Mem. S.A.It. Vol. 83, 138

Memorie della

AGNs in the VHE gamma-ray era: a review

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Abstract. The last decade has been a "silver age" for the study of AGN at Very High Energies (VHE, ≥100 GeV), made possible by a new generation of atmospheric Cherenkov Telescopes and now by Fermi at High Energies (~0.1-100 GeV). Important progresses were achieved in three main areas: the solution of the EBL problem, the X-ray/TeV connection, and the location and size of the gamma-ray emitting regions. The results are revealing that we still miss some fundamental aspect of the jet emission in AGN.

Key words. X-ray: blazars – Gamma-rays: theory – Radiation mechanism: non-thermal

1. Introduction

The new generation of atmospheric Cherenkov Telescopes (CT) like HESS, MAGIC, VERITAS, has dramatically improved the study of radio-loud AGN, in particular those whose jet is pointing close to the line of sight: the blazars. Blazars come in many flavours but can be classified according to two main "axes" of properties: 1) the jet not-thermal emission (energy and luminosity of the two SED humps); and 2) the thermal properties of the circumnuclear environment (accretion rate, disk luminosity, intensity of broad emission lines in their optical-UV spectra and of infrared emission from heated dust in the dusty torus). On this plane, blazars tend to form a continuous sequence, from high-energy-peaked BL Lacs (HBL) to intermediate (IBL), to low-energy-peaked BL Lacs (LBL) and Flat Spectrum Radio Quasars (FSRQ). HBL in general show low luminosity and low Compton dominance (i.e. ratio of the gamma-ray to synchrotron peak luminosity), absence or very weak emission lines, low accretion rates and radiatively inefficient accretion disks. FSRQ are instead the most luminous AGN objects, with strong disk and broad-lines emission, IR emission from hot dust (HD) and high accretion rates (for details, refs and emission models, see e.g. Ghisellini & Tavecchio 2008b).

CT observations found that almost all types of blazars can emit significantly at VHE. However, while the VHE detection of IBL objects corresponded to the expectations of standard synchrotron-self-Compton (SSC) modeling (e.g. Albert et al. 2007), new and surprising insights have come from HBL and FSRQ. Here I focus on the three main issues where most progress was obtained: 1) the solution of the EBL problem, 2) the X-ray/TeV connection and 3) location and size of the gamma-ray emitting region (so-called "blazar-zone").

2. Solution of the EBL problem

Gamma-rays from extragalactic sources are subject to an effective "absorption" caused by

Send offprint requests to: L. Costamante the process of photon-photon collision and pair production with the diffuse Extragalactic Background Light (EBL). At VHE, this absorption is determined by photons in the Optical-NIR band, and since the optical depth increases with energy, EBL absorption causes an effective steepening of the observed spectrum with respect to the intrinsic one (photon index $\Gamma > \Gamma_{int}$). Until 2005, the study of the gamma-rays from blazars or any other extragalactic object was affected by a fundamental ambiguity, caused by the poor knowledge of the EBL intensity and spectrum. The EBL uncertainty was up to a factor of $\sim$10 between 1 and 3 μm, from the lower limits given by the integrated light of resolved galaxies (Madau & Pozzetti 2000) to a possible high flux claimed from direct measurements, and tentatively interpreted as redshifted UV light from heavy Population-III star formation at z$\sim$10 (Santos et al. 2002). Therefore, it was not possible to assess the intrinsic VHE spectrum of a source with sufficient accuracy: almost any observed spectrum could be the result either of an intrinsic soft spectrum little absorbed by a low EBL level, or of an intrinsic hard spectrum heavily absorbed by a high EBL level (see Fig. 1). This resulted in completely different gamma-ray peak energy and luminosity in a blazars' SED. At the same time, however, as cosmological beamers of TeV gamma-rays, blazars provided an alternative way to probe the EBL (see e.g. Costamante et al. 2004), independently from direct measurements which are affected by large systematic uncertainties due to the bright foregrounds (Hauser & Dwek 2001).

The breakthrough was achieved in 2005 with the HESS measurements of two distant HBL, 1ES 1101-232 (z=0.186) and H 2356-309 (z=0.165). The unexpectedly hard spectrum for their redshift leaves only a low EBL level as reasonable solution, since a very high EBL would mean extremely hard intrinsic spectra ($\Gamma \leq 0$), at odds with all known blazar physics and phenomenology so far (Fig. 2). With the assumption of a non-exotic blazar spectrum (photon index $\Gamma_{int} \geq 1.5$), the EBL around 1-2 μm could be constrained within 1/3 of the lower limits from galaxy counts

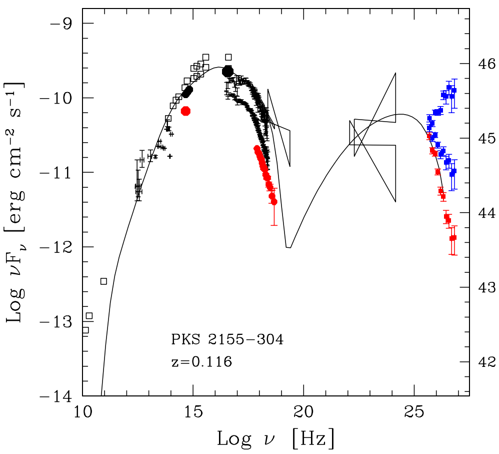

Fig. 1. Historical SED of PKS 2155-304 with the HESS VHE data (Aharonian et al. 2005, red) corrected for EBL absorption with different EBL levels (blue points).

(Aharonian et al. 2006). A similar conclusion was reached also in the near-IR range between 2 and 10 μm, thanks to the HESS spectrum of 1ES 0229+200 (z=0.130) up to $\sim$10 TeV (Aharonian et al. 2007d). With the constraint given by the just-obtained upper limits around 1-2 μm, the hardness of the 1ES 0229+200 spectrum implied that the slope of the EBL should be close to λ^{-1}, thus constraining again the EBL close to the lower limits given by Spitzer galaxy counts. These new data confirmed in a compelling way the previous indication from the multi-TeV spectrum of 1ES 1426+428 obtained by HEGRA (Aharonian et al. 2003).

The result of a low EBL intensity had three fundamental consequences: 1) it solved the fundamental cosmological issue of the origin of the EBL. At these wavelengths (1-8 μm), it seems to be strongly dominated by the direct starlight from normal galaxies, excluding a large contribution from other possible sources (in particular from the first stars formed); 2) it showed that the intergalactic space is more transparent to γ-rays than previously thought, enlarging the gamma-ray horizon; 3) it strongly reduced the ambiguity on blazars VHE spectra (to a $\Delta\Gamma \lesssim 0.2$ within z 0.2-0.3), finally allowing the proper study of their SED features. This result has been later corrobo-

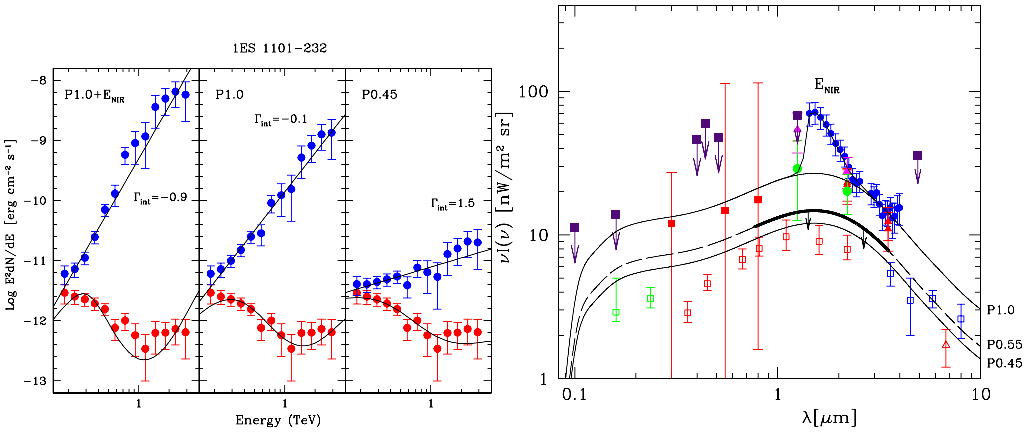

Fig. 2. Left: HESS spectrum of 1ES 1101-232 (red data) corrected for EBL absorption (blue data) with different EBL curves, as shown on the right. Right: SED of the EBL, showing estimates from direct measurements (filled points) and lower limits from galaxy counts (open symbols). From Aharonian et al. (2006).

rated by several other observations and sources (e.g. Aharonian et al. (2007b); Aharonian et al. (2007c); Acciari et al. (2009); Albert et al. (2008)). It is worth to note that all new VHE detections and spectra measured so far are all consistent and explainable with a low level of the EBL and standard blazar physics ($\Gamma \gtrsim 1.5$). There is no need (yet) to invoke any new physics or exotic scenarios to account for the data, and it is also easily possible and expected to detect blazars up to ~300 GeV even at z=1, since their optical depths would be comparable with those of 1ES 0229+200 up to 10 TeV. (Costamante 2007; Franceschini et al. 2008)

With the EBL constraints obtained so far, being already very close to the lower limits, no further significant improvement can be expected from blazars, even with more sensitive telescopes like CTA. The unavoidable systematic limit is represented by the insufficient knowledge of blazars' physics at the required accuracy levels. On the other hand, the real progress from CTA is expected precisely on our knowledge of blazars, by testing the validity of the aforementioned spectral assumptions and searching for possible counterexamples (i.e. blazars with intrinsic $\Gamma_{\rm VHE} < 1.5$ even with the lowest EBL; see e.g. Costamante 2007). Better constraints with CTA will instead be possible in the UV and far-IR branches of the EBL spectrum, as allowed by the much larger sensitivity of CTA at low (<100 GeV) and high (≥10 TeV) gamma-ray energies [1].

2.1. Discovery of the Hard TeV BLLacs

The same sources that allowed such strong constraints on the the EBL represent a new type of HBL with challenging SED properties, precisely for the same spectral feature: their hard TeV spectrum. Even with an EBL intensity as low as the lower limits, their intrinsic VHE spectra are hard ($\Gamma < 2$). Their gamma-ray peak, therefore, must be located above the measured VHE band, at energies greater than ~3-10 TeV. Such hard spectra ($\Gamma \sim 1.5$-1.6) and high peak energies are difficult to explain in a standard one-zone SSC model, because of the decrease of the scattering efficiency in the Klein-Nishina regime and of the energy density of the seed photons available for scatterings in the Thomson regime. Both these effects tend to steepen the emitted γ-ray spectrum at VHE. Many different scenarios have been proposed for these objects, from a low energy cut-off in the electron distribution at very high energies (Katarzynski et al. 2006) to internal γ-γ absorption on a Planckian radiation

[1] The best constraints on the EBL beyond 10 μm are still given by the HEGRA spectrum of Mkn 501, see e.g. Aharonian et al. 2001

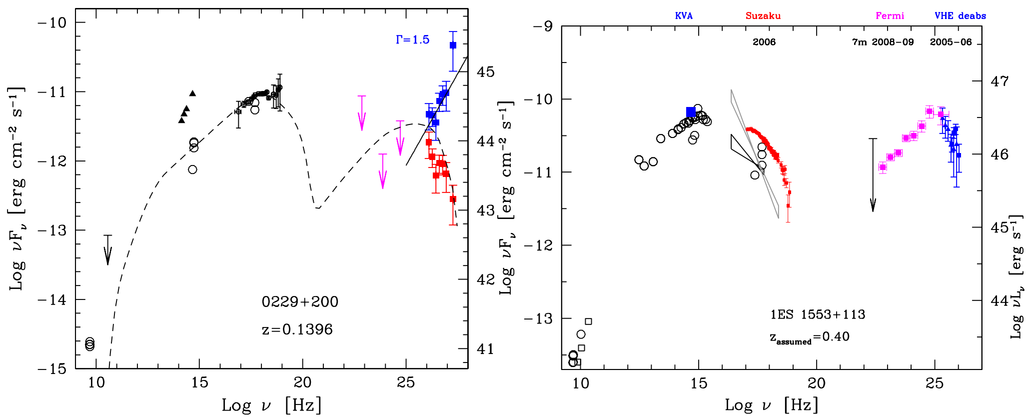

Fig. 3. Examples of SED of two different types of HBL. Left: 1ES 0229+200, the prototypical case of TeV-peaked BL Lacs (TBLs). Right: a classic case of HBL brigth in Fermi, with the gamma-ray peak around 1-200 GeV (GBL). All VHE data deabsorbed with the EBL calculations by Franceschini et al. (2008). Data from Costamante et al. (2002); Tavecchio et al. (2009); Reimer et al. (2008); Abdo et al. (2010).

field (Aharonian et al. 2008). However, none seems fully satisfactory, due to the very ad-hoc conditions and often extreme parameters required (extremely low radiative efficiency, B<mG). Even creating a very hard initial electron distributions, the main problem of leptonic scenarios is how to avoid or compensate for the strong radiative losses which steepen the VHE spectra (e.g. see discussion in Lefa et al. 2011). These objects represent today one of the major challenges for the conventional scenarios of the acceleration and emission processes, and where new insights can be gained.

From the first discoveries with HESS, there are now several objects of this type, constituting a new class of HBL which can be called "TeV-peaked" HBL (or TBL). Most of the known HBL detected so far at VHE show instead a more conventional SED with a gamma-ray peak around 1-300 GeV, and thus can be called "100 GeV-peaked" HBL, or GBL (see Fig. 3). These are more easily and commonly explained with standard SSC models. Note that the large majority of HBL bright in Fermi are of the latter type, GBL, while the TeV-peaked ones are weakly or not detected by FERMI even after 2 years of exposure. The reason is very simple, and is consistent with their VHE spectra: for GBLs, the Fermi energy band is close to (or encompass) the gamma-ray peak, while for TBLs it is deep in the valley between synchrotron and IC peaks. Indeed, the Fermi detections or upper limits confirm the remarkable hardness of their gamma-ray spectrum over several decades in energy.

3. The X-ray/TeV connection

Simultaneous observations in the X-ray and VHE bands represent a powerful diagnostic tool, since in HBLs they can track the emission from the same population of relativistic electrons through two different processes, synchrotron and inverse Compton (Coppi & Aharonian 1999). The idea that one single electron population is at the origin of the two humps in blazars' SED was corroborated by strong observational evidences during major flares, for example in Mkn 501 in 1997, Mkn 421 in several campaigns, 1ES 1959+650 in 2002. Tightly correlated flux variations were observed in the two bands, even down to sub-hour timescales with no evidence of significant lags (e.g. Maraschi et al. 1999; Fossati et al. 2008). However, recent campaigns are revealing a more complex and puzzling behaviour.

3.1. *Acceleration mechanism: flaring vs quiescent states*

While during major flares the two emissions are highly correlated, things become more

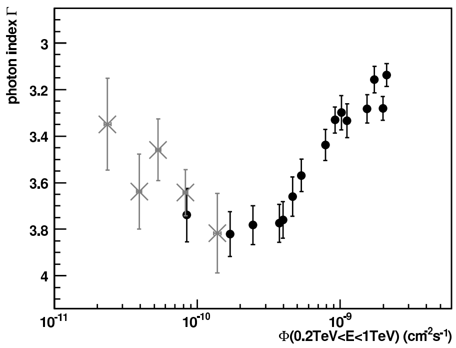

Fig. 4. Spectral index–flux relation at VHE for PKS 2155-304. Grey data correspond to the quiescent epoch 2005-2007, while black data to the activity in July 2006. From Abramowski et al. (2010).

murky during quiescent or less active periods. For example, in the two year following the correlated flare activity in 1997, Mkn 501 at lower flux level showed occasional or no correlation (Gliozzi et al. 2006).

Quite interestingly, a similar behaviour is seen for the X-ray fractional variability: it is generally increasing with energy (corresponding to a harder-when-brighter behaviour), but at low flux levels it can become decreasing with energy (as in July 1997, Gliozzi et al. 2006). That something different is happening in quiescent vs active states is also shown by the different flux-index patterns of PKS 2155-304 at VHE (Fig. 4). Different correlations can also be caused by the VHE and X-ray bands corresponding to different branches of the single electron population, as it was shown for eaxample by the first simultaneous Fermi-HESS campaign on PKS 2155-304, where the VHE emission seems to correlate better with the Optical band (Aharonian et al. 2009b). However, there is also evidence that different acceleration processes might be at work between low/quiescent and high/active states. For example, the synchrotron spectrum of Mkn 421 in 2006, compared to the state in 2005, change dramatically from a log-parabola shape to a pure powerlaw over four decades in energy in the high state, with a peak seemingly above 50-100 keV (Tramacere et al. 2009).

3.2. Flaring behaviours

Three main results are revealing a more complex structure of the jet emission regions than envisaged by one-zone SSC scenarios. The first is that X-ray and VHE emissions, even during major flares, do not always correlate. The most striking example was provided by 1ES 1959+650 in 2002, when a strong (>4 Crab) and rapid TeV flare (7 hours of doubling timescale) was not accompanied by any detectable variations in the RXTE band (Krawczynski et al. 2004). These so-called "orphan" flares are not explained by simple one-zone SSC scenarios, though the sparse sampling does not allow the exclusion of lagged counterparts or counterparts emerging in different energy bands. The second result was obtained from a dense X-ray/TeV campaign in 2001 on Mkn 421 (Fossati et al. 2008). A quadratic relation between VHE and X-ray flux variations was observed during both the rising *and decaying* phases of a flare. This is not expected when a source like Mkn 421 is in the Klein-Nishina (KN) regime, i.e. if TeV electrons do not upscatter their own self-produced synchrotron photons but lower-energy photons produced by lower-energy electrons. Since higher-energy electrons cool faster than lower-energy electrons, they continue to see a roughly constant seed-photon energy density, resulting mostly in a linear decrease.

The third and most surprising result came from a multiwavelength campaign on PKS 2155-304 in July 2006, during a giant flare observed simultaneously with HESS, Chandra and Bromberg optical observatory (Aharonian et al. 2009). While confirming that the X-ray and VHE emission were highly correlated, both in spectrum (extracted down to 7 minutes in both bands) and flux (with a 95% upper limit on lags of 200s), the object showed for the first time in an HBL a high Compton dominance (~10) and a *cubic* relation between VHE and X-ray fluxes in the decaying phase (Fig. 5). With the observed SED, the decay cannot be explained by radiative cooling, nor by adiabatic expansion. The cubic relation would require the magnetic energy

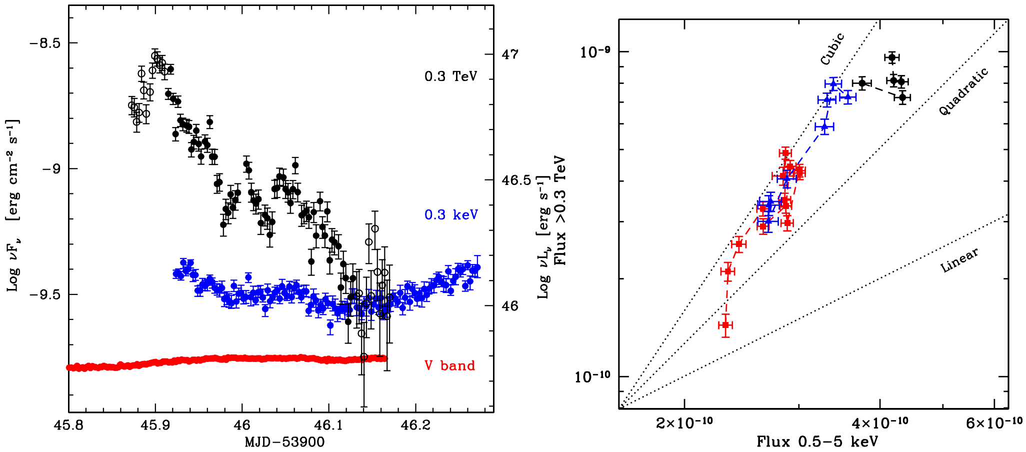

Fig. 5. Multifrequency campaign on PKS 2155-304 on July 29-30, 2006. Left: lightcurve of the monochromatic fluxes in three energy bands, as labelled. Right: plot of the gamma-ray vs X-ray flux variations (in time sequence: black, blue, red), following a cubic relation. From Aharonian et al. (2009).

to increase substantially (as $W_B \propto R^{+3.8}$), and on the same timescales of the VHE variations. This would yield fast correlated variations in the optical band and a decrease by ∼15%, not seen in the optical synchrotron emission.

A simpler explanation is provided by the superposition of two SEDs, produced by two different emitting zones: a flaring one and another responsible for the "persistent", historical SED. The true variations of the flaring X-ray emission are then seen *diluted* in the "persistent" component, which have comparable or higher synchrotron fluxes but much lower inverse Compton fluxes (as measured during the previous 3 years). At VHE, therefore, the variations are seen undiluted. According if the X-ray/VHE relation of this new component is quadratic or linear, the emission must either come from a very compact region –of the order of the Schwarzschild radius of the central black hole (BH)– or be produced by Comptonization of ambient photon fields, as expected in structured jets with a strong radiative interplay between different parts (Aharonian et al. 2009).

Irrespective of the interpretation, the novelty of this event is that the bulk of the luminosity of the flare is now emitted in the Compton channel instead of the synchrotron channel. In all previous major flares (e.g. Mkn 421 in 2000, Mkn 501 in 1997, 1ES 1959+650 in 2002), the Compton luminosity even at the flare maximum was always equal to or less than the synchrotron power (using the same EBL model). A bimodality seems to emerge in the mode of flaring for HBL.

4. Size and location of the gamma-ray emitting region

The location of the "blazar zone", i.e. the zone where the bulk of the SED luminosity is emitted, is still highly uncertain. Since EGRET times, we know that at least in FSRQ the emitting zone cannot be too close to the nuclear regions, otherwise the reprocessing of the pairs produced by γ-γ collisions with the disk photons would yield X-ray spectra much softer than observed (Ghisellini & Madau 1996). On the other hand, this constrain does not hold for HBL, which seem characterized by a radiatively inefficient accretion disk and weak or absent broad-lines luminosities. Quite interestingly, the present data provide indications of opposite sign for HBL and FSRQ, i.e. very close and very far from the BH, respectively.

4.1. Ultrafast variability in HBL/FR-I

At VHE, PKS 2155-304 (Aharonian et al. 2007a) and Mkn 501 (Albert et al. 2007b) showed an extremely fast variability, with doubling timescales as short as 2-3 minutes.

Particularly important is the case of PKS 2155-304, since such fast variations were characterized by large-amplitude (factor 10x within 1 hour) and a luminosity dominating the source power ($\sim 10^{47}$ erg/s). Causality arguments indicate that the emitting region should be extremely compact, of the same order of (or even less than) the Schwarzchild radius of the putative BH ($R \sim 5 \times 10^{12} \delta$ cm $\approx 0.01 \delta R_S$, where δ ~50-100 is the beaming factor). Such fast and large-amplitude variability from small regions is challenging for conventional emitting models, and has been interpreted in new different ways, involving both EC and SSC mechanisms. For example, envisaging fast "needles" in a structured jet (Ghisellini & Tavecchio 2008a) or its "jet in a jet" variant for an overall Poynting-dominated jet (Giannios et al. 2009), or considering magneto-centrifugal acceleration of beams of particles to ultra-relativistic speeds and streaming along the B-field lines (Ghisellini et al. 2009).

Further indication for compact regions and also located very close to the BH is given by the VHE data on the radio-galaxy M87, which is considered an HBL with the jet seen at larger viewing angles ($\theta \sim 18 - 30$deg). The HESS observations found again very fast variability (Aharonian et al. 2006b), on timescales of 1-2 days corresponding to $R \sim 5 \times 10^{15} \delta$ cm $\approx 5 \delta R_S$ (with δ uncertain between <1 and a few). Though at first it was debated if the VHE emission could originate in the knot HST-1 instead of the nucleus, a recent multiwavelength campaign found correlation of strong VHE activity with uncommon radio-to-X-ray nuclear flares, pinpointing the origin of the gamma-rays very close to the BH ($< 50 R_S$), within the jet collimation region (Acciari et al. 2009).

Together, these results suggest that the blazar zone in HBL, at least for the fast flares, is very close to the black hole. It is also remarkable that the VHE spectrum of M87 during the flares is quite hard, with a power-law of $\Gamma = 2.22 \pm 0.15$ up to ~20 TeV. Both the spine-layer scenario and simple SSC modeling of the nuclear emission fail to account for such spectrum (Tavecchio & Ghisellini 2008), as well as the overall HE-VHE spectrum in quiescent states obtained with Fermi (Abdo et al. 2009).

4.2. The surprise of FSRQ at VHE

FSRQ are characterized by intense circumnuclear radiation fields of thermal origin, from the reprocessing of strong ionizing radiation from the accretion disk: by gas clumps orbiting in the so-called Broad Line Region (BLR, with main lines Lyα, CIV and MgII), and by hot dust (HD) in the pc-scale torus. The typical size of both regions seem to scale as $L_{disk}^{1/2}$ (yielding a roughly constant energy density), but at different distances for normalization (see e.g. Ghisellini & Tavecchio 2008b), about 10^{17}cm and 3×10^{18}cm respectively (for $L_{disk} = 10^{45}$ erg/s). These external fields are typically used as seed photons for the External Compton emission models (Sikora et al. 1994), and the location of the emitting region thus determines which field becomes dominant for the cooling of the electrons (Ghisellini & Tavecchio 2008b; Sikora et al. 2009). These same photons however represent targets for the process of γ-γ absorption. The resulting optical depths are very large if the gamma-rays are produced inside the BLR or HD regions, so to effectively suppress all gamma-ray emission around 100 GeV and 1 TeV respectively (at the peak of the γ-γ cross section). If the conventional scenario holds, therefore, FSRQ should not have VHE emission, and should show a cut-off in their HE spectra already from ~20 GeV (restframe), due to the shape of the γ-γ cross section.

The data are now telling a different story. The first indication that the emitting zone is likely beyond the BLR was given by the MAGIC detection of 3C279 (Albert et al. 2008), which would require unrealistic luminosities if well within the BLR (Costamante et al. 2008). The Fermi-LAT data on several FSRQ (with large enough statistics around 10 GeV) are now showing in several cases no evidence of BLR-induced cut-off in their GeV spectra, even in objects with strong disk emission and large BLR, constraining their dissipation region to be $> 0.5 - 1 \times 10^{18}$ cm (Costamante et al. 2011). The recent detection at VHE of the FSRQ 4C 21.35 (Aleksic et al. 2011) is a most puzzling case, because the VHE emission is also rapidly varying (10-minute timescale), corresponding to an emitting size of $R \sim 2.5 \times 10^{14} (\delta/10)$ cm. If the dissipation indeed occurred at the pc scale (to avoid the severe internal absorption by the BLR), it becomes necessary to explain how the bulk of the source luminosity during the flare can come from a region much more compact than the expected size of the jet at those scales.

5. Conclusions

The pinning-down of the EBL has finally enabled us to study the real properties of the AGN emission in gamma-rays. The new results, challenging several aspects of the standard scenarios, are clearly saying that we are still missing some fundamental, basic aspect of the blazar/AGN phenomenon.

6. Discussion

SERGIO COLAFRANCESCO: There are many evidences that all the high-Energy behaviour of blazars can be explained by a two-blob component model in which a second more compact and energetic blob is ejected and interacts along the pre-existing jet with the BLR region, thus releasing radiation (gamma to radio) and producing the fast variability and the observed TeV–X-ray–Optical correlations. This model is based on the VLBI radio observations of polarized blobs seen in many blazars.

Acknowledgements. I want to thank the organizers for their kind invitation, and my many colleagues in Heidelberg, Merate, Rome and Stanford for helpful discussions and support.

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