The new surprising behaviour of the two "prototype" blazars PKS 2155-304 and 3C 279

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Abstract. Recent VHE observations have unveiled a surprising behaviour in two well-known blazars at opposite sides of the blazar sequence. PKS 2155-304 have shown for the first time in an HBL a large Compton dominance, high γ-ray luminosities and a cubic relation between X-ray and VHE fluxes. 3C 279 is the first FSRQ detected at VHE. The high luminosity required to overcome the significant absorption caused by the BLR emission cannot be easily reconciled with the historical and quasi-simultaneous SED properties. Both cases shed a new light on the structure and ambient fields of blazars. Contrary to previous claims, it is also shown that 3C 279 –as any FSRQ– cannot in general provide robust constraints on the EBL.

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INTRODUCTION

At opposite sides in the blazar sequence [1], the well-known, bright blazars PKS 2155-304 and 3C 279 are prototypes of the two blazar classes of high-energy peaked BL Lac (HBL) and Flat spectrum radio quasars (FSRQ). PKS 2155-304 is a classic HBL, characterized by a spectral energy distribution (SED) peaking in the UV-X-ray and GeV-TeV bands, by the X-ray band dominated by synchrotron emission of high-energy electrons, by the absence (or very low intensity) of the Broad Line Region (BLR) emission (typical HBL upper limits at \( \lesssim 10^{41} \) erg/s), and by a Compton dominance \( L_C/L_S \lesssim 1 \). So far HBL have been successfully explained with a pure and homogeneous synchrotron self-Compton model (SSC, [2]), 3C 279 instead is a classic FSRQ, characterized by intense BLR emission (\( L_{BLR} \approx 2.4 \times 10^{44} \) erg/s), though FSRQ can reach \( 10^{46} \) erg/s), by a low-energy-peaked SED (with humps located at IR and MeV-GeV frequencies), by the X-ray band dominated by the inverse Compton (IC) emission of low-energy electrons, and by a very high Compton dominance (up to \( L_C/L_S \sim 100 \)). The redder SED and high Compton dominance have been successfully explained by Comptonization on the external BLR photons, which together with the higher synchrotron luminosity yield stronger cooling for the electrons [3,4].

Since several decades, these two blazars have been observed extensively in all wavebands, except at the highest energies. With the new generation of Cherenkov Telescopes, since 2002 the Very High Energy (\( \gtrsim 100 \) GeV) band started to be explored with sufficient sensitivity. At first these two objects followed the expectations for their class and related emission scenarios. But in 2006, both sources managed to surprise us with new, unprecedented behaviours, showing for the first time properties which were previously seen only in the opposite class. These properties now highlight a more complex role of the ambient fields and external Compton process in both types of sources, and provide us with a new level of insights on the jet structure and emission mechanisms in blazars.

THE NEW PKS 2155-304: COMPTON-DOMINATED HBL

In July-August 2006, PKS 2155-304 entered a phase of exceptional activity at VHE monitored by HESS and other observatories (for a full overview, see [6]). On the night of July 29-30, a simultaneous campaign with HESS, Chandra and the Bronberg optical observatory was performed, obtaining an unprecedented 6-8 hours of continuous coverage in the three bands [5]. Figure 1 shows the main results: the source showed one major flare along the night in all three energy ranges, but with very different variability amplitudes. For the first time, an HBL is characterized by a large Compton dominance (\( L_C/L_S \sim 8-10 \)) – which evolves in few hours to the more usual value of 1 – and shows a cubic relation between VHE and X-ray flux variations, during a decaying phase. The emission in the X-ray and VHE bands are highly correlated, both in flux and spectrum, while the optical lightcurve shows a flare which starts simultaneously with the VHE flare, but remains constant afterwards.

In a typical one-zone SSC model, it is difficult to account for a cubic correlation between synchrotron and IC emissions above the respective SED peaks and during a decaying phase. On one hand, the correlated variability (and flare on-set) does indicate that the emission in all bands likely originates from the same flaring event, and possibly same emitting region. On the other hand, even accepting a large bulk-motion Lorentz factor as implied by a one-zone analysis (e.g. as in [3]), yielding \( \Gamma \gtrsim 100 \) and \( B \lesssim 0.005 \) G) and to have the X-ray emission in the Thomson regime, at most a quadratic relation can
be explained [8]. A possibility is to invoke coincident, fast variations of the magnetic field B, but anti-correlated with the flux variations: namely B increases as the flux decreases. This would enhance the cooling of electrons through the synchrotron channel, further suppressing the VHE emission while at the same time “keeping up” (in part or totally) the X-ray synchrotron flux. However, such possibility seems excluded by the optical data: fast changes of B would lead to correlated variations of the synchrotron emission ($\propto B^2$) of the lower-energy electrons, which emit longward of the synchrotron peak and have not yet cooled (with the aforementioned one-zone parameters). This is contrary to observations: the optical flux remains almost constant in the affected interval.

A more viable explanation seems to be the superposition of two emitting zones. A steady one responsible for the usual “persistent” SED of PKS 2155-304 (peaking in the UV and with low VHE emission), and a second zone –more compact and with larger bulk motion– responsible for the flaring activity. The X-ray (i.e. synchrotron) variations of this second component can thus be as large as the VHE ones, but are simply seen “diluted” in the “persistent” SED, while they are fully visible in the VHE band [5]. A linear relation between VHE and X-ray fluxes means however that the SED of this new component must have a high Compton dominance ($\approx 20$) constant in time during the flare evolution. Such behaviour would point towards an origin of the $\gamma$-ray peak by external Compton rather than a pure SSC mechanism. Indeed, this is expected in scenarios with a strong radiative interplay between different parts of the jet[6, 10]. A two-zone scenario is common to explain major flares in blazars. However, so far all previous events that got extensive VHE sampling have shown flaring components which were synchrotron-dominated, often leading to dramatic shifts of the overall SED peak, as seen in Mkn 501 or 1ES 1959+650. The novelty of this event is that the bulk of the luminosity of an otherwise comparable flare ($\sim 10$ times the average source apparent luminosity) is now emitted in the Compton channel instead of the synchrotron channel. A bimodality seems thus to emerge in the mode of flaring for HBL: either synchrotron or Compton-dominated. More observations are needed to assess if this is only a rare event or a new common feature of the HBL class.

THE PUZZLE OF 3C 279: FIRST FSRQ DETECTED AT VHE

The MAGIC observation of 3C 279 ($z = 0.536$) in Feb. 2006 [12] marks the first detection at VHE of both a FSRQ and a source at $z \geq 0.5$. Contrary to what generally believed, however, the redshift is not the surprise and main aspect of this discovery. In past years, the VHE spectra of several HBL have already indicated that the Universe is more transparent to $\gamma$-rays than previously thought, with an EBL density close to the lower limits given by galaxy counts [15, 16]. As a consequence, it was immediately realized that sources as far as $z = 0.5 - 0.6$ can indeed be detectable around 100-300 GeV with the current-generation instruments, without requiring extreme flux states or modifications in fundamental laws of physics [17]. Specific targets were also proposed, and more detections are expected.

The main surprise is represented by the source being a FSRQ, namely an object with a) intense BLR emission ($L_{\text{BLR}} \approx 2.4 \times 10^{44}$ erg/s [3]), and b) a low-energy peaked SED (Fig. 2), implying few high-energy electrons available to sustain a strong VHE emission. This represents a problem because a high VHE luminosity is instead required to overcome both the extragalactic EBL absorption (high due to the large distance) and the strong internal absorption caused by $\gamma-\gamma$ collisions with the BLR photons. The BLR emission is peaked in the UV range (typically $\sim 9$ eV, rest-frame, around the most prominent lines HeII, Ly$\alpha$ and CIV). This is precisely the energy range where the $\gamma-\gamma \rightarrow e^+e^-$ cross section is maximum for 100-200 GeV photons. Adopting the line

![FIGURE 1. PKS 2155-304 activity on July 29-30. Left: lightcurve of the $\nu F_{\nu}$ flux at 0.3 TeV (EBL-corrected), 0.3 KeV and 5500Å, in 4-min bins. Center: VHE vs X-ray flux in 7-14 minute bins, in a log-log plot and same units (erg cm$^{-2}$ s$^{-1}$). Right: SED of the two highest and lowest states in the simultaneous X-ray/TeV/optical window, together with historical data (details in [5]).](image-url)
luminosity observed in 3C 279, a typical covering factor \(\sim 10\%\) and the observational relation between BLR size and disk luminosity \(R_{\text{BLR}} \propto L_{\text{disk}}^{-1/2}\) \([13, 19]\), the resulting BLR energy density is of the order of \(U_{\text{BLR}} \approx 10^{-2}\) erg cm\(^{-3}\) (ranging between 0.7 and 10) within a radius of \(R_{\text{BLR}} \approx 1 - 4 \times 10^{17}\) cm. This implies a maximal optical depth \(\tau\) at 100-200 GeV (rest-frame) which can be as high as \(\tau_{\text{BLR,max}} \approx 9 \times 10^5\), where \(\tau\) is the \(\gamma\)-ray photon path inside the BLR, in units of \(10^{17}\) cm.

Figure 2 (left) shows the SED of 3C 279 with the VHE fluxes of the MAGIC detection corrected one time for EBL absorption (using [14]) and a second time with \(\tau_{\text{BLR,max}} = 3\). The resulting SED shape suggests that the true initial VHE luminosity can likely be close or above the highest EGRET fluxes \((3 \times 10^{48} \text{ erg/s} [11])\), if the MAGIC flare took place inside the BLR. In such case, the SED suggests that the EGRET flat spectrum observed in high state could extend up to 100-300 GeV with no sign of cutoff. To produce VHE photons by IC, very high energy electrons are required by energy-conservation law \((\gamma \geq 6 \times 10^5/\delta)\), which emit by synchrotron in the UV-X-ray range for the typical parameters used in blazars \((h\nu_{\text{sync}} \geq 4 \times B/\delta \text{ keV})\). Yet, the quasi-simultaneous RXTE spectrum (taken 0.3 and 1 days apart from the MAGIC pointings, during routine monitoring) is hard (photon index \(\Gamma_X = 1.66 \pm 0.11\)), as typical for this source and FSRQ in general, and usually interpreted as the emerging of the IC emission. This X-ray spectrum represents a strict upper limit on the synchrotron luminosity of TeV electrons, unless one adopts the different and unconventional view that such X-ray spectrum corresponds actually to synchrotron emission of a second, “extreme BL Lac”-like component in the jet of 3C 279. In the leptonic scenarios, the hard X-ray spectrum provides also a limit for the \(\gamma\)-ray luminosity absorbed in the BLR, since the resulting pairs would reprocess the VHE power into the X-ray band through IC on the BLR UV photons, leading to much softer X-ray spectra [20]. Upcoming GLAST observations will be crucial to solve all these issues. If confirmed in strictly simultaneous observations with Cherenkov telescopes, the 3C 279 SED might become more easily explained with hadronic rather than leptonic scenarios, like the proton-synchrotron model [21, 22] (see [23] for a detailed discussion on modelling and implications).

The energetic requirements are less if the VHE flare took place outside the BLR, but in such case the external Compton process cannot use the BLR photons as target field. Also the near/mid-IR photons from hot dust [24] cannot be used in this case, since the implied energy densities would typically suppress most of the radiation approaching 1 TeV. (unless assuming extreme values of bulk motion). The huge Compton dominance and low-energy peaked SED have to be explained otherwise, e.g. using seed photons from different parts of the jet (as in the spine-layer or decelerated jet scenarios, [25, 10], or as a purely SSC flaring episode. In the latter case, however, larger X-ray fluxes and a more ”HBL-like” SED are expected, which should be revealed by strictly simultaneous observations.
Not any blazar is suited for EBL studies

In the MAGIC paper [13], the (admittedly poorly determined) VHE spectrum of 3C 279 has been used to derive constraints on the EBL as if this source was an HBL. However, the presence of the BLR target field in this object—as in any FSRQ—cannot be neglected, since it can strongly affect the spectrum emerging from the source. Such influence has been discussed since the COS-B discovery of 3C 273 in 1979 [26], but its impact on EBL limits has been recently recognized by [27] for the redshift dependence and by [13] for the spectral hardening (see also [28, 29]). It has been shown that absorption on a narrow-banded target field leads to the formation of γ-ray spectra of almost arbitrary hardness, irrespective of the primary spectrum emitted by the source [13]. This effect undermines any conclusion on EBL limits that can be drawn from the hardness alone of γ-ray spectra in FSRQ. The spectral hardening depends primarily on the intensity of the target field: the effect is shown in Fig. 2 (center), for a black-body target spectrum with \( T = 4 \times 10^4 K \) (generally adopted as a good approximation of the BLR radiation field [4]) and for three different values of the optical depth \( \tau \). The only limit on the achievable hardness is represented by the higher apparent luminosity required combined internal absorption on a narrow-band field peaking at the BLR line energies (compare right with center panels in Fig. 2).

In conclusion, the important point is that the actual BLR spectrum as seen by the gamma-rays is highly uncertain, with observational evidence both pro and against the narrow-band hypothesis. As long as the hardening effect cannot be excluded, therefore, no robust conclusion can be derived on the EBL from 3C 279 alone, or from any other object with strong emission lines, contrary to what claimed in [12, 30]. Only those objects for which the emission zone is established beyond the BLR (e.g. without the cut-off in the 10-100 GeV range from BLR absorption) can possibly qualify [31]. This problem concerns also some BL Lacs as well as FSRQ, since the relevant factors are the line luminosity and the (uncertain) location of the emitting region inside the BLR, not the equivalent width (which defines the BL Lac class); in fact some LBL have shown line luminosities comparable with FSRQ [32]. The MAGIC result therefore, while neither robust nor innovative concerning EBL constraints, sheds a new light on the structure and emission mechanisms of blazars.

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