On the correct intrinsic VHE properties of the BL Lac H 2356-309

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The high-energy-peaked BL Lac H 2356-309 (z=0.165) was detected by HESS at very high energies (VHE, \( \gtrsim 100 \text{ GeV} \)) with relatively high significance in the years 2004-2007, allowing a good determination of its gamma-ray spectrum. After correction for the interaction with the diffuse extragalactic background light (EBL), the VHE spectrum is flat (\( \Gamma \sim 1.9 - 2 \)) over a decade in energy, locating the gamma-ray peak around or above 0.6-1 TeV. This is remarkably at odds with the interpretation and modeling provided by HESS, which do not correspond to the source properties and can be excluded with high confidence. The overall GeV-to-TeV characteristics of H 2356-309 seem intermediate between the “TeV-peaked” (Fermi-faint) and “100 GeV-peaked” (Fermi-bright) BL Lac objects, and difficult to reconcile with the shape of the synchrotron emission in a single-zone SSC scenario.

1. Introduction

The BL Lac object H 2356-309 (z=0.165) is a High-frequency-peaked BL Lac (HBL), also called High-Synchrotron-Peaked blazar (HSP, [4]). It is usually bright in the X-ray band, and during BeppoSAX observations in 1998 it presented a synchrotron peak in the spectral energy distribution (SED) above few keV, which is the defining characteristic of the so-called “extreme BL Lacs” [7].

At VHE, H 2356-309 was detected for the first time in 2004 by HESS [3, 5]. The VHE spectrum was found to be significantly harder than expected from a source at that redshift, considering the softening effects of \( \gamma-\gamma \) absorption on the diffuse extragalactic background light (EBL), in the detected energy range. Together with other even harder sources, this fact lead to the discovery of a low intensity of the EBL in the component produced by the direct starlight [5].

Since 2004, H 2356-309 has been monitored by HESS for several years, reaching a total detection of \( \sim 13 \) \( \sigma \) in the timespan 2004-2007, with an average flux at the level of \( \sim 1.6\% \) of the Crab flux (above 240 GeV). In this epoch, three simultaneous multi-wavelength campaigns were performed, in 2004 with RXTE and 2005 with XMM-Newton [2, 6], which allowed the characterization of its SED. The results of these campaigns, the VHE monitoring and a synchrotron self-Compton (SSC) modeling of the data were published by the HESS Collaboration in Abramowski et al. 2010 [6].

In that paper, however, while all the data analysis is correct, the HESS Collaboration has apparently misinterpreted the VHE data, providing a wrong assessment of the intrinsic VHE properties of the source. It is also not consistent with previous publications on the same results. This contribution presents the arguments against the interpretation in [3] and tries to provide a more accurate description of the actual gamma-ray properties (from the GeV to the TeV band) of this BL Lac object.

2. Wrong assessment of the intrinsic VHE properties by HESS

Fig. 1 shows the overall SED of H 2356-309 during the HESS multiwavelength campaigns in 2004 and 2005 (from [3]). The two lines shows the single-zone SSC modeling proposed by the HESS Collaboration, with the dashed lines representing the source intrinsic emission (i.e. before absorption effects on the EBL calculated according to [10]). This SSC model is claimed by HESS to represent well the gamma-ray SED properties, with a Compton peak around 50-100 GeV and a steep intrinsic VHE spectrum: the local slope of the intrinsic SSC model (dashed line) in the detected VHE range is \( \Gamma_{\text{int}} \approx 2.65 - 2.7 \).

However, Fig 2 shows this not to be the case. Accounting for EBL absorption –either by correcting the observed data points, as done here, or by fitting an absorbed model– the intrinsic spectrum is in fact much harder. Fig. 2 presents the overall 2004-2006 average HESS data from [3], corrected for EBL absorption with the same EBL calculation [10]. Using a power-law model, the intrinsic photon index of the absorption-corrected data is \( \Gamma_{\text{int}} = 1.97 \pm 0.16 \) (statistical error only), \( \Gamma_{\text{int}} = 1.91 \pm 0.18 \) excluding the last point (which is more like an upper limit, see [3]). The discrepancy with the slope of the SSC model is large and highly significant: the \( \Delta \chi^2 \) needed to recover an index of 2.65 is 15, corresponding to a probability of \( \sim 1\text{E}-4 \) (for 1 parameter). The HESS SSC model, therefore, is excluded by the data at \( \sim 99.99\% \) confidence level.

Note that the 2004-2006 overall spectrum is mostly dominated \( \sim 90\% \) of the excess signal– by the 2004-2005 data set. Moreover, the spectrum in 2006 seems to have been steeper than in 2004-2005 (see Table 4 in [3]), thus the 2004-2005 spectrum should actually be slightly harder than the shown average, increasing the discrepancy.

The importance of this discrepancy is not merely quantitative, but qualitatively: it changes dramati-
Figure 1: The SED of H 2356-309 in different epochs, from the HESS paper (Fig. 8 in [3]). The XMM observations in 2005 are plotted in color (blue for June 13, red for June 15), while the RXTE 2004 data are plotted as black triangles. In the VHE band, the observed (i.e. EBL-absorbed) HESS data are plotted, as black triangles and red dots for the years 2004 and 2005, respectively. The curves are the HESS modeling of the 2005 SEDs with a single-zone SSC model, as described in [3], with (solid lines) and without (dashed lines) the EBL effects included [10]. The SSC model for the 2004 data (RXTE and HESS) is identical to the fit to the June 15, 2005 data (red curve).

2.1. Further arguments

The VHE data shown in Fig. 1 are not the overall average, but correspond to the two years 2004 and 2005 considered separately. It could be argued that the HESS SSC modeling aims to reproduce these two single epochs, and that the lower statistics of each single dataset makes the model viable, despite being excluded by the sum. However, this is not a valid argument: since the model gives identical slopes/characteristics in the two years, if it represented well the spectrum in both epochs it should fit well also the sum of the two, by definition. The situation is similar to having a constant source, properties-wise: the accumulation of statistics is revealing if the model is compatible or not with the data, and in this case it is not.

If this SSC modeling reproduced the actual source spectrum in just one of the two epochs, the spectrum in the other epoch should be much harder than the average, to compensate, and this should show in the data (as well as in the models, i.e. the SSC models for 2004 and 2005 should be very different from each other, to be consistent with the average). Again this seems not the case: the measured slopes of the 2004 and 2005 data sets are identical within the errors ($\Gamma_{\text{VHE}} = 2.97 \pm 0.19$ vs $2.99 \pm 0.39$ respectively, see Table 4 in [3]).

In other words, there is no way that the HESS modeling can represent well the HESS data. Simply stated, the proposed SSC model does not correspond to the SED of H 2356-309, and thus the physical analysis based on its parameters should be discarded.

3. The problem of plotting VHE data

There is a general issue in the interpretation of the VHE data. When presenting the SED of TeV blazars, it is becoming customary to plot only the observed (i.e. not EBL-corrected) data points and to absorb the possible model/curve, plotting at most the curves...
before EBL absorption. This is often misleading and a dangerous habit, and should be avoided.

Even if in principle it is the most proper method for a statistical analysis of the data and to derive fitting parameters, for plotting purposes it does not accurately display the source SED features. It misleads the viewers on the true properties of the object by mixing them with those of intervening systems. It also creates confusion when trying to find an adequate set of parameters with an emission model, because all curves seem to fit well the SED data when spectra are very steep.

The alternative approach is to correct the data points for the EBL (e.g. with the optical depth calculated at the average photon energy in the bin, which provides the same fit parameters of absorbing the model; see e.g. [3]), and plotting the EBL de-absorbed data in the SED. Both methods, if done correctly, should and do give the same results. This second approach, however, provides visually the most accurate representation of the true properties of the source (which is the focus of a SED study), without confusion with those of intervening systems.

Furthermore, this method achieves consistency with the conventions used in the other energy bands on the SED: in the Optical-UV bands, data are usually plotted after correction for at least Galactic extinction. In the X-ray band, data/slopes are always shown with correction for Galactic or line-of-sight intervening column densities. The reason is precisely to focus on the source physics, if that is the goal of the study. Otherwise any extragalactic object would always appear with fake peaks in the SED typically at 1-2 keV (or more, depending on the column density) and in the red-infrared band.

In conclusion, EBL-absorption should be treated and accounted for in the SED as any other absorption effect from intervening systems in the electromagnetic spectrum.

4. The correct SED of H 2356-309

The real intrinsic properties of H 2356-309, as given by the HESS data, are shown in Fig. 3. These are:

1. a flat VHE spectrum of photon index \( \Gamma_{int} \approx 1.9-2 \) over the whole HESS range;

2. a Compton peak either around \(~600\) GeV (as determined by a log-parabolic fit of the HESS data), or \(>1\) TeV (assuming the single power-law model). The statistics of the data do not allow yet to distinguish between the two cases (the curvature parameter can be zero within the errors).

Quite interestingly, the extrapolation of the HESS 2004-2006 average spectrum to the Fermi-LAT band corresponds almost "spot on" to the fluxes in the 1FGL catalog (2008-2009, TS=50, detection mainly in the 1-3 GeV bin; [1]). A single power-law model over 3 decades in energy provides surprisingly a good fit (\( \chi^2_r \sim 0.3 \)) with \( \Gamma_{int} = 1.94 \pm 0.03 \). The 2FGL values, instead, show a reduced overall flux (by roughly 2x), but retaining very similar spectral properties (\( \Gamma = 1.89 \pm 0.17 \), [13]).

With the big caveats of the non-simultaneity of the gamma-ray data and of the different integration times of the Optical-to-X-ray data vs the gamma-ray data, such a GeV-TeV gamma-ray spectrum is not easy to model within one-zone SSC scenarios, given the very different synchrotron spectra in the optical to X-ray bands, which trace directly the shape of the electron distribution. Regardless, the average SED seems synchrotron-dominated in luminosity, and thus the electron cooling as well.

5. Comparison with other HBL

HBL objects are typically characterized by hard (\( \Gamma < 2 \)) Fermi-LAT spectra [4] but show a wide range of VHE slopes, depending on the location of the gamma-ray SED peak. To this respect, H 2356-309 seems intermediate between two types of HBL objects: those with the peak around \(~100\) GeV, i.e. inbetween the Fermi-LAT and VHE bands (see for
Figure 4: Typical SED of a Fermi-bright “100-GeV peaked” HBL: 1ES 1553+113. They are characterized by soft intrinsic VHE spectra locating the gamma-ray peak close to 100 GeV (like PKS 2005-489 or PKS 2155-304). The redshift is constrained by HST/COS data [9]. Fermi-LAT spectrum from [2]. Other data from [14]. VHE data corrected for EBL according to [10].

Figure 5: Typical SED of a Fermi-faint TeV-peaked HBL: 1ES 1101-232. This was the first HBL object discovered with a gamma-ray peak above few TeV (i.e. with a hard VHE spectrum irrespective of the EBL model used; [5]). Fermi-LAT data from the 1-FGL catalog [1]. The LAT point corresponds to a flux estimate for the $\sim 4\sigma$ signal in the 1-FGL catalog. Other multiwavelength data/campaigns from [14] and refs therein. VHE observed data (red) corrected for absorption (blue) according to [10].

example Fig. 4, and those with a gamma-ray peak above 1 TeV, or “TeV-peaked” HBL (Fig. 5). The formers are characterized by soft intrinsic VHE spectra, and are more easily detected in Fermi because the peak of the SED is close to the Fermi-LAT band. The TeV-peaked HBL, instead, are characterized by hard intrinsic VHE spectra ($\Gamma_{\text{VHE}} < 2$), irrespective of the EBL model, locating the peak all the way beyond the detected VHE range. They remain often very weak or undetected in Fermi, because the LAT band falls now deep into the valley between the synchrotron and gamma-ray humps. These objects however, despite being rarer among HBLs, are at present the most challenging AGN for SSC modeling and to gain new insights on particle acceleration and emission mechanisms. (e.g. [11, 12, 15, 16]).

Disclaimer: As co-author of the HESS paper on H 2356-309, these findings were already provided to the HESS Collaboration, in the early stage and also after publication, to no positive effect. The co-authorship, therefore, is to be intended as data-related only, as proposer and PI of the multi-wavelength campaigns and for providing the XMM-Newton data analysis. It does not extend to the interpretation, which was finalized after I left the collaboration.

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