff due to absorption within the BLR has been shown not to exist in all cases [e.g., 12].

All things considered, it appears likely that the origin and the dominating mechanism – as the details of the jets – vary between sources, perhaps depending on the object class [13].

2.2. The synchrotron spectrum

Gamma-ray models typically assume a single homogeneous component of some size and velocity filled with a particle population following a power-law distribution, and tune the model details to make the IC spectrum fit the X-to-\(\gamma\)-ray datapoints. EC models also require the existence of a bright IR-to-optical spectral component from, e.g., the accretion disk or the dust torus in order to provide the seed photons needed to make the EC fit the data, although in most sources there is not much direct observational evidence of such components. This simple approach can often produce good fits for the high-energy part of the SED, but it has also caveats one needs to take into account.

Firstly, although the synchrotron spectrum is the primary signature of the underlying particle population, it is often largely neglected; typically only the IR-to-optical-to-UV part of the synchrotron component is compared to the observations. Even advanced models that otherwise take the particles and the synchrotron spectrum accurately into account [see, e.g., 14], concentrate on the optical-UV part and only consider upper limits for the lower frequencies. For a single-zone model focusing on the high-energy variability and the upper end of the particle energy distribution this is understandable, but in going beyond the one-zone approach, the wealth of information in the radio-to-IR regime can provide significant insights into the shape of the particle spectra, cooling and acceleration processes, and the underlying jet [e.g., 15, Tammi et al., in preparation].

Secondly, regardless of the exact mechanism behind the high-energy peak, young shocks in the jet can also contribute to the IC spectrum, and this contribution needs to be taken into account in the model fits. In some sources the shocks can produce a part or all of the observed X- and gamma-ray emission through the SSC mechanism [e.g., 15; 16; 17], and, as reported by

\(^1\) The abbreviations EC and SSC are used both for the physical processes and the emission they produce, but the meaning is always clear from the context.
Türl & Björnsson (elsewhere in this volume), higher-order SSC might be enough to account for the gamma-rays in some cases. On the other hand, models including both SSC and EC from various seed photon sources suggest that the highest-energy gamma-rays could be dominated by the EC process [e.g., 14]. In particular, as discussed in Sec. 2.1, the GeV break observed in 3C 454.3 [18], for example, appears to be best explained by EC models [2; 3]. It should be noted that as the distance of the radiating region from the black hole increased, the previously dominating EC yields to first- and second-order SSC [14], highlighting the importance of finding the location of the gamma-ray flaring.

Furthermore, in many cases there are multiple jet components contributing to the total SED at the same time. As a component ages it goes through various phases and emits a different spectrum in each phase [19; 20], and by modelling the evolution of the components it is possible to trace the spectral variability of many sources in great detail from radio to optical [see, for example, 15]. The possibility of contribution from multiple components needs to be taken into account when testing the models, and long-term multifrequency lightcurve and VLBI monitoring are needed to limit the number of free parameters.

3. What a gamma-ray modeller should know about the Planck results

Although the Planck satellite’s task is mainly cosmological, its results are also highly relevant for AGN modelling. [21] published the spectral energy distributions of a hundred radio-bright northern AGNs from the first Planck all-sky survey, taken between August 2009 and June 2010 covering nine frequency bands between 30 and 857 GHz, together with simultaneous observations across the electromagnetic spectrum. (Simultaneous here means that the accompanying radio observations were taken within two weeks, and optical and higher energies within five days of the Planck measurement.) These early results mostly include one or two observing epochs depending on the source, and for many sources the published SED is the average of the two. The final release of the data will provide us with the complete SEDs for individual epochs for all observed sources, but already now a couple of interesting implications can be pointed out. In the following, all quantitative results are taken from [21] where they are discussed in detail.

\( \alpha \) and \( s \) are used for the power-law indices of the photon spectrum \( S_\nu \propto \nu^\alpha \) and the particle energy distribution \( N(E) \propto E^{-s} \), correspondingly.

First of all, the Planck radio spectra are, in general, flatter than expected. At lower frequencies (\( \leq 70 \) GHz, the limiting frequency between Planck’s two instruments) the spectral indices concentrate around \( \alpha \approx 0 \) and on higher frequencies (\( > 70 \) GHz) the average index is \( \alpha \approx -0.6 \) both for the single-epoch cases and for the total sample that also included the time-averaged sources. For the standard optically thin synchrotron spectrum the spectral index depends on the particle energy spectral index according to \( \alpha_{\text{thin}} = (1 - s)/2 \). Traditionally \( s = 2.2 - 2.5 \), corresponding to \( \alpha = -0.6 - -0.75 \), and most Planck’s high-frequency spectra are flatter than this.

**Low-frequency flatness** The lower-frequency flatness is usually taken to be due to either an unresolved, optically thick core or a combination of aging synchrotron jet components moving to lower frequencies. Multiple individual spectra with different ages and self-absorption turnover peak frequencies are known to create a generally flat but bumpy spectrum [22]. It is likely that also here the low-frequency flatness in many sources is due to superposition of multiple synchrotron components, although in some cases the spectrum is so smooth that the multi-component explanation seems unlikely.

**High-frequency flatness** The higher-frequency spectral flatness seen in many sources is even more interesting. Even though many of the spectra have the "expected" optically thin spectral index between \(-0.7 \) and \(-1.2 \) (synchrotron losses steepen the spectrum by an additional
\[ \Delta \alpha = -0.5 \), most of them are harder that this. 15 sources even have a high-frequency spectrum flatter than \(-0.3\). [21] concluded that even though the early release data are not sufficient enough to be definite, it is unlikely that the flatness of all, or even most of the sources, could be due to multiple shock spectra or additional IR components, although in some cases this might be the case.

In particular, [21] listed 10 sources that were observed only once (to exclude the flatness caused by averaging over multiple epochs) and whose high-frequency radio spectrum was flatter than \( \alpha \gtrsim -0.5 \). For seven of these they ruled out flatness due to multiple components and claimed the spectrum to be straight within the error bars. In these example cases the synchrotron spectrum could not be explained with standard acceleration scenario and particle spectra with \( s \geq 2 \). Instead, the observations are compatible with an electron index \( s \approx 1.5 \) and \( \alpha_{\text{thin}} \) having flattest values around \(-0.2\) and the steepest around \(-0.7\) (presumably after the steepening due to synchrotron losses). Similar suggestions have been made already earlier by, e.g., [23; 24; 25].

3.1. Examples: Preliminary case studies

[21] discussed a few examples in order to illustrate the general features. For most of them no detailed numerical modelling was done, but only simple spectral components were fitted to the radio–optical spectra according to the shock-in-jet scenario. In addition, they also analysed the radio lightcurves to gain some information regarding the past activity of the sources. Here I describe four of their sources as examples; the spectra and the lightcurves are given in [21].

0234+285 A good example of a single-component spectrum with optically thin high-radio-frequency spectral index \( \alpha \approx -0.61 \) that after a steepening of \( \Delta \alpha = -0.5 \) joins the optical data. This is what one would expect from one relatively old dominating component (shock), and is in accordance with the previous major flare, which peaked at 37 GHz two years before the Planck snapshot.

0235+164 A much bumpier spectrum shows evidence of multiple components contributing to the total emission, and [21] fitted the source with two synchrotron components. The lack of smoothness due to multiple components is again understandable looking at the long-time monitoring lightcurve that shows at least four large outbursts during the previous five years, but with no flaring during the Planck snapshot. They also speculated that these shocks would also still produce significant amounts of SSC X-rays while the fact that Fermi only observed upper limits for the gamma-ray flux is expected because even the most recent shock was already two years old during the Planck observation.

1253-055 (3C 279) Also here the highest-peaking radio component, peaking around 50 GHz, with \( \alpha_{\text{thin}} = -0.6 \), can be made to join the optical spectrum after strong steepening (by \( \Delta \alpha \approx 1 \)) in the IR regime. Especially in this source there is little room for additional IR components in the spectrum regardless of whether the spectrum is modelled by one flat and strongly steepening component or two steeper components, setting upper limits for possible EC seed photon distributions.

2251+158 (3C 454.3) This was the only source modelled numerically (Tammi et al., in preparation). The spectrum shows two separate structures best modelled with jet emission at the lowest frequencies (see Fuhrmann et al., elsewhere in this volume) and a synchrotron spectrum from a strong shock-in-jet component dominating the sub-millimetre-to-optical spectrum. The spectrum was obtained during the early stages of the strongest outburst ever seen in this source, and the radio-to-optical part was fitted with a very flat \( \alpha_{\text{thin}} = -0.2 \) synchrotron spectrum.
3.2. Implications
As said, the results are compatible with an electron index $s \approx 1.5$, significantly harder than the
$\sim 2.2–2.5$ associated with the standard first-order Fermi acceleration scenario. As discussed in
[21], it is possible to have harder spectra by making assumptions about the shock geometry or
the particle scattering process, or when the turbulence effects across the shock are considered.
The last alternative of these is an especially interesting one, because the combination of low
matter density and relatively strong magnetic field — conditions likely to be found in early
Poynting-flux-dominated AGN jets — can enhance the effective strength of the shock and lead
to very hard particle spectra [26; 27, and the references therein].
Furthermore, in these conditions also the second-order Fermi acceleration can become
dominating over some energy range and produce very hard power-law spectra as well as enable
high injection energies for the first-order shock acceleration on time-scales comparable to the
fastest gamma-ray flares [28; 29]. Although there are only a few models that include the effects
of the second-order mechanism and time-dependent particle acceleration, the attempts so far
have been successful and encouraging [e.g., 16; 17].

4. Summary
The synchrotron emission originating in in the shocks in the jet is the primary signature of the
relativistic particles that are responsible for the IC scattering. Together with the radio spectra
and monitoring improved synchrotron modelling offers information and tests that could benefit
also many high-energy models.

The recent Planck early results have increased the motivation and need for developing multi-
zone and multi-component models and working our way from particle-level physics to primary
emission and all the way to the observed EC and SSC spectra. In particular they have highlighted
the importance of the radio-to-submillimetre observations and the synchrotron modelling even
in blazar models concentrating on the highest energies.

Based on the early release data of about one hundred northern AGNs over Planck frequencies
and simultaneous multifrequency observations, the following key points relevant to gamma-ray
modelling can be made [21]:

- The low-frequency radio spectra often shows signs of multiple synchrotron components of
different ages contributing to the total spectrum. Different emission sites mean different
sets of parameters, making single one-zone models unsuitable for these sources. The number
of components affecting the observations at a given frequency range can be estimated from
long-term multifrequency lightcurves and VLBI monitoring.
- The high-frequency radio spectrum is in many cases too flat to be explained with the
traditional scenario. Instead, particle spectral indices closer to $s = 1.5$ seem to be required.
- Many sources showed ongoing millimetre-to-submillimetre flaring and spectra that can be
remarkably well modelled with one dominating synchrotron component. On the other hand,
in sources where the last outburst had already happened longer time ago often multiple
separate components were seen.

In short, the Planck early results highlight the importance of low-energy modelling and long-
time monitoring in finding the correct properties of the synchrotron spectra and, consequently,
the IC-scattering particle populations responsible for the gamma-ray flares.

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