Studies of Active Galactic Nuclei with CTA

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Abstract

In this paper, we review the prospects for studies of active galactic nuclei (AGN) using the envisioned future Cherenkov Telescope Array (CTA). This review focuses on jetted AGN, which constitute the vast majority of AGN detected at gamma-ray energies. Future progress will be driven by the planned lower energy threshold for VHE gamma-ray detections to ~ 10 GeV and improved flux sensitivity compared to current-generation Cherenkov Telescope facilities. We argue that CTA will enable substantial progress on gamma-ray population studies by deepening existing surveys both through increased flux sensitivity and by improving the chances of detecting a larger number of low-frequency peaked blazars because of the lower energy threshold. More detailed studies of the VHE gamma-ray spectral shape and variability might furthermore yield insight into unsolved questions concernining jet formation and composition, the acceleration of particles within relativistic jets, and the microphysics of the radiation mechanisms leading to the observable high-energy emission. The broad energy range covered by CTA includes energies where gamma-rays are unaffected from absorption while propagating in the extragalactic background light (EBL), and extends to an energy regime where VHE spectra are strongly distorted. This will help to reduce systematic effects in the spectra from different instruments, leading to a more reliable EBL determination, and hence will make it possible to constrain blazar models up to the highest energies with less ambiguity.

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1. Introduction

Active Galactic Nuclei (AGN) are extragalactic sources of enhanced activity that are powered by the release of gravitational energy from a supermassive central black hole. Energy linked to the black hole spin (e.g., Blandford & Znajek, 1977) may be instrumental for forming prominent jets which transport material from the innermost region of the AGN to kpc-, sometimes even Mpc-scale distances with relativistic speed. Such jets are usually identified through the detection of bright non-thermal radio emission as observed in radio-loud AGN. Only a small percentage (~ 10 %) of all AGN are known to be radio-loud[1]. In the vicinity of the central region of an AGN matter is accreted from a disk onto the black hole, line-emitting clouds of material (the so-called broad-line region, BLR, and narrow line region, NLR) swirl at pc to kpc distances from the central engine, dusty material surrounding the accretion disk may imprint thermal signatures in the infrared part of the AGN spectrum, and the prominent jets of material in case of radio-loud AGN dominate the non-thermal radiative power in such systems (see Figure 1).

The radiation from material which moves relativistically with speed $\beta_\Gamma c$ (with $\Gamma = 1/\sqrt{1-\beta_\Gamma^2}$ being the bulk Lorentz factor) along the jet axis is beamed into an angle $\sim 1/\Gamma$ around the direction of propagation. Because of this beaming effect mostly those AGN whose jet axes are close to alignment with our line of sight (i.e., blazars) are favorably detected as sources of high-energy (gamma-ray) emission. However, also some mis-aligned AGN (i.e., radio galaxies) can be detected, if they are sufficiently nearby. Blazars therefore offer an excellent opportunity to study jet physics of massive black hole systems, and through population studies also their evolution over cosmic time. Because the bolometric radiative energy output of AGN jets is often dominated by the gamma-ray regime[2], the observed peak flux $(\nu F_\nu)^{\rm pk}$ in this band, together with a knowledge of the bulk Lorentz factor Γ, provides a robust lower limit for the overall jet energetics constrained by the

[1]Radio-loud AGN are conventionally characterized with a radio-to-optical flux ratio $S_{5GHz}/S_{440nm} > 10$.

[2]We note that the apparent dominance of gamma rays in the overall blazar budget was recently shown to be affected by selection effects (Giommi et al., 2011).

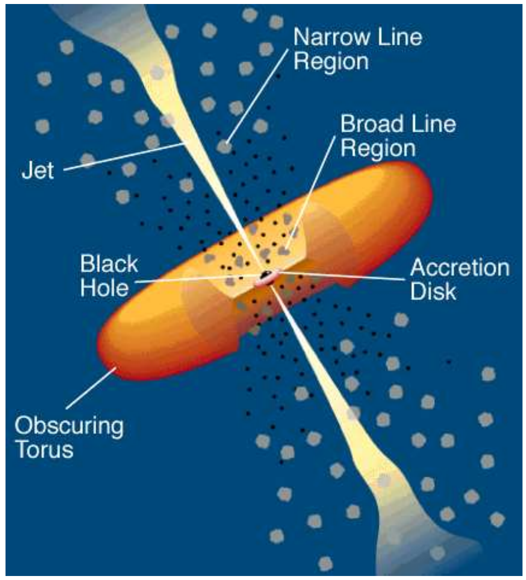

Figure 1: Sketch illustrating the constituents and geometry of a radio-loud AGN (from Urry & Padovani, 1995).

total radiative power, $L_{\rm jet} > L_{\rm rad}$, with

$$L_{\rm rad} \approx \frac{d_L^2}{\Gamma^2} \, (\nu F_\nu)^{\rm pk}, \tag{1}$$

where d_L is the luminosity distance. Such limit is not only crucial for constraining jet formation scenarios and the overall particle and field content of a jet including its impact for searches for the sources of the ultrahigh energy cosmic rays, but also for, e.g., investigating the jet's feedback on its environment. Comparing disk and jet energetics may give important clues on the physical connection between disk accretion and jetted outflows. Because these jets form in the vicinity of the strong gravitational fields of massive, probably rotating, black holes, studying events occuring close to the central engine may contribute to understanding jet formation. Size scales of the emission region of the order of the Schwarzschild radius are implied by extreme variability observed e.g., down to minute time scales at TeV energies (Aharonian et al., 2007; Albert et al., 2007a), in a few radio-loud AGN, and this might imply a location of the emission region very close to the central black hole. On the other hand, the observation of systematic variations of the optical polarization over several days associated with a gamma-ray flare (e.g., Abdo et al., 2010f), and distinct gamma-ray flares coinciding with the peak polarization of the mm-core (Jorstad et al., 2009) seem to favour rather pc-scale distances of the emission region relative to the central engine. This highlights the current debate regarding the location of the emission region. Studying the gamma rays from jets within the multifrequency context offers a view towards the global structure and composition of magnetized relativistic outflows, which provide constraints on the dominant radiation mechanisms. Monitoring the transition from flaring events to the quiescent phases together with the estimates on the overall flaring duty cycles may provide hints on the origin of variability.

Gamma rays probe the highest energy particles present in these jets, and therefore are relevant for our understanding of how charged particles are accelerated in jet plasmas, e.g., via shocks, and/or turbulence and/or magnetic reconnection. This may also have implications for our understanding of the origin of ultrahigh energy cosmic rays.

In this article, we review the prospects of CTA to facilitate progress in our understanding of the AGN phenomenon and its related physics including the large-scale impact of the associated jets.

2. CTA and the population of AGN

According to the unification scheme of radio-loud AGN (e.g., Urry & Padovani, 1995), flat spectrum radio-quasars (FSRQs) and BL Lac objects (commonly refered to as "blazars") are sources which are observed under a small viewing angle with respect to the jet axis. Those observed at large viewing angles are classified as Fanaroff Riley I and II radio galaxies (Fanaroff & Riley, 1974). Hence, they are commonly considered as the parent populations of blazars[3]. Jetted AGN are oberved as sources of radiation across the electromagnetic spectrum, from the radio band up to very-high energy (VHE: $E > 100$ GeV) gamma-ray energies. The blazar class is subdivided into observationally weak-lined AGNs, identified as BL Lac objects, and strong-lined ones, called flat-spectrum radio quasars (FSRQs) (Landt et al., 2004). The latter show signatures of a bright accretion disk (e.g., a

[3]The recently proposed scenario of Giommi et al. (2011) considers high-excitation (HERG) and low-excitation (LERG) radio galaxies as the parent populations of blazars. Nearly all FRIs, however, are LERGs, and FRIIs are mostly HERGs except for a small FRII LERG population.

"blue bump") and strong emission lines, whereas the former are lacking such features. However, the lack of thermal (accretion disk) and emission line features in the spectra of objects typically classified as BL Lac objects may be — at least in some cases — due to the bright non-thermal continuum of jet emission outshining those features rather than their actual absence (Giommi et al., 2011).

The SEDs of jetted AGN consist generally of two broad components (see, e.g., Fig. 7). The low-energy component is commonly attributed to synchrotron radiation from relativistic electrons, and possibly positrons, in a relativistically moving emission region ("blob") in the jet. The origin of the high-energy emission is still a matter of debate, depending strongly on the overall jet composition (see below). Spectrally, blazars can be classified according to the frequency of the synchrotron peak in their broadband SED, independent of the optical emission-line based characterization of being a BL Lac object or a quasar (Abdo et al., 2010c). Low-synchrotron-peaked (LSP) blazars have their low-energy peak at $\nu_{s,peak} < 10^{14}$Hz, intermediate-synchrotron-peaked (ISP) blazars at $10^{14} \leq \nu_{s,peak} \leq 10^{15}$Hz, and high-synchrotron-peaked (HSP) blazars at $\nu_{s,peak} > 10^{15}$Hz. Considering the BL Lac population only, we shall distinguish low-frequency-peaked BL Lacs (LBLs), intermediate-frequency-peaked BL Lacs (IBLs) and high-frequency-peaked BL Lacs (HBLs), correspondingly.

The census of gamma-ray detected blazars has recently experienced a dramatic increase from less than 100 blazars detected by the EGRET instrument onboard the *Compton Gamma-Ray Observatory* and Cherenkov telescopes to nearly 10^3 high-latitude objects detected by the Large Area Telescope (LAT) on board the *Fermi* Gamma-Ray Space Telescope (Ackermann et al., 2011a), that have been associated with AGN. Only a few non-blazar AGN are detected at gamma-ray energies to date: nearly a dozen radio galaxies, a few Narrow-Line Seyfert 1 (NLS1) galaxies and a few unusual sources that escaped a convincing identification so far (Ackermann et al., 2011a).

Untill now, there is no convincing case of a gamma-ray detection of a "classical" radio-quiet Seyfert galaxy. An upper limit for the GeV luminosity of hard X-ray selected radio-quiet Seyferts as a class is currently probing the level of about 1 % of their bolometric luminosity, corresponding to a few 10^{-9} ph cm^{-2} s^{-1} in the 0.1 – 10 GeV band (Ackermann et al., 2011b). With CTA at its predicted sensitivity at low energies it will be possible to extend this energy range to several tens to hundreds of GeV at a comparable energy flux level. This would probe whether there exists a smooth extension of

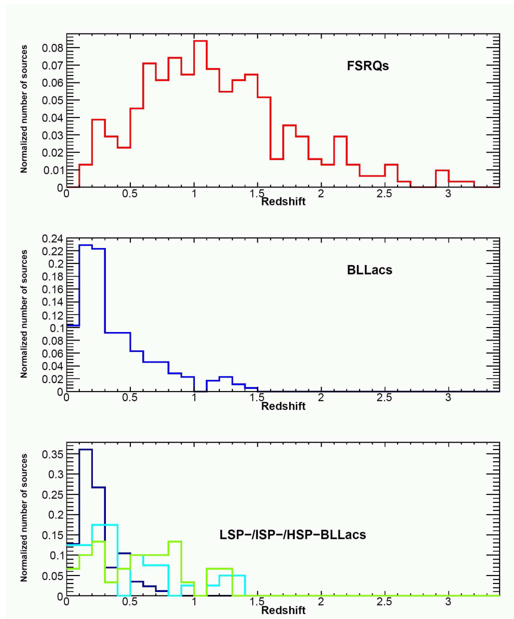

Figure 2: Redshift distribution of *Fermi*-LAT detected blazars (from Ackermann et al., 2011a).

radio-loud low-luminosity AGN towards the Seyfert population [4], or whether those are distinct source classes.

The low number ratio of FR II to FR I radio galaxies detected at gamma-ray energies to date is surprising in the framework of the unification scheme. Though the doubling of the Fermi survey time from one to two years has increased the overall number of detected gamma-ray emitting AGN by $\sim$ 50 %, the relative number of LAT FSRQs to LAT BL Lacs has decreased from ~ 0.9 to ~ 0.8[5]. The number of gamma-ray detected misaligned AGN has not changed significantly, and neither has the FR II to FR I number ratio (Ackermann et al., 2011a). Three of the four radio galaxies detected at VHE gamma-ray energies (M87, Cen A, NGC 1275) belong to the FR I class (the

[4]We note that the conventional definition of a radio-loud AGN may allow accretion-dominated HSPs and/or AGN with a comparably weak non-thermal emission component be possibly classified as radio-quiet.

[5]This discrepancy may be even larger due to the many non-associated BL Lacs because of either missing redshift information or incomplete cataloguing at the southern hemisphere.

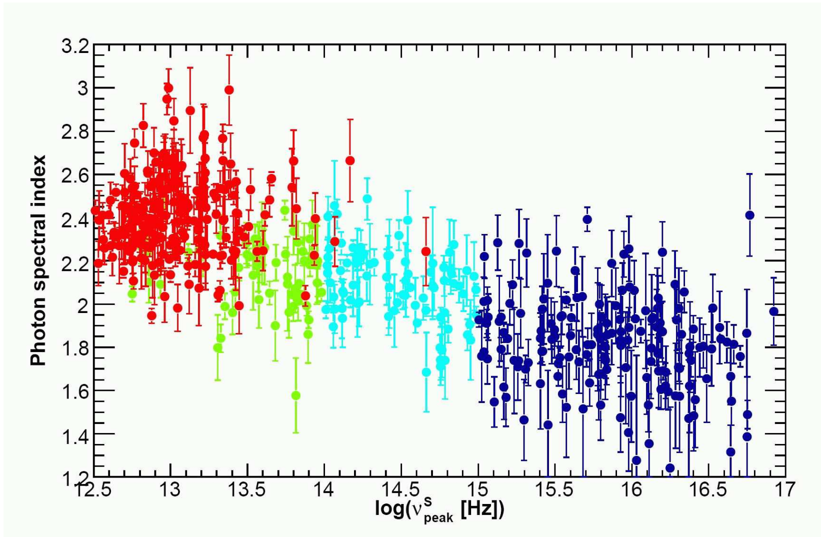

Figure 3: Synchrotron peak frequency vs. *Fermi*-LAT spectral index for *Fermi* detected blazars (from Ackermann et al., 2011a). Red = FSRQs; green = LBLs; light blue = IBLs; dark blue = HBLs.

fourth one, IC 310, is of unknown class, possibly a head-tail radio galaxy: Aleksic et al., 2010). A deeper survey of FR I and FR II radio galaxies with CTA at energies > 10 GeV is expected to increase the sample of VHE gamma-ray emitting radio galaxies and may lead to the detection of a few FR II radio galaxies. This might facilitate the determination of the ratio of VHE gamma-ray emitting FR II to FR I sources over a broader energy range. Such studies might reveal whether the less prominent gamma-ray emission from FR IIs is indicative of less efficient particle acceleration in their jets, a difference in jet structure (e.g., Chiaberge, et al. (2000)) and/or beaming pattern between FR Is/BL Lacs and FR IIs/FSRQs (e.g., Dermer (1995)), whether possibly $\gamma\gamma$ absorption in the dense nuclear radiation fields of these generally more powerful sources (Reimer, 2007; Liu et al., 2008; Sitarek & Bednarek, 2008; Poutanen & Stern, 2010; Roustazadeh & Böttcher, 2010, 2011) plays a role in suppressing observable gamma-ray emission, or whether FRII/HERGs are intrinsically less numerous as a consequence of being located at the high-luminosity end of an overall radio galaxy luminosity function (Giommi et al., 2011).

Among the LAT-detected BL Lacs the high-synchrotron peaked sources (HSPs) are the largest subclass, which is also the AGN subclass that is mostly detected in the VHE-regime by current Atmospheric Cherenkov Telescope (ACT) instruments. The (nearly permanent) survey observation mode of *Fermi*-LAT has triggered many follow-up observations of selected flaring AGN also with H.E.S.S., MAGIC and VERITAS. Until a few years ago, almost all AGNs detected by ground-based Cherenkov telescopes were HSPs, primarily because of their harder GeV gamma-ray spectra (see Fig. 3), indicating higher gamma-ray peak frequencies than other blazar subclasses. However, due to their permanently improving flux sensitivity and decreasing threshold energies, more than 40 blazars of all subtypes (FSRQs, all types of BL Lac objects: LBLs, IBLs, HBLs) have meanwhile been detected in VHE gamma-rays, covering the redshift range 0.03 to at least 0.536, thereby nearly doubling the census of VHE blazars during the past couple of years[6]. This may indicate that with CTA it will be possible to significantly expand the population of low-frequency peaked VHE AGN, both FSRQs and BL Lac objects, in addition to the HSP population. A systematic unbiased study may reveal then the required environment and jet properties that allows particles and photons to reach high energies. In particular, future observation of a larger number of BL Lac – FSRQ transition objects in the VHE gamma ray band, accompanied by multifrequency coverage, may provide more insight in this regard. So far only few (e.g., 3C 279 whose thermal components may be overwhelmed by a strong non-thermal flux in a bright state (Pian et al., 1999); or the BL Lac prototype, BL Lacertae, which shows occasionally broad lines (e.g., Capetti, Raiteri & Buttiglione, 2010)) of such objects have been detected at VHEs when they reached an elevated flaring state (Albert et al., 2008; Böttcher et al., 2009; Albert et al., 2007b). E.g., while monitoring 3C 279 in 2006 in a dedicated multifrequency campaign (Böttcher et al., 2007, see Figure 4) this source transitioned to an overall high state observed in the optical as well as at X-rays. During this state, in February 2006, a VHE signal from 3C 279 was detected by the MAGIC telescope (Albert et al., 2008). The observations of a larger sample of such objects with CTA might uncover a particular spectral and/or variability pattern with possible relations to other frequency bands that may help to finally reveal the conditions in the jet that allows charged particles to reach extreme energies. A similar consideration can be applied to LBL – HBL transition AGN. Broad-

[6]see `http://www.mpp.mpg.de/ rwagner/sources/` or `http://tevcat.uchicago.edu/`

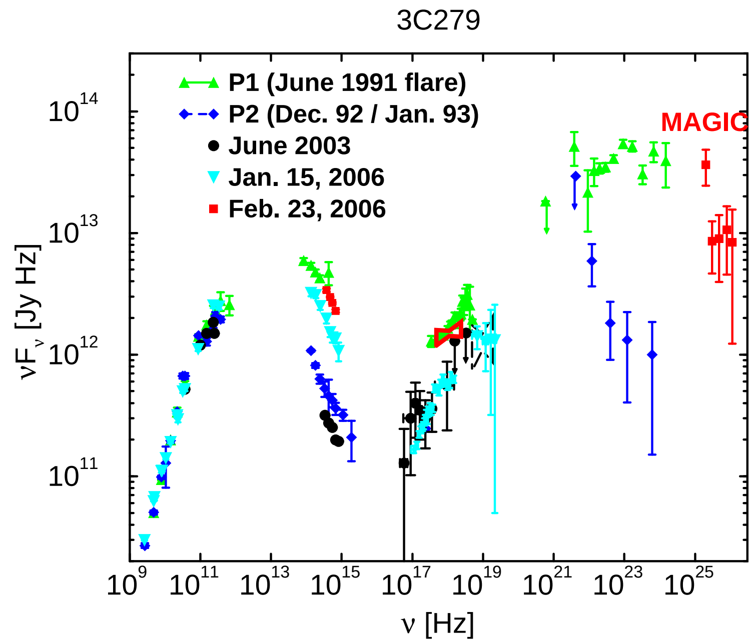

Figure 4: Broadband spectral energy distribution of FSRQ 3C 279 during the June 1991 and February 2006 flaring state in comparison to 1992/1993 and 2003 observations where the source was in a quiescent state (Böttcher et al., 2009).

band studies of such objects, including the important VHE regime, may shed light on the physical origin of such behaviour, and will help to determine to what extent LBLs and HBLs are fundamentally different AGNs.

Both the expected increased sensitivity of CTA and extension of the available energy range towards tens of GeV will also facilitate studies of the AGN population at VHE gamma-rays to very large redshifts. The so far highest-redshift source detected at VHEs is 3C 279 at $z = 0.537$. The redshift range of AGNs covered by Fermi-LAT extends to $z < 3.1$ (unchanged from the first to the second year of Fermi exposure; see Figure 2), above ~ 20 GeV it is $z < 3$ (Ackermann et al., 2011a), while FSRQs are known to exist up to $z \sim 5.5$ (e.g., Q 0906+6930: Romani (2006)).

With CTA, a new quality of the study of AGN evolution over cosmic time will be possible. The VHE range is important as it provides an undiluted view on the pure jet. Proposed cosmological evolution scenarios (Böttcher & Dermer, 2002; Cavaliere & D'Elia, 2002) consider a gradual depletion of the circum-nuclear matter and radiation fields over cosmic time thereby turning highly-accreting into pure non-thermal jet systems. This would suggest a transition from external-Compton to synchrotron-self-Compton dominated high-energy emission in the framework of leptonic emission scenarios or from photo-pion dominated to proton-synchrotron dominated high-energy emission in the framework of hadronic emission scenarios (see §4). If this scenario is correct, a systematic study of the sub-GeV – TeV spectra of the various sub-classes of blazars should therefore reveal a gradual transition from multi-component gamma-ray emission in accretion-dominated blazars to featureless single-component gamma-ray emission in pure jet sources.

For the first time, it will be possible to build large, well-defined, statistically complete[7] and unbiased[8] samples at VHEs which allow us to derive population properties like the VHE Log(N)-Log(S) distribution for the various types of AGN, the luminosity function at VHE gamma-rays and compared to other wavelengths, and to study their cosmological evolution. This will extend our knowledge on the origin of the extragalactic gamma-ray background (e.g., Abdo et al. (2010e)) up to the highest photon energies, and its impact on the evolution of the intergalactic medium and structure formation (Puchwein et al., 2011)

As the AGN population detected at VHE gamma-rays will penetrate to larger redshifts, predominantly the high luminosity tail of this population will be detected. In particular, verifying the existence or non-existence of a high-luminosity HSP population and its broadband spectral properties will be interesting as this would contradict the traditional understanding of the blazar sequence (Fossati et al., 1998)[9]. According to this picture, a sequence of blazar sub-classes has been proposed to be linked to their bolometric luminosity, black hole mass, accretion disk luminosity and accretion mode (e.g., Ghisellini et al., 2011). It has been suggested that FSRQ activity is powered by accretion at a high Eddington ratio ($\dot{M}/\dot{M}_{\rm Edd} \gtrsim 10^{-2}$), which might be related to dense circum-nuclear environments. The corresponding dense

[7]A completely identified sample of sources where all are detectable above its statistical limits is generally referred to as a complete sample.

[8]We refer to a sample above its statistical limits as unbiased with respect to pre-specified parameters if the process that selects the sample sources does not favour or disfavour any objects with particular values of the considered parameters.

[9]However, selection effects and other sample biases may impact the physical existence and significance of this proposed sequence (for a review, see Padovani, 2007)

circum-nuclear radiation fields are expected to leave their imprints in two-component gamma-ray spectra as well as potentially $\gamma\gamma$ absorption features, if the gamma-ray production zone is located within the broad-line region of the AGN (Poutanen & Stern, 2010). At the same time, efficient radiative cooling of relativistic particles in these dense radiation fields might then impede their acceleration to very high energies, resulting in SED peaks at low frequencies. On the other hand, BL Lac objects are suspected to be powered by radiatively inefficient accretion at low rates ($\dot{M}/\dot{M}_{\rm Edd} \ll 10^{-2}$), possibly — at least in part — due to larger black-hole masses (and hence larger $\dot{M}_{\rm Edd}$). If the jet power correlates positively with the accretion rate (e.g., Rawling & Saunders, 1991), this implies a lower power in the jets produced in these objects, compared to FSRQs. At the same time, the circum-nuclear radiation fields are expected to be very dilute, with only minor impact on the formation of the high-energy (gamma-ray) emission. The search for high-luminosity (high-redshift) BL Lac objects with high synchrotron and gamma-ray peak frequencies with CTA, in combination with on-going monitoring by *Fermi*-LAT promises progress in verifying the existence of and understanding the origin of the blazar sequence, or whether the peak energy is intrinsically unrelated to the blazar luminosity (Giommi et al., 2011). The redshift of these objects, if lacking as argued by Giommi et al. (2011), could be constrained using UV-to-NIR photometry (Rau et al., 2011), or limits inferred from the shape of the de-absorbed spectrum if the extragalactic background light (EBL) and its evolution were known (e.g. Abdo et al., 2010a; Prandini, Mariotti & Tavecchio, 2011).

3. The Extragalactic Background Light and blazar spectra

VHE gamma-rays from sources at cosmological distances will be attenuated through $\gamma\gamma$ absorption on the Extragalactic Background Light (EBL; e.g., Dwek & Krennrich, 2005; Stecker et al., 2006; Franceschini et al., 2008; Gilmore et al., 2009; Finke et al., 2010). The SED of the EBL has two maxima: one at $\sim 1\,\mu$m due to star light from cool stars, and one at $\sim 100\,\mu$m due to cool dust (see Figure 5). A direct measurement of this background is extremely difficult because of bright foreground emissions (both within our solar system and our Galaxy). The recent measurements of unexpectedly hard VHE gamma-ray spectra from blazars at relatively high redshifts (see, e.g., Figure 6) has led to the conclusion that the intensity of the EBL must be near the lower limit set by direct galaxy counts (e.g., Aharonian et al.,

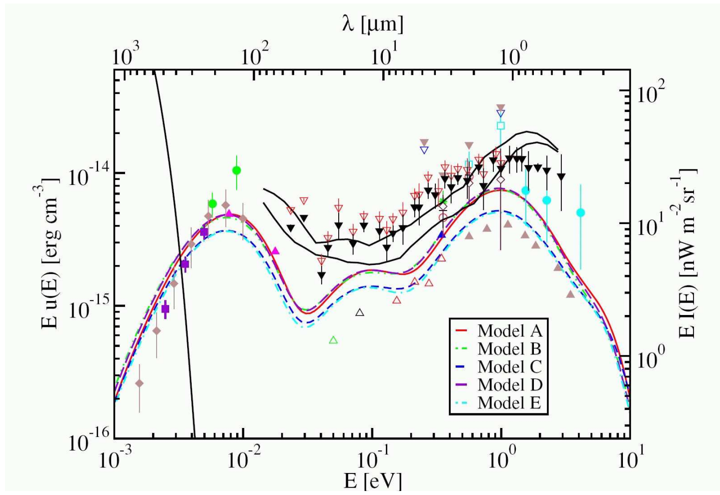

Figure 5: Spectral energy distribution of the Extragalactic Background Light. From Finke et al. (2010).

2006; Abdo et al., 2010d). However, details of its spectral shape and, in particular, its cosmological evolution are still under debate.

Indirectly, the EBL and its cosmological evolution can be studied by analyzing simultaneous broadband SEDs of VHE gamma-ray blazars at various known redshifts. In particular, simultaneous *Fermi*-LAT and ground-based VHE gamma-ray spectra are crucial for such an analysis. However, this requires an a-priori knowledge of the SED throughout the GeV – TeV energy range. The uncertainties and ambiguities in blazar jet models (see §4) currently preclude definite conclusions about the EBL based on blazar SED modeling alone. An observational challenge in such studies lies in the often vastly different integration times over which gamma-ray spectra in the *Fermi*-LAT energy range are measured (typically several weeks), compared to VHE gamma-ray spectra, often extracted from a few hours of good data from ground-based ACTs. This often leads to mis-matches in the spectral shapes and flux normalizations, which complicates or impedes any meaningful theoretical interpretation.

With the reduced energy threshold of CTA, down to ~ 10 GeV, it will be possible to determine the shape of the gamma-ray spectrum from energies at which EBL absorption is negligible (typically below a few tens of GeV) out to > 100 GeV energies where the spectrum might be significantly affected by EBL absorption, depending on redshift. The significant overlap with

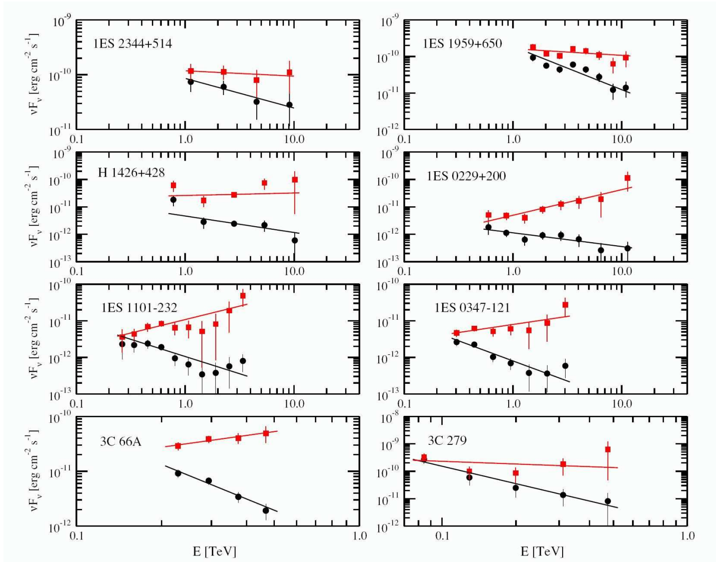

Figure 6: VHE gamma-ray spectra of eight blazars at various redshifts, corrected for EBL absorption using the model of Finke et al. (2010).

Fermi-LAT will then also allow for a more reliable cross-calibration between LAT and ground-based ACTs. Given the often very moderate variability of the gamma-ray spectral indices of many LAT-detected blazars (Abdo et al., 2010b), the cross-calibration with CTA might then allow for the construction of reliable, truly simultaneous gamma-ray SEDs through the LAT and VHE gamma-ray energy ranges. Simultaneous multiwavelength data sets at lower wavelengths may then be used to constrain SED models for a meaningful study of EBL absorption effects at the highest energies.

4. The physics of extragalactic jets

Active galactic nuclei are thought to be systems that are powered by the release of gravitational energy. How, where and in which form this energy is released, and especially the physics governing to the formation, acceleration and collimation of relativistic jets and the conversion of jet power into radiative power is poorly understood (for a review of the current status of the field, see, e.g., Böttcher, Harris & Krawczynski, 2012). The observed links (see §1) between enhanced emission at high photon energies and changes in the polarization properties in the emission region may indicate an important impact of the magnetic field topology and strength on the broadband spectral variability behaviour of jetted AGN and possibly on the intrinsic acceleration of jet knots (e.g., by magnetic driving: Vlahakis & Königl, 2004). As we will outline below, studies of the SEDs and variability of blazars with CTA, *Fermi*-LAT, and co-ordinated observations at lower frequencies will be crucial to gain insight into these issues.

4.1. Radiative processes in extragalactic jets

Depending on the jet's relativistic matter composition two types of emission models have emerged during the last decade. *Leptonic* models consider relativistic electrons and positrons as the dominating emitting relativistic particle population, while in *hadronic*[10] emission models the relativistic jet material is composed of relativistic protons and electrons (for a recent review of blazar emission models, see Böttcher, 2010; Reimer, 2011). In both scenarios, cold (i.e., non-relativistic) pairs and/or protons may exist as well, allowing charge neutrality to be fulfilled. There is meanwhile mounting evidence that jets of powerful AGN have to be energetically and dynamically dominated by protons and/or ions (see e.g., Celotti & Ghisellini, 2008), albeit little is known about their spectral distribution (cold, relativistic) and number density with respect to the electrons.

In both leptonic and hadronic models, the low-frequency emission is produced as synchrotron radiation of relativistic electrons in magnetic fields in the emission region, which is moving with relativistic speed corresponding to a bulk Lorentz factor Γ along the jet. For ease of computation, the magnetic field is typically assumed to be tangled (i.e., randomly oriented), and the electron distribution is assumed to be isotropic in the co-moving frame of the emission region.

In leptonic models, the high-energy emission is produced via Compton upscattering of soft photons off the same ultrarelativistic electrons which are producing the synchrotron emission. Both the synchrotron photons produced within the jet (the SSC process: Marscher & Gear, 1985; Maraschi et al., 1992; Bloom & Marscher, 1996), and external photons (the EC process) can serve as target photons for Compton scattering. Possible sources of external seed photons include the accretion disk radiation (e.g., Dermer et al., 1992; Dermer & Schlickeiser, 1993), reprocessed optical – UV emission from circumnuclear material (e.g., the BLR: Sikora et al., 1994; Dermer

[10]So-called *lepto-hadronic emission models* follow the same physics as *hadronic emission models*.

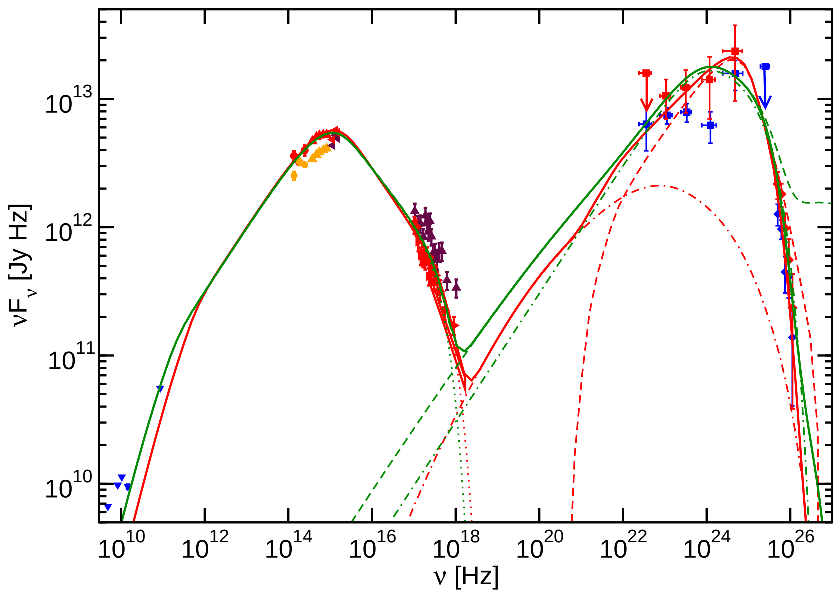

Figure 7: Spectral Energy Distribution of the intermediate BL Lac Object 3C66A during its bright gamma-ray flare in 2008 October (from Abdo et al., 2011a). Red = leptonic SSC + EC fit; green = hadronic model fit.

et al., 1997), infrared emission from warm dust (Błażejowski et al., 2000), or synchrotron emission from other (faster/slower) regions of the jet itself (Georganopoulos & Kazanas, 2003; Ghisellini & Tavecchio, 2008).

Relativistic Doppler boosting allows one to choose model parameters in a way that the $\gamma\gamma$ absorption opacity of the emission region is low throughout most of the high-energy spectrum (i.e., low compactness). However, at the highest photon energies, this effect may make a non-negligible contribution to the formation of the emerging spectrum (Aharonian et al., 2008) and reprocess some of the radiated power to lower frequencies. The resulting VHE gamma-ray cut-off or spectral break, and associated MeV – GeV emission features may be revealed by high-resolution, simultaneous Fermi and CTA observations.

Hadronic models consider a significant ultra-relativistic proton component in addition to primary ultrarelativistic electrons, to be present in the AGN jet. The charged particles interact with magnetic and photon fields. In heavy jet models the interaction of protons/ions with matter may dominate (Pohl & Schlickeiser, 2000). Particle-photon interaction processes in hadronic models include photomeson production, Bethe-Heitler pair production for protons, and inverse Compton scattering of pairs. An inevitable by-product of hadronic interactions is the production of neutrinos. The target photon fields for such processes include internal jet synchrotron photon fields (Mannheim & Biermann, 1992; Mücke & Protheroe, 2001; Mücke et al., 2003), and fields external to the jet such as direct accretion disk radiation (Bednarek & Protheroe, 1999), jet or accretion disk radiation reprocessed in the BLR (Atoyan & Dermer, 2003), or infrared radiation by warm dust. The secondary particles and photons from interactions of ultrarelativistic hadrons in general initiate synchrotron and/or Compton-supported pair cascades which redistribute the power from very high to lower energies (e.g., Mücke et al., 2003). For high magnetic field strengths, any IC component is in general strongly suppressed, leaving the proton-initiated radiation as the dominating high energy emission component.

Figure 7 compares a steady-state leptonic (SSC & EC) fit to a corresponding hadronic fit of the SED of the IBL 3C66A detected in VHE gamma-rays by VERITAS in 2008 (Acciari et al., 2009; Abdo et al., 2011a). Both leptonic and hadronic models provide excellent fits to the simultaneous SEDs obtained during the prominent 2008 October gamma-ray flare, with plausible physical parameters.

Because hadronic interactions convert some protons into neutrons[11] via charge exchange, collimated neutron beams may form (Eichler & Wiita, 1978; Atoyan & Dermer, 2003) which can transport a significant portion of the initial energy to large distances from the black hole. When such powerful jets interact with the intergalactic medium, large amounts of their power and momentum are expected to be deposited into the surroundings as huge lobes. The good angular resolution of CTA may permit the imaging of such extended emission, and will provide valuable information about the total power stored in jets, which in turn may constrain jet formation scenarios and jet composition.

Because of the suppression of the Compton cross section in the Klein-Nishina regime[12] and efficient radiative (synchrotron + Compton) cooling, leptonic models are typically hard-pressed to explain hard (energy spectral index $\alpha \lesssim 1$, where $F_\nu \propto \nu^{-\alpha}$) gamma-ray spectra extending to $E \gtrsim 1$ TeV

[11]e.g., in hadronic pγ-interactions 30 % – 70 % of the initial protons are converted into neutrons (Mücke et al., 2000)

[12]$\epsilon\gamma \gtrsim 1$, where $\epsilon = h\nu/[m_e c^2]$ is the dimenionless photon energy and gamma the electron Lorentz factor

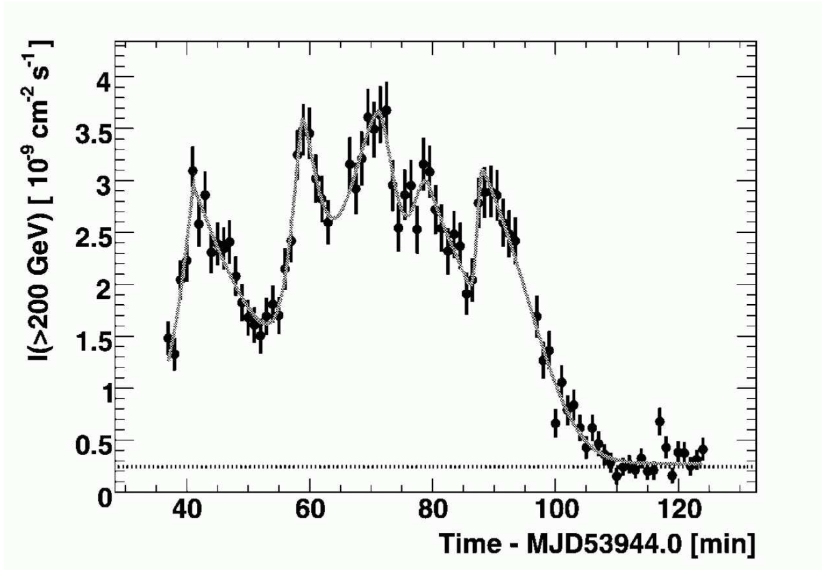

Figure 8: Rapid VHE gamma-ray variability of the HBL PKS 2155-304 observed by H.E.S.S. in 2006 (Aharonian et al., 2007).

after correction for $\gamma\gamma$ absorption by the Extragalactic Background Light (e.g., Aharonian et al., 2006). Detailed spectral measurements in the GeV – TeV regime through simultaneous observations by *Fermi*-LAT and CTA are expected to reveal the signatures of radiative cooling of leptons and/or Klein-Nishina effects in leptonic models, or of proton-synchrotron emission and ultra-high-energy induced pair cascades in hadronic models. These might therefore distinguish betwen leptonic and hadronic models.

Simultaneous multi-wavelength coverage will be crucial to put meaningful constraints on models. In this context, e.g., Böttcher et al. (2009) have demonstrated that the extension of the gamma-ray emission of the FSRQ 3C 279 into the VHE regime (Albert et al., 2008) poses severe problems for homogeneous, leptonic one-zone models, and may favor hadronic models, or multi-zone models. The lowered energy threshold of CTA compared to current ACTs promises the detection of VHE gamma-ray emission from a larger number of low-frequency peaked blazars (including FSRQs), which will allow for similar studies on a larger sample of LSP blazars.

The radiative cooling time scales are generally expected to be much shorter for leptons than hadrons. Therefore, measurements of rapid variability (e.g., Aharonian et al., 2007; Albert et al., 2007a, see also Figure 8) might be an indication for a leptonic origin of (at least parts of) the gamma-ray emission from blazars exhibiting variability on sub-hour time scales. Variability on minutes time scale has been observed at VHEs from few blazars both of HSP and LSP type (e.g., PKS 2155-304 (Aharonian et al., 2007), Mkn 501 (Albert et al., 2007a), PKS 1222+216 (Aleksic et al., 2011)) so far. This implies extremely large bulk Doppler factors if interpreted within a homogeneous emission model, or TeV emitting sub-structures within the jet such as filaments, reconnection zones (Giannios et al., 2009), etc. For example, the spine-sheath picture (Ghisellini et al., 2005) of a jet envisions an ultra-fast spine surrounded by a slower sheath. If the jet points almost towards the observer, radiation from the strongly beamed fast spine dominates the observed spectrum, while the radiation from the sheath contributes only weakly. In AGN where the jet is more inclined to the sight line the spine appears as a dim source while the radiation from the slower sheath becomes dominant. In order to test this behaviour a larger sample of rapidly varying sources, both blazars and radio galaxies, at VHEs is required. With current technology, only the brightest of such sources can be detected, and only in extreme flaring states. The increased sensitivity of CTA compared to present-generation ACT facilities will allow for the extension of the study of rapid gamma-ray variability to a large sample of sources and to more quiescent states. Variability information in addition to high resolution spectra is particularly important for unambiguously constraining the parameter space im emission models since in many cases (see, e.g., Figure 7), pure snap-shot SED modeling is unable to distinguish between a leptonic and a hadronic origin of the gamma-ray emission.

4.2. Probing particle acceleration using CTA

Both the SED shape and multi-wavelength variability patterns in blazar emission can provide constraints on the mode of particle acceleration in the jets of AGN. The shape of the high-energy end of the particle spectrum — which will be directly reflected in the shape of the high-energy end of the gamma-ray emission — will provide valuable information about the competition between radiative (and possibly adiabatic) losses, escape, and energy gain at those energies (e.g., Protheroe & Stanev, 1999). The decreased energy threshold and improved sensitivity of CTA over current ACTs will enable detailed studies of the shape of the high-energy cut-offs of blazar spectra (including LSP blazars) and, in particular, trace the cutoff in sources not yet detected at VHEs.

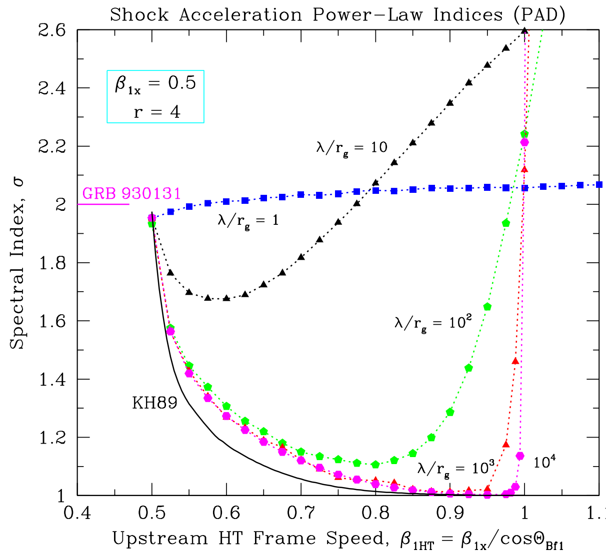

Figure 9: Dependence of the relativistic, non-thermal particle spectral index σ on the obliqueness and particle mean-free-path λ for pitch-angle scattering on magnetic turbulence. From Baring (2009).

Different particle acceleration scenarios (e.g., diffusive shock acceleration at relativistic shocks, first-order Fermi acceleration, perpendicular vs. oblique shocks, diffusive acceleration in shear layers) and different magnetic field topologies predict characteristically different spectral indices in the resulting particle spectra (e.g., Ostrowski & Bednarz, 2002; Stawarz & Ostrowski, 2002; Ellison & Double, 2004; Stecker et al., 2007, see also Figure 9). These will be directly reflected in the spectral indices of the non-thermal synchrotron and gamma-ray emission of blazars. Simultaneous multiwavelength observations, including at the highest energies, will be helpful to probe potential mis-matches between the low-energy (synchrotron) and high-energy (gamma-ray) SEDs. In leptonic models, such spectral-index mis-matches typically require multi-component gamma-ray emission scenarios, if they can be re-conciled with these models at all. In hadronic moels, they might be explained through different acceleration modes (and hence, different particle spectral indices) for electrons and protons.

In addition to simultaneous snap-shot SEDs, spectral variability can provide crucial insight into the particle acceleration and cooling mechanisms in AGN jets (e.g., Kirk et al., 1998; Chiaberge & Ghisellini, 1999; Li & Kusunose, 2000; Böttcher & Chiang, 2002). Detailed measurements of spectral variability have so far been restricted to lower-energy observations (e.g., X-rays: Takahashi et al., 1996), or to the brightest gamma-ray AGN only (e.g., 3C 454.3 at LAT-energies: Abdo et al., 2011b). The improved sensitivity of CTA in the > 100 GeV regime might enable the study of precision spectral variability and persistent long-term variability patterns in this energy range for a large sample of sources. In particular, this will provide a probe of the dynamics of the highest-energy particles in LSP blazars in which the high-energy end of the synchrotron component is often not observationally accessible because it is (a) located in the UV / soft X-ray regime, which is notoriously difficult to observe, and (b) overlapping with (and often overwhelmed by) the low-energy end of the high-energy emission.

5. Concluding Remarks

This surely incomplete list of topics discussed above reveals the potential of CTA for significant progress in the field of AGN research. Improvements in sensitivity and energy coverage will allow for the study of a much larger population of AGN. This will enable to tackle a large range of topics from population studies and questions of cosmological evolution of AGN via studies of the formation and composition of extragalactic jets and the microphysics of the production of high energy emission in relativistic jets, to studies of the Extragalactic Background Light, which will shed light on the broader issues of cosmological galaxy evolution and structure formation. Most exciting, as CTA will enlarge the dynamical flux range and explore the high-redshift universe at VHEs, unexpected, possibly surprising, phenomena may challenge current theoretical concepts, and trigger to deepen our understanding of the extragalactic sky. This review might provide some insight into possible ways that observations by CTA — coordinated with simultaneous observations at other wavelengths — might lead to progress in the study of some of the most pressing questions of the VHE sky.

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