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# Very High Energy gamma-rays from blazars

**Helene Sol**

LUTH, CNRS, Observatoire de Paris,
Place J. Janssen, 92195, Meudon cedex, France
email: helene.sol@obspm.fr

**Abstract.** The extragalactic very high energy (VHE) gamma-ray sky is dominated at the moment by more than fifty blazars detected by the present imaging atmospheric Cherenkov telescopes (IACT), with a majority (about 90%) of high-frequency peaked BL Lac objects (HBL) and a small number of low-frequency peaked and intermediate BL Lac objects (LBL and IBL) and flat spectrum radio quasars (FSRQ). A significant variability is often observed, with time scales from a few minutes to months and years. The spectral energy distribution (SED) of these blazars typically shows two bumps from the radio to the TeV range, which can usually be described by leptonic or hadronic processes. While elementary bricks of the VHE emission scenarios seem now reasonably well identified, a global picture of these sources, describing the geometry and dynamics of the VHE zone, is not yet available. Multiwavelength monitoring and global alert network will be important to better constrain the picture, especially with the perspective of CTA, a major project of the next generation in ground-based gamma-ray astronomy.

**Keywords.** gamma-ray astronomy, active galactic nuclei, blazars

## 1. Introduction: the extragalactic sky seen at VHE gamma-rays

Observational VHE astronmy has made tremendous progress over the last decade Hillas (2013). Current ground-based IACT such as H. E. S. S., MAGIC and VERITAS, have detected more than 55 active galactic nuclei (AGN) in the TeV range, up to redshift of the order of 0.6. Among the 147 TeV sources confirmed in the current version of the on-line catalog TeVCat (tevcat.uchicago.edu), there are 58 extragalactic ones, including about 42 HBL, 7 IBL, one LBL, three FSRQ, three radiogalaxies and two starburst galaxies. The classification between the various kinds of blazars is sometimes still a matter of debate, but it is clear in any case that the sample of AGN detected at VHE includes more than 90% of presumably beamed sources. It is highly biased towards sources with relativistic beaming and strong Doppler boosting. High Doppler factors induce a great increase in the apparent flux which promotes detection. They also help to account for fast variability and to avoid strong intrinsic absorption.

## 2. The current AGN sample at very high energies

The AGN sample is largely dominated by the HBL sources which, following the blazar sequence, have a synchrotron peak at high frequencies above $10^{15} Hz$. A majority of the sources have been detected during pointed observations of selected targets, already known from multiwavelength data to be potentially active at VHE. However there are at least two cases of serendipitous discoveries in the field of view of another target, like the blazar-like radiogalaxy $IC310$ in the field of the radiogalaxy $NGC1275$ in the Perseus cluster, and the HBL $1ES1312-423$, one of the faintest extragalactic source ever detected at VHE (0.5% Crab unit) in the field of $CenA$. These findings suggest that the extragalactic space is richer than expected at VHE. The redshift distribution goes from 0.00183 with the nearby radiogalaxy Cen A to above 0.6 with the two blazars $KUV00311-1938$ and $PKS1424+240$. However most of the sources detected at the moment are at redshift smaller than 0.2, which is due to the poor sensitivity of the current experiments but also to the fact that VHE gamma-rays interact with the extragalactic bachground light, inducing pair creation, and can therefore be significantly absorbed during their propagation in the intergalactic space. Despite a somewhat poor time coverage due to the IACT duty cycle, most of the AGN appear variable at VHE, over timescales from a few minutes to years. It is quite possible that the current sample is biased towards active states because of the sensitivity limit and of the observational strategy which tends to favor the observation of flaring AGN as targets of opportunity. Nevertheless stationary quiescent states seem to be detected as well for some of the brightest sources as $PKS2155-304$.

Two families of scenarios, leptonic and hadronic, have been proposed to explain the VHE emission of AGN, both considering the emission of accelerated particles. The emitting zone is then believed to be relativistic and located somewhere along the jet, from the black hole magnetosphere to the VLBI structure. The SED of TeV-emitting AGN show two large bumps at lower (from radio to X-rays) and higher (from X-rays to VHE gamma-rays) energies. Leptonic scenarios explain the low-energy bump by the synchrotron emission of a population of highly relativistic electrons in the magnetic field of the source, while the high-energy bump is due to the inverse-Compton emission of the same population of electrons interacting with background photons, either the synchrotron radiation itself (Synchrotron-self-Compton scenario, SSC), or external photons (External inverse-Compton scenario, EC) due to the radiation from the disk, torus, broad line region (BLR) or extended jet. Hadronic scenarios describe the interaction of very energetic protons with local gas and radiation backgrounds, which produce cascades of secondary particles with a large production of pions, especially $\pi^0$ which decay into VHE photons with energy of the order of 10% of the energy of the primary protons and induce the SED bump athigh and very high energies. The synchrotron emission of secondary electrons produced during the cascades then contribute to the SED bump at lower energies. Lepto-hadronic scenarios which include synchrotron and inverse-Cmpton radiation of electrons together with hadronic processes describe the more general case but the number of free parameters is then difficult to handle.

Strictly speaking, completely different types of scenarios could be imagined to explain the VHE emission of AGN from top-down scenarios and annihilation of Dark Matter particles. There are some predictions in this sense from supersymmetric and Kaluza-Klein theories. However there has been no observational clues so far suggesting that such effects were detected. This remains a great challenge for the future of gamma-ray astronomy.

In any case, AGN appear as extremely large band sources, radiating over the whole electromagnetic spectrum from radio to multi-TeV gamma-rays. Mutliwavelength campaigns and studies are clearly mandatory to constrain SED, lightcurves and models in a useful way.

## 3. Spectral energy distribution and non-thermal emission from blazars: the elementary bricks

Simple SSC scenarios are widely used to reproduce SED and light curves of VHE blazars. SSC models are especially interesting because of their limited number of free parameters, namely the size R of the VHE emission zone, its magnetic field B and Doppler factor D, and the characteristics of a relativistic particle distribtuion with a broken

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power-law with density factor K and index n. High energy SED of stationary states of HBL can most often be reproduced by one-zone SSC scenarios with typical parameters in the following ranges, B between 0.01 and 0.2 G, R between $10^{14}$ and $10^{17}$ cm, D between 10 and 50, K of the order of $10^{3.5}$ $cm^{-3}$, first index around 2 and second one larger than 2.7. Several VHE and MWL flares of HBL can also be reproduced by SSC time dependent models, but they usually need at least two different emitting zones, namely one compact component varying on short time scale and an extended slowly varying one. This can be the case for instance if the VHE zone is embedded in a radio jet. In the cases of IBL, LBL and FSRQ, statistics are still very poor. However it seems that simple SSC models can usually work for sparse data sets, but that multi-zones models, external Compton or hadronic contribution are needed to reproduce detailed data sets with high-quality spectra and light curves. In the case of radiogalaxies, where only a handful of sources has been detected at VHE to date, alternative SSC scenarios with multi-zones seem to be able to give account for the observed data, but there are several options and the issue is still open.

The situation is still underconstrained. SSC scenarios work reasonnably well for stationary emission and flares and favour particle dominated emitting zones. The relative importance of the EC contribution seems to increase from HBL to FSRQ, which is coherent with the standard view of the blazar sequence, although there are some evidences that not all objects fit the trend. Hadronic scenarios can work as well, and sometimes better, except for highly variable cases that they usually fail to reproduce. They are characterized by much higher values of the magnetic field, typically larger than 10 G in the VHE emitting zone. The detection of gamma-ray emission at extremely high energy, at several tens of TeV, would be difficult to explain only by leptonic scenarios since inverse-Compton emission at such high energies should be limited by the Klein-Nishina regime and could request an hadronic origin. The next generation of VHE instruments should clarify the relative importance of the two processes. To illustrate these general comments, let us hereafter consider a few typical VHE blazars (HBL, LBL/IBL and FSRQ).

The first two blazars detected at VHE are indeed the Markarian galaxies Mkn 501 and Mkn 421, which have a HBL nucleus. They are still among the most well-known and studied by IACT, and can be regarded as prototypes of nearby VHE blazars. A large multi-wavelength campaign gathered high-quality data on a low activity state of Mkn 501 in 2009, with a SED well reproduced by a standard one-zone SSC model plus a host galaxy contribution. The size of the VHE emitting zone is of the order of $1000R_G$ or 0.1 pc ($R_G$ = 1.51014 cm), which corresponds to a few times the size of the VLBA core around 30 GHz and suggests an emission coming from the inner jet. Comparison of that low-state with the very active state of Mkn 501 observed in 1997 shows that the X-ray peak shifted by a factor 100 in frequency, while the VHE peak varies little. This specific effect is well explained by SSC scenarios, in which the Klein-Nishina effects reduce the cross section for inverse-Compton scattering of the energetic electrons and limit the gamma-ray emission at extremely high energies. For the other prototype of nearby TeV blazar, Mkn 421, detailed multiwavelength light curves and SED have been obtained during an intense VHE activity phase in 2008. It was shown that one-zone SSC scenarios can reproduce the SED, but require very high Doppler factors, between 40 and 80. Another difficulty is that SSC models are far from the equipartition (with low B) and can not directly explain the observed fast variability by the cooling time of the electrons. Alternative SSC scenarios with multi-zone models have been proposed, which consider stratified "spine-layer" jets, or "minijets" in jet, as well as a possible additional contribution of EC radiation.

PKS 2155-304, a bright southern HBL, presents a quiescent state observed over years which can be reproduced by both SSC and hadronic scenarios. On the other hand, this AGN is known to have shown various active states, and in particular exceptional VHE flares in July 2006. Time-dependent SSC modeling with two zones of emission, typically a compact blob embedded in a more extended jet, were able to reproduce light cuves and spectra of those flares in X and gamma-rays, two energy ranges which appear to be highly correlated during flares. However they do not directly explain the behaviour seen in the optical and radio ranges. The strong VHE flares were detected at the beginning of a long term increase (over months) of the radio flux, which might have been induced by the VHE activity, but this requires further analysis. In turn, hadronic scenarios have difficulties to reproduce the very fast variability detected down to timescales of a few minutes. Indeed such fast variability is a challenge for all particle acceleration and emission models since the size of the emitting zone appears comparable with the gravitational radius of the central black hole, even for very high Doppler factors, which make the final identification of the emitting zone rather problematic. Another multi-lambda campaign performed during a low activity stat ein 2008 with ATOM, SWIFT, RXTE, Fermi and HES,S probed the complexity of the links between the different spectral ranges, which can show significant or elusive correlation, or no correlation at all. Furthermore,such correlation properties appear different during active and low states. Further detailed monitoring in radio, optical, X-rays and gamma-rays is needed to better investigate these trends. However the interpretation of these complex data sets requires absolutely the development of comprehensive models of these sources, that are not yet fully available.

The objects BL Lac and W Comae, two well-known blazars, provide interesting examples of the TeV-emitting LBL/IBL family. Their SED show relatively broad high energy bumps, which are difficult to reproduced by simple SSC scenarios. External Compton (or alternatively hadronic) component seems to be needed. Once again, muti-lambda monitoring and comprehensive models are needed. For such types of sources, especially VLBI monitoring could shed light on overall scenarios since there are some claims of correlation between the detection of TeV flares and the emergence of new VLBI component. Such circumstance was found for instance in BL Lac, in which a new superluminal knot (K11) was shown to have been ejected from the core in June 2011, at the time of a VHE flaring activity of the source. Note that in this case the flare was also observed simultaneously in the optical range, while the radio flux slowly increased afterwards and reaches a maximum four months later.

The blazar 3C279 is the first FSRQ detected in the VHE range. Modeling multi-lambda data obtained in 2006 and 2007 concluded that simple one-zone SSC scenarios can not explain the observed SED. Various alternatives have been studied which can reproduced the data at the cost of greater complexity. The observations of 2006 have been reproduced by one-zone SSC scenarios plus an additional EC component, either inside the BLR (with the VHE flux dominated by IC on the UV of the BLR) or outside the BLR (with the VHE flux dominated by IC on the IR of a putative dust torus). Such models can work although they appear challenging and raise several questions, such as the impact of internal absorption. Conversely, the observations of 2007 have been reproduced by a two-zone SSC+EC model, where the emission from the optical to the HE ranges is supposed to come from inside the BLR, while the VHE flux is supposed to come from outside the BLR, with a delay of a few days. Lepto-hadronic scenarios have been also considered as further alternatives.

To summarize, basic leptonic scenarios appear quite successful to explain "simple cases" especially for HBL, though it should be noted that stricto sensu various SSC models can apply since scenarios are not fully constrained yet, as recently illustrated for instance in the case of 1ES 2344+514 (Aleksic *et al.* 2013). Moreover, EC components are important for FSRQ and probably LBL/IBL. Even HBL might need some additional EC component as recently suggested for 1ES 1959+650 by Aliu *et al.*(2013) who consider EC emission related to dust at a temperature of 20K. Hadronic models can reproduce most of the quiescent states but have difficulties for time-dependent analysis. SSC scenarios usually lead to particle dominated jets, while SSC+EC and lepto-hadronic models can be closer to equipartition. The difficulty to reach a firm conclusion to date is due to the lack of a coherent comprehensive picture of blazars. The available emission models are only efficient "elementary bricks" to reproduce the observed fluxes, but indeed we still fail to know the exact location, geometry and dynamics of the VHE emitting zone(s). Following different observational clues and specific cases, it could be related to the black hole magnetosphere, the base of jets, inner jets, or more extended jets and knots. We do not know either the origin and site of the primary particle acceleration, Fermi processes in shocks and turbulence, magnetic reconnection, direct electric or centrifugal forces ... As a result, the origin of power and variability at VHE frequencies is not fully identified and remains difficult to interpret. A better understanding of the physical connection or evolution between the different AGN types seen at VHE would be very helpful in this regard and could clarify the true place of TeV-emitting blazars within the current AGN unificatoin schemes. This could be possible with the next generation of IACT which should be able to gather larger samples of TeV sources to allow statistical studies.

## 4. Outcome from VHE data on blazars

Further observations of blazars in the TeV range should shed light on thedominant physical mechanisms at work in the environment of supermassive black holes, increasing constrains on acceleratin and emission processes by monitoring low and high states and probing the shortest timescales. This should give access to specific zones around AGN, not probed at any other frequencies. It might allow for instance to explore the still issing link between black hole magnetospheres and jet formation zones. One can also expect to identify atypical or transition sources, which would be useful to test unification schemes by "bridging the gap". In this regard, the source IC310 which shows a spectral behavior of a HBL butwhich is much weaker could be an intermediate case between BL Lac and FRI sources, which requires further investigation.

Distant TeV-emitting blazars can also be used as beacons of gamma-rays to probe their extragalactic line of sight since VHE photons interact with background photons from the extragalactic background light (EBL) and from the cosmic microwave background (CMB), and with the intergalactic magnetic field. This allows to deduce interesting constrains on the EBL, or conversely on intrinsic spectra and redshifts of the sources, since the imprint of the EBL which absorsb TeV photons by pair creation process is present on the spectra of high redshift sources. It also provides for the first time non-zero lower limits on the value of the intergalactic magnetic field. A lower limit of the order of $10^{-17}$ G has been proposed from the non-detection of delayed secondary GeV emission following TeV flares from remote sources (Durrer & Neronov 2013).

## 5. Perspectives at VHE and conclusion

CTA, the Cherenkov Telescope Array, is the global project of the next generation of IACT. It aims to increase by a factor10 the sensitivity at TeV energies and improve the angular and spectral resolution relatively to current instruments. It should significantly enlarge the spectral range, from a few tens of GeV to about 100 TeV, and the field of view to about 5 to 10 degrees. A full sky coverage is expected with the construction of two arrays, in the southern and in the northern hemispheres. A possible configuration for the future southern array includes large, medium and small size telescopes (LST, MST and SST), with a low-energy section with four 23 m parabolic telescopes observing above a few tens of GeV, a core-energy array with about twenty-three 12 m Davies-Cotton telescopes observing in the range from 100 GeV to 10 TeV and a high-energy secttion with about sixty 4m Davies-Cotton or Schwarzschild-Couder telescopes observing at multi TeV energies, up to 100 TeV. If construction begins as expected in coming years, partial operation could start by 2016, with a full array completed around 2019. It should allow to reach hundreds of AGN of various types and open the possibility of statistical studies (Sol *et al.* 2013). The SST sub-array will allow to explore the extreme energy tail of the spectra and search for possible signatures of hadronic processes.

VHE data explore a new facet of AGN, related to extreme processes, fast variability and compact zones, not yet self-consistently understood in the general environment of supermassive black holes. High VHE fluxes from AGN appear up to now as a tracer of strong relativistic beaming. Therefore VHE observations could provide constrain on the orientation of the central engine itself relatively to the line of sight, since they seem to explore for the first time, at least in some sources, a specific zone near the black hole magnetosphere and the jet formation zone, in the imediate neighborhood of the black hole. Elementary bricks of HE emission scenarios are currently available, it can be expected that future VHE observations, coordinated with multi-lambda and multi-messenger ones, allow to reach a comprehensible picture of the VHE emitting zone, its location and its dynamics, and to understand the place of TeV emitting sources in the AGN unification schemes.

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