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# Semi-analytical Model of Time-variable Blazar Jet Spectra

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**Abstract:** We present a detailed leptonic model for the temporal spectral evolution of TeV blazars. The TeV component is explained by Inverse Compton upscattering of both synchrotron photons and photons originating externally to the jet. The Broad Line Region and the accretion disc are considered as the source of soft external target photons. We investigate the effects of the emission region's passage through the BLR on the evolution of the observed spectra. We have developed a fast kinetic-equation solving numerical code to fit the time-resolved X-ray and gamma-ray (MeV to TeV) spectra from current satellite observatories and imaging Cherenkov telescopes. Predictions are made for the time-averaged TeV photon spectra on timescales of 30 minutes. The possible appearance of orphan TeV flares (without an X-ray peak) due to the emission region's emergence from the BLR is proposed.

## Introduction

The jet matter content and the mechanisms that govern the spectral evolution of its constituent particles are some of the most debated issues in high-energy astrophysics. Here the problem is explored within the framework of the leptonic scenarios.

In the leptonic models, pairs synchrotron radiate in the ambient magnetic field, giving rise to a lower, X-ray peak, and these photons produced internally to the jet can be upscattered to gamma-ray energies by the same electrons via the Inverse Compton process, thus accounting for the higher SED peak. This is the most widely used model of the blazar SED – Synchrotron Self-Compton (SSC) from a simple, one-zone, spherical emission region. Another possible source of the Inverse Compton target photons is the radiation external to the jet (External Compton, EC) from various ambient fields in the AGN – Broad Line Region clouds, accretion disc, the reprocessed radiation from the dust in the torus (disc radiation absorbed then re-radiated at longer wavelengths, see e.g. [1] and the references therein), or it could be the synchrotron photons from the jet reflected (hence reprocessed again) from the disc or BLR clouds (see e.g. [2, 3]). In our model we concentrate on what are widely considered to be the three most important target fields – synchrotron, accretion disc and BLR photons.

The EC models are very useful in mapping the location where the jet flares occur, since they are sensitive to the distance and nature of the target field in question. They also could provide an explanation for the orphan TeV flares [4]. Time-variable profiles of the external field, for example due to the emission region's passage through the BLR (whose parameters change with the distance from the centre of AGN), could generate TeV fluxes without a detectable synchrotron counterpart if the magnetic field is weak enough.

The model described in this paper reproduces the observed TeV spectra with the little explored EC model but also includes the SSC component. The external field of primary interest is the Broad Line Region but the accretion disc component is also included. By assuming a particular structure of the BLR and the disc, as well as the peculiarities of their radiation whilst evolving the particle population in a self-consistent manner, it is possible to learn more about the physical processes and the geometry of the AGN radiative fields.

## The Model

The variable TeV emission of blazars is commonly believed to originate in a blob of high-density plasma that travels at relativistic speeds from the vicinity of the supermassive black hole outwards along the jet perpendicular to the accretion disc. In the internal shock scenario, two colliding shocks provide the acceleration region for the electrons (in situ acceleration as opposed to initial injection of fresh particles), which are then pumped to higher energies.

We have developed a detailed numerical code to study, self-consistently, the temporal evolution of the particle distributions in pair plasmas that populate a spherical emission region homogeneously filled with isotropic electron/positron pairs. Since the cooling of the particles should occur on timescales much smaller than the light crossing time of the emission region [5], what we observe at any instant is a convolution of spectra produced at different times, owing to the fact that the spectra from the back of the blob take longer to reach us, w.r.t. to the spectra from the top layers. This effect was modelled by dividing a spherical emission region into slices that are narrow enough to be individually well-approximated as uniform emitters.

The steepening effect of the Inverse Compton cross-section at higher energies is accounted for by using the full Klein-Nishina cross-section integrated analytically over the isotropic electrons (derived by [6]). Approximations, such as the outgoing photon moving in the same direction as electron or the monoenergetic treatment of the accretion disc, have been avoided in the numerical integrations (for which we used CUBPACK [7]). Particle energy losses are also treated in an exact manner – particles lost from each energy bin are redistributed over different (in practice only lower) particle energy bins, rather than all being shifted in energy by the amount of the average energy loss.

The lower SED peak has been modelled with the synchrotron emission and the higher peak with the Inverse Compton Scattering for various seed photons (accretion disc, BLR, synchrotron photons). Pair absorption by the local AGN photon fields, namely the accretion disc and the BLR, has been taken into account. Intergalactic absorption of gamma-rays was accounted for by incorporating the function describing the EBL with a model and look-up tables given by [8].

## Broad Line Region Photons

The accretion disc radiation does not make a significant contribution anywhere except very close to the disk, since it has no non-radial component (its radiation is redshifted). The BLR on the other hand can contribute from a wide range of angles.

The BLR is often invoked when considering the target fields for the EC models, since it should exist at the subparsec scale at which the observed TeV radiation originates. Since it is not spatially resolved in HBLs, the knowledge of the structure and parameters of these objects is inferred indirectly from reverberation mapping.

To describe the Broad Line Region, a simplistic approach as outlined in [9] was adopted. The region is modelled as a spherical shell of gas clouds, that are approximated with spheres of a radius which increases with the distance from the centre. Accretion disc photons ionise the BLR gas, giving rise to a line spectrum. A simplification is made that all the luminosity is contained in the H$\alpha$ line (656.3 nm). The BLR clouds are assumed to be optically thin ($\tau_{BLR} \ll 1$), and that the number density of clouds in the BLR region falls off with distance as a power law, while the radius of clouds in the BLR region increases with distance as a power law (see fig. 1).

The BLR can absorb a significant amount of the produced gamma rays before the emission region emerges out of it. For very small distances of the blob to the central engine, the BLR becomes opaque at gamma-ray energies as low as a couple of hundred GeV. The opacity treshold slowly shifts towards the higher energies as the blob passes through the BLR, which finally becomes transparent to the blob radiation as it approaches the BLR's outer edge.

## Observed Photon Spectra

A static spectrum of particles, with a matching synchrotron distribution, is present in the emission re-

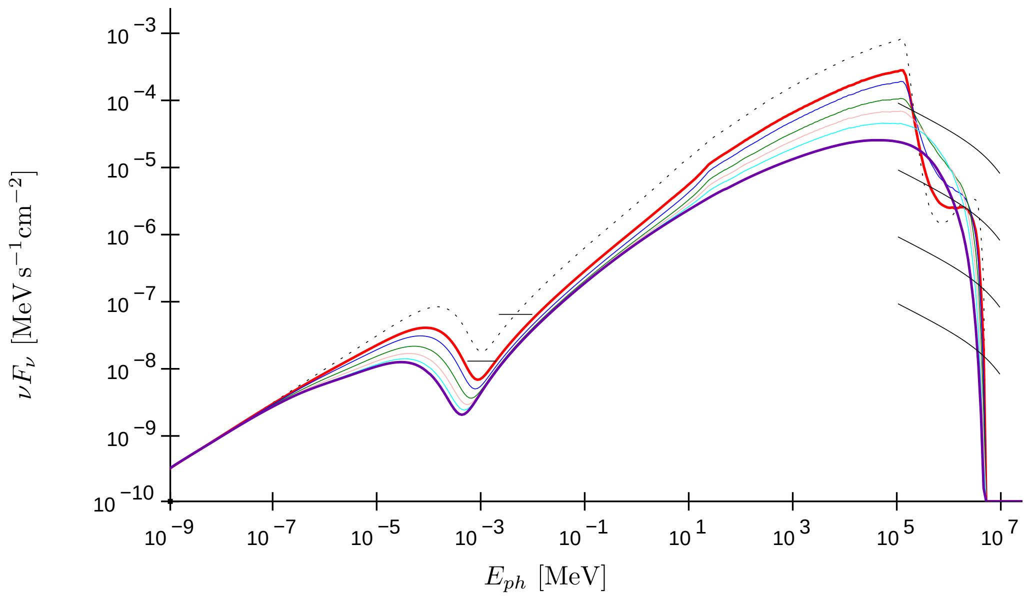


Figure 2: Evolving observed photon spectrum for the simulation starting distance of 5 mpc. The lines show the spectra with half an hour integration times but for clarity the time spacing of the spectra shown is 1hr. At lower energies of the IC peak the flux can be observed to fall monotonously, while at TeV energies the rise and fall of the flux over time is visible. The short black lines are given as reference points. The two in the X-ray energy range represent an approximate $5\sigma$ point source detection sensitivity for a 1000 s integration time in the 0.5 – 2 keV and 2 – 10 keV energy ranges with the respective flux levels of $2 \cdot 10^{-14}\,\mathrm{erg\,s^{-1}}$ and $10^{-13}\,\mathrm{erg\,s^{-1}}$. In the TeV energy range, the top black line is the Crab Nebula spectrum between 100 GeV and 10 TeV [10] while the lower black lines are at 0.1, 0.01 and 0.001 fractions of the Crab flux.

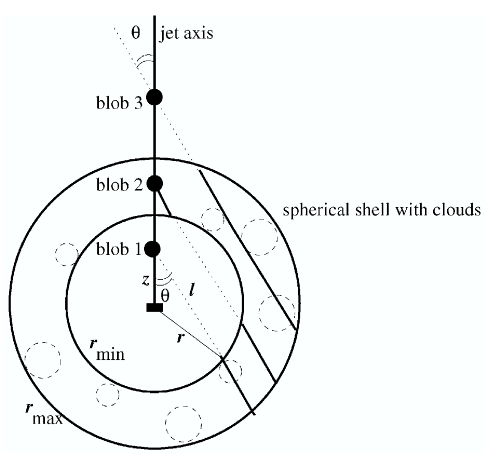


Figure 1: The schematic representation of a model of the Broad Line Region. The drawing is taken from [9].

gion at time $t = 0$ s, at a particular distance from the central engine. This spectrum is modelled with a simple, truncated power law, with lower and upper cutoffs and the slope which is set to a canonical value of $p = 2$. From this scenario as a the starting point, particles are allowed to cool down radiatively.

The resulting evolution of the observed spectra, averaged over the time intervals of 30 minutes (observer's frame) is shown in fig. 2 at a starting distance of 5 mpc. The first observed spectrum results from averaging over the observer's time interval which starts only after one light-crossing time since the start of the simulation (after the blob is empty of any photons previously emitted).

Since the magnetic field is kept at a low value, the synchrotron flux is below the minimum detectable level throughout. The simulated observed photon spectra follow a similar trend to that observed during the orphan flare in 1ES 1959, when a TeV flare was observed to rise as the X-ray flux was dying out [4]. It is noteworthy that, while the X-ray flux would be observable with XMM, the orphan flare was observed while monitoring the X-ray range with RXTE, an instrument with a sensitivity that peaks at higher energies, where the predicted flux in the above scenario is low.

The rise in the TeV flux is due the decrease in the BLR attenuation of TeV photons. At some point (after a few hours obervers' time) the TeV flux reaches its peak, determined by the balance between the decrease in emission and the decrease in BLR absorption. Thereafter the flux can only subside, as the electrons are continuously cooling down, and after a few hours it falls below its starting value. If the starting point is shifted to further than about 10 mpc this behaviour does not occur. The hardening of of the TeV spectrum is visible. As the blob starts to emerge, the TeV flux goes up and the slope becomes flatter.

It should be noted that the fraction of disc luminosity reprocessed by the BLR is taken to be relatively low here, 0.01, while it is often quoted as being as high as 0.1. Here only one BLR and disc configuration is investigated, so it would be of interest to study how the predictions may change with different geometries of AGN photon fields.

## Summary and Conclusions

A model is presented that explores the External Compton target fields' role, together with the flaring features that are seen in the TeV observations of highly-peaked BL Lacs, as an alternative to the pure SSC models usually considered. We present a possible scenario for an "orphan" flare and the hardening of the TeV spectra with the flux increase.

To test the predictions, clearly time-resolved multiwavelength spectra are necessary to get a realistic picture of the observed spectral shape. Spectra averaged over many hours/days/weeks are likely to measure a superposition of many individual flares, for which fitting spectra is less meaningful. With our model, the averaging of observed spectra was done over shorter time-intervals (30 minutes), in anticipation of the better resolved spectra from the new generation of imaging atmospheric Cherenkov detectors (e.g. H.E.S.S., MAGIC, VERITAS).

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