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Break in the VHE spectrum of PG 1553+113: new upper limit on its redshift?

D. MAZIN[1] AND F. GOEBEL[1].
[1]*Max-Planck-Institute for Physics, D-80806 Munich, Germany*
mazin@mppmu.mpg.de

Abstract: PG 1553+113 is a known BL Lac object, newly detected in the GeVTeV energy range by H.E.S.S. and MAGIC. The redshift of this source is unknown and a lower limit of $z > 0.09$ was recently estimated. The very high energy (VHE) spectrum of PG 1553+113 is attenuated due to the absorption by the low-energy photon field of the extragalactic background light (EBL). Here we correct the combined H.E.S.S. and MAGIC spectrum of PG 1553+113 for this absorption assuming a minimum density of the evolving EBL. We use an argument that the intrinsic photon index cannot be harder than Gamma=1.5 and derive an upper limit on the redshift of $z < 0.69$. Moreover, we find that a redshift above z=0.42 implies a possible break of the intrinsic spectrum at 200 GeV. Assuming that such a break is absent, we derive a much stronger upper limit of $z < 0.42$. Alternatively, this break might be attributed to an additional emission component in the jet of PG 1553+113. This would be the first evidence for a second component detected in the VHE spectrum of a blazar.

Introduction

PG 1553+113 is classified as a high-frequency peaked BL Lac [1], similar to most of the AGNs detected at very high energies (VHE). The redshift of PG 1553+113 is essentially unknown. It was initially determined to be z=0.36 but later this claim was withdrawn. To date no emission or absorption lines have been measured despite several observation campaigns with optical instruments. No host galaxy was resolved in *Hubble Space Telescope* images of PG 1553+113. A recent publication claims a lower limit on the redshift of $z > 0.09$ using the ESO-VLT optical spectroscopy survey of 42 BL Lacertae objects of unknown redshift [2].

Recently, VHE γ-ray emission from PG 1553+113 was measured by H.E.S.S [3] and by MAGIC [4]. Both collaborations reported a soft energy spectrum with a differential photon index of $\Gamma = 4.0 \pm 0.6$ and $\Gamma = 4.2 \pm 0.3$ respectively. The VHE data from the two measurements were used independently to derive an upper limit on the redshift of the source of $z < 0.74$. This limit is based on the assumption of a minimum possible level of the EBL and the maximum hardness of the intrinsic VHE spectrum. Although the intrinsic VHE γ-ray spectra of the AGNs are not well known, it can be assumed that the intrinsic photon index of the sources is not harder than $\Gamma_{\rm int}$=1.5 [5]. However, there are emission scenarios where the maximum possible VHE photon index is even harder ($\Gamma_{\rm int} = 2/3$, [6]).

Here we use the combined H.E.S.S. and MAGIC spectrum of PG 1553+113 to derive upper limits on its redshift, assuming the two limits on the hardness of the intrinsic photon index ($\Gamma_{\rm int}$=1.5 and $\Gamma_{\rm int} = 2/3$). In addition, we present an alternative method to estimate an upper limit on the redshift of PG 1553+113 assuming that there is no break in the intrinsic VHE spectrum of the source.

Minimum EBL

The most likely reaction channel in the interaction of VHE γ-rays with the low energy photons of the EBL is pair production $\gamma_{\rm VHE} + \gamma_{\rm EBL} \rightarrow e^+ e^-$. The intrinsic (de-absorbed) VHE photon spectrum, dN/dE_i, of a blazar located at redshift z can be determined using:

$$dN/dE_i = dN/dE_{obs} \times \exp[\tau_{\gamma\gamma}(E, z)],$$

where dN/dE_{obs} is the observed spectrum and $\tau_{\gamma\gamma}(E, z)$ is the optical depth. In the present study,

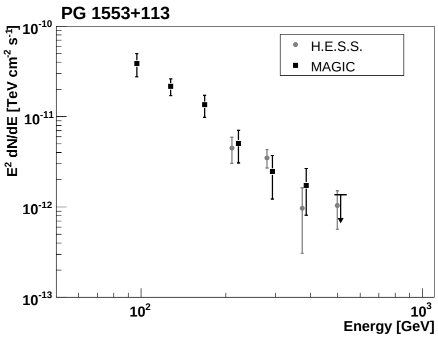

Figure 1: Differential measured energy spectrum of PG 1553+113 multiplied by E^2 to represent energy density.

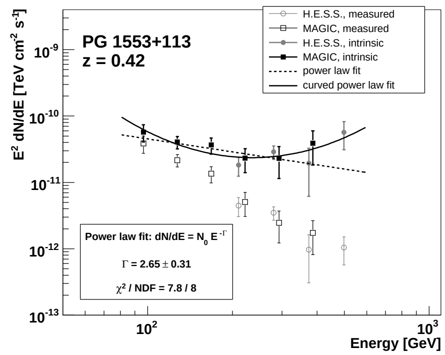

Figure 2: Constraint on the redshift of PG 1553+113. *Hollow points*: measured combined (normalized) differential energy spectrum of PG 1553+113 using MAGIC (squares) and H.E.S.S. (circles) data from 2005 and 2006. *Filled points*: intrinsic spectrum of PG 1553+113, using minimum possible density of the evolving EBL and the redshift of $z = 0.42$. *Black dotted line*: power law fit to the intrinsic spectrum; the fitted photon index is listed in the inlay. *Black solid line*: curved power law fit.

we want to use the lowest possible realistic level of the EBL in order to derive a minimum redshift, above which a break in the VHE spectrum of PG 1553+113 becomes evident. Several EBL models have been developed, taking into account the evolution of the EBL, which is related to star and galaxy evolution (e.g. [7, 8, 9]). Though different in approach, the models agree in their predictions within a factor of 2. For this study, we use the lower limit model from [7], which is just at the level of the direct lower limits set by the galaxy counts.

Combining the spectra of PG 1553+113 from H.E.S.S. and MAGIC

The differential VHE γ-ray spectra of PG 1553+113 published by H.E.S.S. and MAGIC are shown in Fig. 1. The photon fluxes are multiplied by E^2, which is equivalent to a $\nu F(\nu)$ representation. The H.E.S.S. data are shown as grey circles and the MAGIC data by black boxes. The last spectral point in the MAGIC data is a 95% upper limit and will not be used in the further analysis. AGNs are known to be variable sources in flux so that, in general, it is not trivial to combine non-simultaneous data sets. In the present case, however, the agreement between the spectra measured by H.E.S.S. and MAGIC is very good (see [10] for more details). The measured flux levels differ by 10%, which is small compared to the individual statistical errors. In order to increase the statistical power of the tests described below, we use the combined spectrum of MAGIC and H.E.S.S. data on PG 1553+113. We normalize the spectra by multiplying the H.E.S.S. fluxes by a factor 1.1 to avoid a possible bias in our results. In order to show the effect of the normalization we also perform the same study on a combined spectrum without this normalization.

Determination of upper limits on the redshift of PG 1553+113

Two different methods are used. The first one assumes that the spectral index of the intrinsic differential photon spectrum is not higher than 1.5 (or, alternatively, 2/3). The second one assumes that the intrinsic photon spectrum has no break in the measured energy region from 80 to 600 GeV.

Maximum intrinsic photon index $\Gamma_{\rm int}$

A fit of Eq. 1 is performed to the intrinsic spectrum of PG 1553+113. The fitted index $\Gamma_{\rm int}$ and its error σ_Γ are combined to $\Gamma_{\rm max}$, where $\Gamma_{\rm max} = \Gamma_{\rm int} + 2 \times \sigma_\Gamma$ corresponding to a 95% confidence level. A redshift z is considered to be unrealistic if $\Gamma_{\rm max} < 1.5$ or, in case of the extreme scenario, $\Gamma_{\rm max} < 2/3$.

Presence of a break in the intrinsic photon spectrum

The second method is based on the indication that for larger redshifts ($z > 0.3$) the intrinsic spectrum of PG 1553+113 exhibits a break at about 200 GeV with the intrinsic energy spectrum rising after the break (see Fig. 2). Such a break in the intrinsic spectrum of PG 1553+113 cannot be excluded *a priori*. However, in none of the measured VHE γ-ray spectra of extragalactic sources such a component has been found. Thus, if a spectrum shows a break, either it is the first time a second emitting component is found in a VHE γ-ray spectrum or a lower redshift value z has to be assumed.

To test the presence of a second component (or the presence of a break) in the VHE spectrum of PG 1553+113 we performed a likelihood ratio test on the intrinsic spectrum. Two hypotheses are tested. Hypothesis A is a simple power law (2 free parameters):

$$dN/dE = N_0 E^{-\Gamma_{\rm int}} \qquad (1)$$

Hypothesis B is a curved power law (3 free parameters):

$$dN/dE = N_0 E^{-(\alpha + \beta\, \ln(E))}\,, \qquad (2)$$

which corresponds to a parabolic law in a $\log(\nu\,{\rm F}_\nu)$ vs. $\log(\nu)$ representation. A parabolic shape is a natural choice to describe the transition region of a break between two spectral components. The curved power law will be accepted if its probability to be a superior hypothesis is greater than the confidence level, which is set to 95%.

Results

We examined a wide range of redshifts values z between 0.1 and 0.9 in steps of 0.02. Each time,

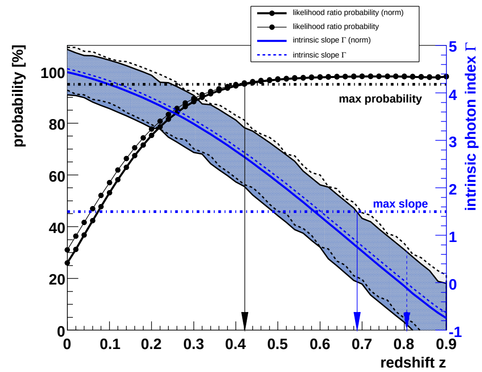

Figure 3: Constraints on the redshift of PG 1553+113 (see text for details).
Black points and left Y-axis: probability of the likelihood ratio test. The black arrow indicates the minimum redshift, at which the break in the intrinsic spectrum of PG 1553+113 is evident.
Blue line and right Y-axis: intrinsic photon index $\Gamma_{\rm int}$. Shaded areas correspond to 2 σ confidence belt. The blue arrow indicates the limit in case of $\Gamma = 1.5$. The dashed blue arrow indicates the limit in the extreme case of $\Gamma = 2/3$.

the corresponding optical depth was calculated and the intrinsic spectrum of PG 1553+113 was determined using the low limit model from [7]. The probability of the likelihood ratio test and the intrinsic photon index $\Gamma_{\rm int}$ as a function of redshift z are shown in Fig. 3. The intrinsic photon index $\Gamma_{\rm int}$ as a function of the redshift is shown by the thick blue line in Fig. 3. A 2σ confidence belt is drawn as blue shaded area. The result without the normalization between the H.E.S.S. and MAGIC measured spectrum of PG 1553+113 is shown by the dashed blue line with a corresponding 2σ confidence belt as grey shaded area. Assuming that the intrinsic photon index can not be harder than $\Gamma_{\rm int} = 1.5$, we obtain a redshift limit of $z < 0.69$ with a confidence of 95%. Assuming the maximally hard spectrum as proposed by [6] with $\Gamma_{\rm int} = 2/3$, we obtain a redshift upper limit of $z < 0.80$.

The intrinsic spectrum was considered to have a break if the likelihood ratio test gave more than 95% confidence. The probability of the likelihood ratio test as a function of the redshift is shown by the black points and thick black line in Fig. 3. The smallest redshift, for which the test gave more than 95% confidence, is $z = 0.42$ (see Fig. 2). The assumption that there is no break in the intrinsic spectrum of PG 1553+113 thus leads to an upper limit on its redshift of $z < 0.42$. The result without the normalization between the H.E.S.S. and MAGIC measured spectrum is shown by the thin black line. The systematic uncertainty in the derived limits, arising from the applied normalization of 10% between the H.E.S.S. and MAGIC data, is below 10%.

Conclusion and Outlook

In this study, we combined H.E.S.S. and MAGIC data using their good agreement and used a realistic minimum density of the EBL to reconstruct the intrinsic spectrum of PG 1553+113. We showed that the intrinsic photon index $\Gamma_{\rm int}$ becomes smaller than $\Gamma_{\rm int} = 1.5$ at $z = 0.69$, which can be considered a robust upper limit on the redshift of PG 1553+113. In case of the extreme emission scenario with $\Gamma_{\rm int} = 2/3$, we obtain an upper limit of $z < 0.80$. Moreover, we showed that a break in the intrinsic spectrum at about 200 GeV becomes evident at a redshift of $z = 0.42$. The break can either be interpreted as an upper limit on the redshift of PG 1553+113 or as evidence for a second emission component in the VHE spectrum of the object. The upper limit of $z < 0.42$ implies values of the intrinsic slope indicating that the peak of the high-energy component of the SED lies below few hundred GeV, as typically derived for the closest TeV blazars Mrk 421 and Mrk 501 (in low flux state). We note that increasing the statistics by combining the spectra of MAGIC and H.E.S.S. resulted in a moderate improvement of the redshift upper limit. On the other hand, the second method, which is based on the search for structures in the intrinsic spectrum and which resulted in much more stringent limits, became only feasible using the combined data set.

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