A new upper limit on the redshift of PG1553+113 from observations with the MAGIC Telescope

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***Abstract*. Very high energy gamma ray emission from the active galactic nucleus PG 1553+113 was observed during 2005 and 2006 by the MAGIC collaboration, for a total observation time of 18.8 hours. Here we present the results of follow up observations: more than 20 hours of good quality data collected by the MAGIC Telescope during the 2007 and 2008 campaigns. The obtained spectra are compared and combined with previous measurements, and corrected for absorption adopting different EBL models. Upper limits on the unknown source redshift are derived by assuming the absence of a break in the intrinsic spectrum, or alternatively by constraining the hardness of the intrinsic source spectrum.**

***Keywords*: BL Lacs: individual (PG 1553+113), unknown redshift, gamma-rays:Observations**

I. Introduction

The BL Lac object PG 1553+113, located at RA 15h55m43.0s, dec +11d11m24s, is one of the 27 Active Galactic Nuclei (AGNs) detected to date as Very High Energy (VHE) gamma ray emitters. AGNs are supermassive black holes surrounded by an accretion disk and, in radio loud AGNs, bipolar jets of relativistic particles perpendicular to the disk plane. The spectral properties of the observed radiation are strictly related to the viewing angle to the observer [1].

AGNs whose jet points directly or at a small angle to the observer belong to the class of blazars. BL Lac objects, like PG 1553+113, are blazars showing very weak emission lines. The observed spectrum from a BL Lac is totally dominated by the jet, since the power of the radiation emitted by the jet is enhanced by relativistic beaming effects. Typically, radiation emitted from these objects covers the entire electromagnetic spectrum, from radio wave to gamma-ray frequencies. The spectrum is composed of two bumps: one at low energy and a second at high energy, peaking in the GeV range. The first component is identified as electron synchrotron radiation, whilst the nature of the second component is still under debate. The most popular models of GeV component, the so-called leptonic models, invoke inverse Compton scattering of ambient photons on electrons. Alternatively, the high energy photons observed in BL Lac spectra could be of hadronic origin through the emission of secondary electrons.

A. The redshift of PG 1553+113

The distance of PG 1553+113 is still unknown. Despite several observing campaigns with optical instruments, no emission or absorption lines have been detected. Moreover, the observed jet emission from this source is so bright that it prevents optical observation of the host galaxy, which was recently attempted using the Hubble Space Telescope and the ESO Very Large Telescope. These measurements resulted in a lower limit on the redshift of $z > 0.78$ and $z > 0.09$ respectively [2], [3]. Under the assumption that the luminosity of the host galaxy of BL Lac objects can be considered constant, a lower limit of $z > 0.25$ was recently reported [4].

The distance of a gamma-ray emitting extragalactic object is of crucial importance for VHE observations. The presence of a diffuse optical/near-infrared background in intergalactic space, the so-called Extragalactic Background Light (EBL), causes a partial/total absorption of the VHE photons coming from distant sources. The most distant object with known redshift detected so far in VHE is the FSRQ 3C279, located at redshift $z = 0.54$.

The detection of γ emission above 100 GeV from the source of unknown redshift PG 1553+113 has been reported using the H.E.S.S. and MAGIC telescopes [5], [6]. This has allowed the development of new methods to determine the source distance, based on the source spectral features [7], [8]. An upper limit on the redshift can be inferred by requiring that the VHE component of the EBL corrected (i.e. deabsorbed) spectrum satisfies particular physical conditions. A combination of MAGIC and H.E.S.S. spectra has been used to set upper limits of $z < 0.69$ and $z < 0.42$, depending on the intrinsic spectrum assumed [8].

In this paper, we set new upper limits on the redshift of PG 1553+113 from the observed VHE spectrum. We combine previously published 2005-2006 MAGIC data with new MAGIC data taken in 2007 and 2008. We utilise the lower limit EBL model from [9], which is at the level of direct lower limit set by galaxy counts (see Fig. 2) and for comparison the recent model [10], based on real data.

II. Observations and data analysis

A. The MAGIC Telescope

MAGIC [11] is a new generation Imaging Atmospheric Cherenkov Telescope located on La Palma, Canary Islands, Spain (28.3°N, 17.8°W, 2240 m asl). Due to its low energy trigger threshold of 60 GeV, MAGIC is well suited to multiwavelength observations together with instruments operating in the GeV range. The parabolically-shaped reflector, with a total mirror area of 236 m^2 allows MAGIC to sample a part of the Cherenkov light pool and focus it onto a multi-pixel camera, composed of 576 ultra-sensitive photomultipliers. The total field of view of the camera is 3.5° and the collection area is of the order of 10^5 m^2 at 200 GeV for a source close to zenith. The incident light pulses are converted into optical signals, transmitted via optical fibres and digitised by 2 GHz flash ADCs [12].

B. Data analysis

PG 1553+113 was observed with the MAGIC Telescope for nearly 19 hours in 2005 and 2006 [6]. It was also the subject of a multi-wavelength campaign carried out in July 2006 with optical, X-ray and TeV γ-ray telescopes [14]. Follow-up observations with the MAGIC telescope were carried out for 14 hours in March-April 2007 and for nearly 26 hours in March-May 2008, parts of which were taken simultaneously with other instruments [15]. Unfortunately the 2008 observations were severely affected by bad weather (including *calima*, Saharan sand-dust in the atmosphere) that greatly reduced the final dataset and resulted in an increased energy threshold. Data from both periods were taken in the false-source tracking (wobble) mode [13], in which the telescope was alternated every 20 minutes between two sky positions at 0.4° offset from the source. The zenith angle of the 2007 observations varied from 17° to 30°, while in 2008 it extended to 36°.

The analysis was performed using the standard MAGIC analysis software [16]. In the early stages of the analysis, an absolute calibration with muons and an absolute mispointing correction were performed. The arrival time information for pulses in neighbouring pixels was later used to suppress the contribution from the Night Sky Background (NSB) in the shower images [17]. After these steps, the camera images were parameterised via the so-called Hillas image parameters [19]. Two additional parameters, namely the time gradient along the main shower axis and the time spread of the shower pixels, were computed [18].

Severe quality cuts based on event rate after NSB suppression were applied to the sample. 20.2 hours of good quality data remained after these cuts, of which 11.5 hours were taken in 2007 and 8.7 hours in 2008. An additional cut removed the events with total charge less than 80 photoelectrons (phe) in 2007 to ensure a better background rejection. A harder cut, at 200 phe, had to be applied to the 2008 dataset due to the poor observing conditions. For the successive steps of the analysis, Monte-Carlo simulations of γ-like events were used. Hadronic background suppression was achieved using the Random Forest (RF) method [20], in which each event is assigned an additional parameter, the hadronness, which is related to the probability that the event is not γ-like. The RF method was also used in the energy estimation. The energy threshold was estimated to be 80 GeV in 2007 and 150 GeV in 2008. Due to a change in the telescope performance, the optical point-spread function (PSF) of the two periods differs: the σ of the PSF was measured to be 13 mm and 10 mm in 2007 and 2008 respectively. To take this into account, data were analysed separately. Effects on the spectrum determination introduced by the limited energy resolution were corrected by "unfolding" the final spectra.

C. Results

The 20.2 hours of observations of PG 1553+113 carried out between 2007 and 2008 resulted in a signal of 12σ significance, in the energy range between 150 and 600 GeV. The differential spectra measured by MAGIC in 2007 and 2008 were fitted with a power law function of the form

$$\frac{dF}{dE} = f_0 * \left(\frac{E}{200\,\mathrm{GeV}}\right)^{-\alpha} \qquad (1)$$

where f_0 is the flux at 200 GeV and α is the power law index. The resulting indices are listed in Table I, along with the integral fluxes above 200 GeV, as estimated from the fit. The systematic uncertainty is estimated to be 35% in the flux level and 0.2 in the power index [22].

The absolute flux above 200 GeV observed in 2008 spectrum is a factor 2.5 larger compared to the one measured in 2007. The differential spectrum seems harder in 2008 than in 2007, though consistent within the errors. The absolute flux above 200 GeV from the

[1]published data [6]

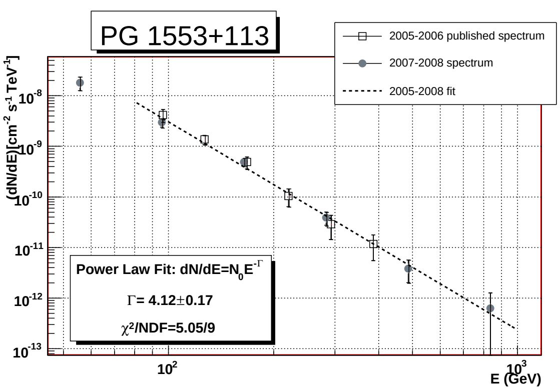


Fig. 1. Combined differential measured energy spectrum of PG 1553+113.

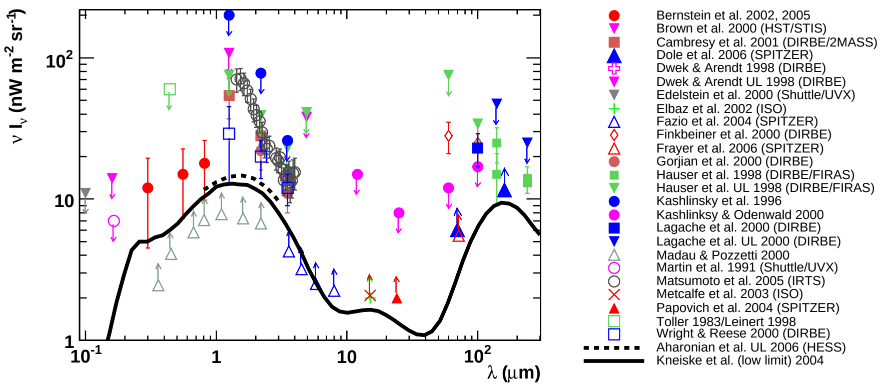


Fig. 2. Energy density of the Extragalactic Background Light. Direct measurements, galaxy counts, low and upper limits are shown by different symbols. The dashed black line represents the upper limit set by H.E.S.S. [7]. The black solid curve is the minimum EBL spectrum at z=0 from the model adopted in this work.

TABLE I
PG 1553+113 MEASURED SPECTRUM

Year	F(E > 200 GeV) $(10^{-11} cm^{-2} s^{-1})$	photon index
2007	0.69 ± 0.13	4.20 ± 0.28
2008	1.76 ± 0.24	3.95 ± 0.32
2007+2008	1.12 ± 0.19	4.03 ± 0.23
2005+2006[1]	1.0 ± 0.4	4.21 ± 0.25
2005-2008	1.13 ± 0.14	4.12 ± 0.17

combined dataset is in good agreement with previous measurements carried out by the MAGIC Telescope in 2005 and 2006 [6]. Hence, all data were combined in a single dataset, in order to increase statistics. The overall spectrum, drawn in Fig.1 can be well described by a simple power law fit of steep index 4.12 ± 0.17.

III. Absorption of VHE gamma-rays

The VHE spectrum emitted by distant sources is strongly affected by the interaction with the EBL [23]. EBL is composed of stellar light emitted and partially reprocessed by dust throughout the entire history of galaxy evolution. The expected spectrum of this light is composed by two bumps at near-infrared and far-infrared wavelengths [23]. Direct measurement of the EBL has proven to be a difficult task, primarily due to the zodiacal light that forms a bright foreground which is difficult to suppress. In Fig. 2, from [8], a collection of recent experimental data is shown.

VHE γ-rays from distant sources interact with the low-energy photons of EBL through electron-positron pair production. As a result, VHE spectra from AGNs are exponentially attenuated by a factor $\tau_{\gamma\gamma}(E, z)$, where τ is the optical depth and is a function of both energy and redshift of the source. The EBL wavelength range for this absorption of VHE γ-rays extends from the UV to the far-infrared. We adopt the optical depth values from [9] and from the recent model [10] to correct the observed spectra from PG 1553+113 for EBL absorption and derive a new upper limit on the redshift. Both models take EBL evolution into account.

IV. Upper limits on the redshift of PG 1553+113

For the determination of the upper limit on the redshift of the source PG 1553+113, we decided to use two different approaches. The first is to require a *minimum value for the power law index* of the deabsorbed spectrum. According to the "standard scenario" of particle acceleration, the minimum allowed index in AGN spectra is $\Gamma_{int}^{st} = 1.5$ [7]. Several theoretical possibilities have been proposed to create harder spectra. As an "extreme case" we also consider the value $\Gamma_{int}^{ex} = 2/3$, discussed in [21]. The second method, recently adopted in [8], is based on the hypothesis that there is no break in the intrinsic VHE source spectrum.

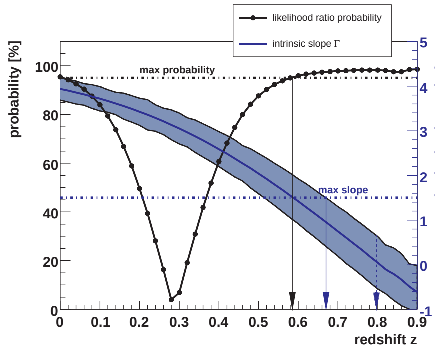
A. Maximum intrinsic photon index

We make the requirement that the power law index, Γ_{int}, obtained by fitting the deabsorbed spectrum with the simple power law of Eq. 1, plus twice its statistical error, is not harder than $\Gamma_{int}^{st} = 1.5$ in the standard scenario and $\Gamma_{int}^{ex} = 2/3$ in the extreme scenario case. The corresponding confidence level is 95%. We examined a wide range of redshift values z between 0.1 and 0.9 in steps of 0.02. Each time, the intrinsic spectrum was determined using the model [9] and fitted.

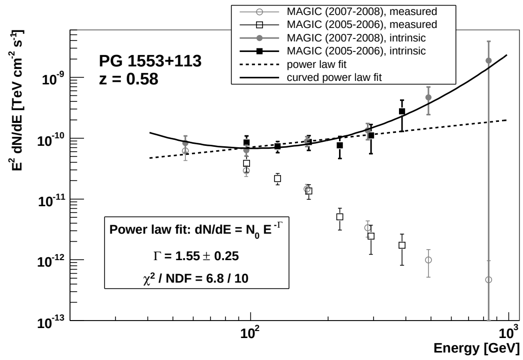
The results and the corresponding 2σ confidence belt are shown in Fig. 3a, thick blue line. The redshift limits obtained with this method are z<0.67 in the standard scenario case, and z<0.80 in the extreme one. The same analysis, performed by adopting the recent EBL model [10], led to comparable values.

B. Absence of a break in the intrinsic spectrum

In order to test the absence of a break in the deabsorbed spectrum, we performed a likelihood ratio test between the hypothesis A, data fitted with the simple power law of Eq.1, and hypothesis B, data fitted with a curved power law, of index $-\alpha + \beta \ln(E)$. This corresponds to a parabolic law in a $\log(E^2 dN/dE)$ vs $\log(E)$ representation. More details about this method can be found in [8].



(a) Constraints on the reshift of PG 1553+113 with the likelihood ratio test. See text for details.



(b) Intrinsic spectrum of PG 1553+113 at redshift 0.58, using minimum EBL model. See text for details.

Fig. 3. Constraints on the reshift of PG 1553+113.

The resulted probability of the likelihood ratio test is shown in Fig. 3b, thick black line. With a confidence level of 95%, the deabsorbed spectrum shows a break at redshift z=0.58. The deep of the likelihood value at z=0.28 indicates that at this redshift the intrinsic combined spectrum is a strict power law. The requirement that the intrinsic spectrum from PG 1553+113 does not show a pile up at high energies, leads to an upper limit of z<0.58 on its distance. The same analysis performed by adopting the recent EBL model, gives the limit z<0.60.

V. CONCLUSIONS

Follow-up observations of PG 1553+113 at VHE carried out with the MAGIC Telescope in 2007 and 2008 have shown that the source was in a quite steady state, within a factor 2.5, between 2005 and 2008 at these wavelengths. From the combined spectrum we have derived an upper limit on the source redshift, taking into account the absorption of VHE photons with the EBL.

With a low EBL model, we showed that the intrinsic photon index Γ_{int} becomes harder than 1.5 at z=0.67. This can be considered as a robust upper limit on the redshift of PG 1553+113, taking into account the standard scenario of shock-accelerated electrons. Moreover, the the spectral index of PG 1553+113 was recently measured in the energy range 0.2-100 GeV by the Fermi LAT [24] and has a value of $\Gamma = 1.70 \pm 0.06$.

In case of extreme emission scenario, $\Gamma_{int}^{ex} = 2/3$, our limit becomes z= 0.80. A break in the intrinsic spectrum becomes evident at redshift z=0.58. The pile up can either be interpreted as an upper limit on the source redshift or as evidence for a second emission component in the VHE spectrum from PG 1553+113.

The limits obtained here are apparently higher than the ones resulted in a previous work in which the same EBL model was adopted [8]. In that case, however, data from different experiments were combined.

The larger data sample used here, together with the fact that the data were taken with a single experiment, leads to comparably smaller statistic and systematic errors in the flux evaluation, and results in a more realistic determination of the upper limits on the source distance.

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