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The origin and emission mechanism of VHE (>100 GeV) emission from FSRQs

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Abstract. Flat Spectrum Radio Quasars, unlike BL Lac objects, are blazars that show prominent line-emission and strong thermal components associated with the accretion disk, the broad-line region (BLR), and/or the dusty torus. The low energy peak in the continuum is from synchrotron emission (of electrons), and the high energy peak is well explained by external-Compton emission. In these models the relativistic electrons in the jet up-scatter photons from the thermal photon fields up to GeV energies. Beyond a few tens of GeV such models predict cutoffs due to Klein-Nishina effect and internal absorption via pair production. While more than 300 FSRQs have been seen with *Fermi*-LAT (between 100 MeV−30 GeV), only three have been detected at VHE (Very High Energy, E > 100 GeV) with Cherenkov telescopes. The detection of VHE emission constrains the location of the blazar zone based on internal absorption estimates, but challenges the emission models that predict cutoffs. While a number of GeV flaring states (in various FSRQs) have been observed with Cherenkov telescopes only few have resulted in detection of a VHE signal. The broadband emission characteristics of VHE FSRQs (including the VHE-detected FSRQs) are studied and put in context to better understand their location and emission mechanism.

1 Introduction

Flat Spectrum Radio Quasars (FSRQs) are one of the two sub-classes of blazars that show strong line emission, have the synchrotron peak at low frequencies (infra-red to optical), and exhibit high Compton dominance[1]. Those FSRQs that are detected above 100 MeV, i.e., at γ-ray energies, have a steep spectrum (with the powerlaw photon index[2], $\Gamma \gtrsim 2.5$) at these energies, as compared to the BL Lacerate type objects (BL Lacs for short) [13].

The *Fermi*-LAT has published a sample of 353 FSRQs[3] in the HE range (100 MeV–30 GeV) [13], a number of which were also previously detected by the EGRET instrument on the CGRO satellite [8]. However, there are currently only 3 FSRQs detected in the VHE range (Very High Energy, E > 100 GeV). These are - PKS 1510−089, PKS 1222+21, and 3C 279 [2–4]. The non-thermal emission of FSRQs, as also in BL Lacs, extends over a very broad frequency range - from radio to γ-rays. FSRQs have a two peak structure, with the low frequency peak (generally accepted as synchrotron emission from relativistic electrons) at IR to optical frequencies and the high frequency peak in the 100s of MeV.

There are various reasons why a bright emission component from these sources in the VHE band is disfavored. The low peak-frequency of the synchrotron bump indicates that the electron population does not extend to very high energies hence cannot produce inverse-Compton emission up to VHE energies. This assumes that the high-frequency bump is dominated by inverse-Compton emission of a population of relativistic electrons. In the hadronic scenario, where relativistic protons are assumed to be responsible for the non-thermal emission in the high-energy bump, this argument is no longer valid. However, the extremely short time scale variability seen in the VHE emission of PKS 1222+21[3] suggest that in this case the emission is probably dominated by electrons. In the leptonic scenario, due to the large Compton dominance, the target photon field cannot be the synchrotron photons but should be from a source external to the blazar zone (the part of the blazar jet from where the bulk of the non-thermal emission is assumed to be produced from), presumably from the accretion disk emission, or the reprocessed emission from the BLR and/or the dusty torus [14, and references therein]. If the blazar zone is within the BLR region, in both the leptonic and hadronic cases, much of the VHE emission will suffer in-situ extinction due to pair-production ($\gamma_{VHE} + \gamma_{IR} \longrightarrow e^+e^-$) on the intense photon-fields from the BLR and the torus. Finally, since FSRQs are more numerous at higher redshifts, the VHE emission suffers higher extinction than BL Lacs due to the extragalactic background light (EBL).

The multi-wavelength (MWL) observations of the 3 VHE-detected FSRQs show that these are highly variable

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1. Compton dominance is defined as the ratio of the luminosity in the high energy component to the luminosity in the low-energy component.
2. The powerlaw spectral shape is defined as $\frac{dN}{dE} \propto E^{-\Gamma}$.
3. *Fermi*-LAT second source catalog, 2FGL.

in all frequencies, most notably in the HE band. Though this might be biased due to the fact that these objects were observed when they were flaring in *Fermi*-LAT and/or other bands. Nevertheless, the variability timescale and the detection of VHE emission suggests that the blazar zone must be compact and lie outside the BLR radius [e.g., see 15, among others]. PKS 1510−089 shows a complex variability pattern in the different bands. Since the *Fermi*-LAT and optical bands are sometimes correlated but at other times not, this suggests that there could be different origins for the different flares [10]. MWL SED models for *Fermi*-LAT FSRQs usually show an external-Compton (EC) component probably dominated by the scattering of BLR photons, i.e., the EC-BLR models [1], where the high energy component cuts off at a few 10s of GeV due to Klein-Nishina effect. In this scenario, rather large fluxes in the *Fermi*-LAT band are required to reproduce the VHE emission ([3, 6], among others).

The fact that VHE emission is not detected beyond ~ 500 GeV might indicate that there is a cutoff in the VHE spectrum [15, 16]. This could mean that the possible cutoff is due to absorption by the dusty torus photons, further constraining the location of the blazar zone. Though it should be mentioned that the flux upper-limits around 500 GeV are not very constraining in this respect.

In the following sections we give qualitative description of a leptonic model describing the MWL SED of the VHE-bright FSRQ, PKS 1510−089, followed by a discussion on the implication of this model (the details of the model are published in [5]), and present the future outlook with respect to understanding the VHE observations of FSRQs.

2 PKS 1510−089: A VHE-detected FSRQ

PKS 1510−089, an FSRQ at a relatively far $z = 0.36$, was discovered in the VHE band with the H.E.S.S. array of imaging atmospheric Cherenkov telescopes (IACTs) in 2009 [2], during a high state in the *Fermi*-LAT and optical bands. The VHE emission however did not show evidence of statistically significant variability. This source is very bright in the *Fermi*-LAT band and has presented a rich range of flares between 2008 and 2011. The variability index in *Fermi*-LAT is very high [13]. The MWL data during the H.E.S.S. observation has been published elsewhere (e.g. see [10])

2.1 Observational characteristics

This source has a distinct blue bump (evidence of a bright accretion disk) as well as a clear thermal components in the infra-red, attributed to the torus emission. The peak of the synchrotron component is at IR as seen from archival data. The *Fermi*-LAT spectrum has a photon index of around 2.5 [2]. It cannot be ruled out that the VHE spectrum and the *Fermi*-LAT spectrum are consistent with a single power law [2]. For the 2009 epoch when it was detected at VHE simultaneous data are available from *Fermi*-LAT, *Swift*, the optical band from the ATOM telescope, and the radio frequencies [5, and references therein]. While not much can be said about the location of the synchrotron peak during the H.E.S.S. detection in 2009, the high energy component peaked around 100 GeV.

2.2 SED modeling characteristics

MWL models describing the SED (sans the VHE data) have been published by a number of authors (e.g., see [12], and [9] for a pre-*Fermi*-LAT era SED model). Following the general prescription given in [11] (also used in [9]) we present an SED model of the data taken during 2009 (including the VHE emission) in [5].

As discussed in [12], due to Klein-Nishina suppression the BLR emission does not extend to the VHE band. Therefore we need to invoke EC from the dusty-torus emission. In [5] we have therefore taken an EC-DT component to describe the emission in the VHE band (see Figure 1, for a schematic representation of the SED model). Note that the *Fermi*-LAT band is still dominated by the EC-BLR component. To avoid internal absorption from the BLR the blazar zone was located at the outer edge of the BLR. The resulting SED model gives a good description of the simultaneous data and does not need to invoke unusual parameters for the blazar properties.

3 Discussion and Outlook

There are some interesting consequences of detecting VHE emission from FSRQs. On one hand the possibility of internal absorption constrains the location of the blazar zone to the outside the BLR. On the other hand the very short time scales seen in PKS 1222+214 imply a small region dominates the emission at these energies, challenging the general wisdom of the jet size at large distances implied for the BLR radius. Also rather large Doppler factors might be required for such scenarios. Moreover, the curvature seen in the *Fermi*-LAT spectra of PKS 1510−089 suggests that there might be some absorption from BLR for this component. In a low phase, [12] show that a two zone model is necessary to describe the SED, in particular the HE emission. An independent, detailed study of the light curves of PKS 1510−089 in [7] also comes to the conclusion that multiple emission zones seem to be necessary to explain the *Fermi*-LAT and VHE emission of PKS 1510−089.

If this is a general feature of VHE emission from FSRQs a number of interesting conclusions can be drawn. Firstly, the variability timescales would be modulated over long times (months to years) following the generally slow variation of the dusty torus emission. The fast variability (days or less) in the VHE for some FSRQs could then only be explained by either a change in the properties of the ultra-relativistic particle population, or a change in the photon field from external sources. The latter could be, for instance, a contribution from the extended jet emission. The multi-zone models scenario would imply that the *Fermi*-LAT and VHE emissions need not be correlated at

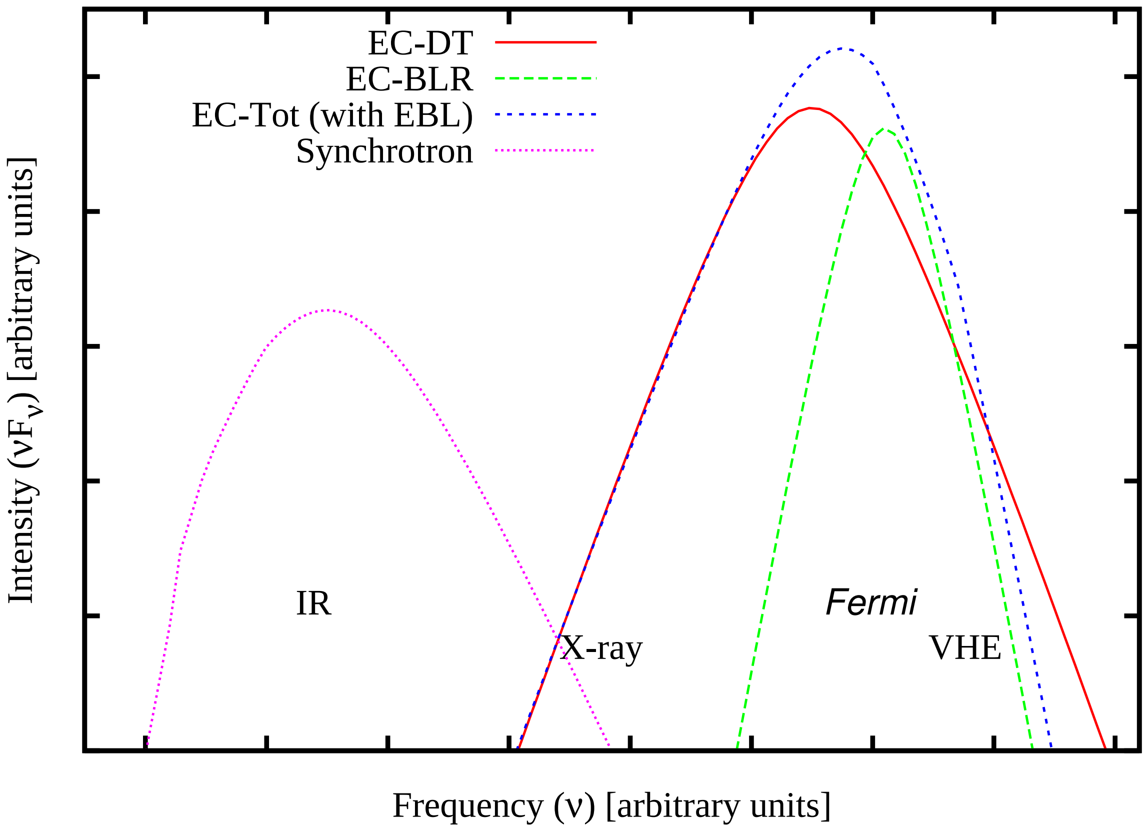

Figure 1. Schematic representation of the proposed leptonic SED-model for FSRQs showing the major non-thermal contributions. The magenta curve is the synchrotron component that is self absorbed in the radio. The EC-DT (red curve) is the external-Compton radiation up-scattering the infra-red photons from the dusty torus. While the EC-BLR (green curve) is the external-Compton radiation on the BLR photon field. The total EC emission is shown in blue, after taking EBL absorption into account.

all times. If VHE emission can be detected from an FSRQ while it is in a low *Fermi*-LATstate then certain models could be ruled out.

While it has proved difficult to detect many FSRQs with the current generation of IACTs, future experiments, such as the planned Cherenkov telescope array (CTA), which will have higher sensitivity, could enlarge the VHE FSRQ sample. Furthermore, with more MWL studies it is expected to be able to better explain the emission mechanism in these objects.

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