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Redshifts of distant blazar limited by Fermi and VHE γ-ray observations

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Abstract

Our goal is to limit the redshifts of three blazars PG 1553+113, 3C 66A and PKS 1424+240, through the investigation of their Fermi and VHE (very high energy) γ-ray observations. We assume that the intrinsic spectra of PG 1553+113, 3C 66A, and PKS 1424+240 have not any cutoff across the Fermi and VHE γ-ray energy ranges. The intrinsic spectra of VHE γ-rays are obtained through the extrapolation of Fermi spectra. Comparing the measured and intrinsic VHE spectra due to extragalactic background light (EBL) absorption, we give the redshift upper limits of three blazars assuming a specific EBL model. The redshift upper limits of PG 1553+113, 3C 66A and PKS 1424+240 are 0.78, 0.58, and 1.19 respectively. Near the TeV energy the optical depth of VHE γ photons might be overestimated by Franceschini (2008) EBL model, or the second emission component might be present in the VHE spectra and lead the intrinsic photon index harder than the Fermi ones.

Key words: gamma-rays: observations — BL Lacertae objects: individual: PG 1553+113, 3C 66A, PKS 1424+240 — diffuse radiation

1. INTRODUCTION

Blazars are a subclass of AGN characterized by strong non-thermal radiation across the entire electromagnetic spectrum, from radio to very high energy (VHE) bands. They include Flat-spectrum radio-loud quasars (FSRQs) and BL Lac objects. BL Lac objects usually present no or weak emission lines, and their redshifts are not easily determined. However, the redshift is crucial for the understanding of VHE emissive properties of these sources due to EBL absorption(Hauser & Dwek 2001).

PG1553+113 is a high-frequency peaked BL Lacertae object (HBL) (Giommi et al. 1995 ; Beckmann et al. 2002). 3C 66A is classified as an intermediate-frequency peaked BL Lac (IBL) due to its synchrotron peak being between 10^{15} and 10^{16} Hz (Perri et al. 2003). The position of the synchrotron peak of PKS 1424+240 has not been measured, but it can be constrained from optical and X-ray data to be between 10^{15} Hz and 10^{17} Hz. Therefore, PKS 1424+240 is either regarded as an IBL (Nieppola et al. 2006). Their redshifts are not determined as yet. The redshift of PG1553+113 was 0.36 (Miller & Green 1983), and then was wrong due to the misidentification of emission line (Falomo & Treves 1990). Subsequent observations did not reveal any spectral features (Falomo & Treves 1990 ; Falomo et al. 1994 ; Carangelo et al. 2003). Hubble Space Telescope (HST) images do not also determine its redshift (Sbarufatti et al. 2005;Sbarufatti et al. 2006 ; Treves et al. 2007), and only give a lower limit of $z > 0.78$ (Sbarufatti et al. 2005). Sbarufatti et al. (2006) used the spectra of ESO VLT to give a limit of $z > 0.09$. Mazin & Goebel (2007) also gave an upper limit on the redshift of PG 1553+113 as $z < 0.69$. For 3C 66A, the redshift was estimated to be 0.444 (Miller et al. 1978 ; Lanzetta et al. 1993), and exits large uncertain (Bramel et al. 2005). Recently, Finke et al. (2008) give a lower limit of $z > 0.096$. For PKS 1424+240, Scarpa & Falomo (1995) derived a limit of $z > 0.06$, and Sbarufatti et al. (2005) gave a limit of $z > 0.67$. Recently, Acciari et al. (2010) deduced the redshift to be less than 0.66.

The EBL consists of the sum of the starlight emitted by galaxies through the history of the Universe, and includes an important contribution from the first stars (Hauser & Dwek 2001). The VHE photons will be absorbed by the EBL through pair production. We can use VHE blazars with redshifts to study the EBL density. On the contrary, we can use the EBL model to limit the redshifts and intrinsic spectra of VHE blazars.

To date, 35 AGN sources have been detected at TeV energies[1]. The observed spectra have power law shapes with the index $\Gamma \geq 2$, in which distant sources have large Γ, up to 4 (e.g. Acciari et al. 2009b ; Albert et al. 2007b ; Albert et al. 2008 ; Aharonian et al. 2005). The Fermi Gamma-ray Space Telescope has detected their emissive spectra between 20MeV and 300GeV. Assuming a single spectral index, Abdo et al. (2009b) extrapolate the Fermi spectrum up to 10 TeV as an in-

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[1] update see: http://www.mppmu.mpg.de/˜rwagner/sources/

trinsic VHE spectrum, and find that the break of the observed TeV spectra is consistent with the absorption predicted by the minimal EBL density model. For a TeV source, the presence of a break between the Fermi and VHE energy range might be caused by some internal or external factors. The internal factors include a break of emitting particle distribution or an intrinsic absorption caused by strong optical-infrared radiation within the source (Donea & Protheroe 2003). The external factors usually refer to the cosmic attenuation effect. Furthermore, it is difficult to well predict the intrinsic spectrum from simultaneous multi-wavelength observations because of the complexity of VHE emission mechanism. In this work, we assume that the Fermi spectral index measured by Fermi-LAT is the lower limit of intrinsic VHE spectral index for TeV blazars. In the other words, form the Fermi energy range to the VHE energy range, the photon index can only be softened, not hardened (of course, there are exceptions, for example, existing a new emitting component (Yang & Wang 2010), or presence of monochromatic radiation fields within the source (Aharonian et al. 2008b)). Then, we limit the redshifts of three blazars based on the observed GeV and VHE spectra.

In § 2 we describe the method to limit the redshift assuming a specific EBL model, and then apply the method to three blazars. Discussions and conclusions are presented in § 3.

2. THE Methods

The VHE γ-ray absorption by the EBL is caused by the pair production of photon-photon collision. The observed VHE γ-ray flux is given by

$$f_{obs}(E_\gamma) = e^{-\tau(E_\gamma)} f_{int}(E_\gamma) , \quad (1)$$

where $\tau(E_\gamma)$ is the optical depth, E_γ is the observed VHE γ-ray photon energy, $f_{obs}(E_\gamma)$ and $f_{int}(E_\gamma)$ are observed and intrinsic flux respectively. Therefore, we can determine the opacity of VHE gamma-rays through the observed and intrinsic spectra. Now we derive an upper limit of the redshift from the opacity by assuming a specific EBL model. Recently, many EBL models are available in the literature (Totani & Takeuchi 2002; Kneiske et al. 2004; Primack et al. 2005; Stecker et al. 2006; Franceschini et al. 2008; Raue & Mazin 2008; Gilmore et al. 2009; Finke et al. 2010). In this work, we adopt the EBL model of Franceschini et al. (2008). The model includes evolutionary effects and the lowest level of the EBL intensity over the concerned range(0.1-10μm, see the Fig. 7. of Finke et al. 2010). The model is consistent with the lower limits from galaxy counts and upper limits from observations of TeV blazars. Therefore, using the minimum EBL intensity and the hardest intrinsic VHE spectrum, we obtain the upper limits of three objects' redshifts.

If the observed Fermi spectral index represents the hardest limits of intrinsic VHE ones, the EBL will cause the difference of the observed Fermi and VHE spectral indices. The difference, $\Delta\Gamma = \Gamma_{VHE} - \Gamma_{Fer}$, will increase with the redshift. For example, M 87 and Cen A with low redshifts have $\Delta\Gamma \approx 0$, while blazars with redshifts greater than 0.1 show $\Delta\Gamma \geq 1.5$(Abdo et al. 2009b).

In the VHE bands, PG 1553+113 is detected by the HESS and MAGIC telescopes without simultaneous Fermi observation (Aharonian et al. 2006 ; Aharonian et al. 2008a ; Albert et al. 2007a ; Albert et al. 2009). 3C 66A is observed by the VERITAS (Acciari et al. 2009a), and its neighbor 3C 66B is a possible source of VHE emission (Tavecchio & Ghisellini 2008). Recently the MAGIC favors 3C 66B as a VHE source and excludes 3C 66A at an 85% confidence level (Aliu et al. 2009). However, 3C 66A has the near-simultaneous observation of the Fermi and VERITAS in the 2008-2009 season, we favor 3C 66A as a VHE source. For the PKS 1424+240, Acciari et al. (2010) reported the first detection of VHE gamma-ray emission above 140 GeV band.

In the Fermi energy ranges, PG 1553+113 is a bright source detected by the Fermi LAT (Abdo et al. 2009a) and has a photon index of 1.70 ± 0.06 (Since the VHE and Fermi observations are not simultaneous for PG 1553+113, we will discuss this issue in the Section 3.). 3C 66A and PKS 1424+240 are also detected by the Fermi survey in the first three months and have an index of 1.97 ± 0.04 and 1.80 ± 0.07, respectively (Abdo et al. 2009a). 3C 66A has the near-simultaneous observation of the Fermi and VERITAS. For PKS 1424+240, Acciari et al. (2010) discovered its VHE emission and carried out simultaneous multi-wavelength observations, in which Fermi observations obtain the photon index of 1.73 ± 0.07. In this work, we adopt the near-simultaneous or simultaneous observations to discuss the upper limits of redshift for 3C 66A and PKS 1424+240.

We derive the variation of the optical depth with the redshift for different VHE bands using the Franceschini et al. (2008) EBL models, in which the method of linear interpolation is used. PG 1553+113 has 22 observed VHE bands, while 3C 66A and PKS 1424+240 have less observed VHE bands.

Using the optical depth for specific observed VHE bands, we can correct the intrinsic spectra to get the expected spectra. We then calculate the χ^2 between the expected and observed spectra for different redshifts shown in the Fig.1. Finding the redshift with the minimum χ^2, we get z =0.78 for PG 1553+113, z = 0.58 for 3C 66A, and z=1.19 for PKS 1424+240. We assume there is no cutoff across the intrinsic GeV and VHE bands, the extrapolated VHE spectra represent the upper limits. Therefore, our obtained redshifts should be the upper limits.

3. DISCUSSIONS AND CONCLUSIONS

In the Fig.2, we plot the optical depths τ of three Blazars at different VHE bands E_γ. The model optical depths given by Franceschini et al. (2008) (black line, almost lowest EBL intensity over the concerned range) and Best-fit Kneiske et al. (2004) (red line, moderate level) are also shown in this figure. Since the intensity of Franceschini et al. (2008) EBL model is lower than one of the Kneiske et al. (2004) at the range of 0.1-10μm, which have larger contribution to the absorption of VHE photons (interaction cross section of pair production sharply peak at $\lambda(\mu m) \approx 1.24 E_\gamma(TeV)$(Guy et al. 2000; Hauser & Dwek 2001) for the EBL photons). For the same VHE photons the Franceschini et al. (2008) EBL model give smaller optical depth than the Kneiske et al. (2004) model. Therefore, using the Franceschini et al. (2008) EBL model the deprived upper limits of redshifts will be larger for the same optical depths. We find that the derived τ have flat trend with E_γ than ones given

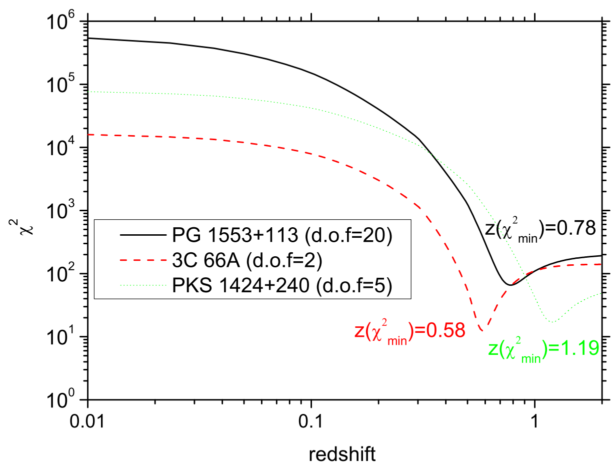

Fig. 1. Change of χ^2 with reshift for PG 1553+113, 3C 66A, and PKS 1424+240. The solid line indicates PG 1553+113, the dashed line denotes 3C 66A, and the doted line is PKS 1424+240. We also label the redshifts at the minimum χ^2.

by these models. The derived τ at lower energy bands are close to the model values with larger redshift. It imply that the optical depth at higher energy E_γ might be overestimated by their EBL models. The EBL at optical-infrared wavelengths is more transparent for TeV sources than one predicted previously. Of course, we can not rule out a flux break at TeV band caused by the second emission component. If the intrinsic spectra have a hard change at TeV band, the optical depths will be underestimated.

The redshifts of three blazars derived by the minimum χ^2 are compatible with the Franceschini et al. (2008) EBL model ones shown in the Fig.2. For PG 1553+113, our derived redshift is consistent with the lower limit given by Sbarufatti et al. (2005) under the HST snapshot survey. Abdo et al. (2010) use the same method to derive the redshift with $z < 0.75$. We note the different redshift to be caused by the selected VHE data from Aharonian et al. (2006). Mazin & Goebel (2007) also made an upper limit on the redshift of PG 1553+113 as z < 0.69. They used an argument that the VHE intrinsic photon index cannot be harder than $\Gamma = 1.5$ instead of the GeV ones observed by the Fermi. The different results mainly come from different EBL model used. For the EBL photons of 0.1-10μm which cause serious absorption of the VHE photons, their intensity given by Franceschini et al. (2008) model is lower than one used by Kneiske et al. (2004) model. For PG 1553+113, we use 22 VHE data to derive the redshift, the result might be reliable. However, for 3C 66A and PKS 1424+240, the derived redshift has large uncertainty due to less VHE data. Acciari et al. (2010) deduced that the redshift of PKS 1424+240 is less than 0.66. The difference with our result comes from the adopted EBL models.

Because Blazars are variable sources, the simultaneous observations at GeV and VHE range are reliable to constrain the redshifts of BL Lacs using this method. For the 3C 66A, there is near-simultaneous Fermi LAT and VERITAS observations. VERITAS observed 3C 66A for 14 hr from September 2007 through January 2008 and 46 hr from September through November 2008. Note that there were 1431 excess events detected during the period from MJD 54740 (October 1 2008) through MJD 54749 (October 10 2008), which accounts for 80% of the total(Acciari et al. 2009a). Thus, while the spectrum adopted here is for the full data set, it is dominated by this period. Fermi spectrum adopted by us is from August 4 to October 30 2008(Abdo et al. 2009a). We assume that the VERITAS and Fermi observations are in the same state. For the PKS 1424+240, Acciari et al. (2010) also provided the VHE and contemporaneous Fermi LAT observations. The VHE flux is steady over the observation period from February 19 2009 to June 21, the LAT data overlapping with the VERITAS observations were analyzed by them (Acciari et al. 2010). PG 1553+113 has four VHE data sets(Aharonian et al. 2006 ; Aharonian et al. 2008a ; Albert et al. 2007a ; Albert et al. 2009), but they are not simultaneous with the Fermi LAT ones. The VHE photon index of PG 1553+113, respectively reported by HESS and MAGIC with $\Gamma_{obs} = 4.0 \pm 0.6$, $\Gamma_{obs} = 4.5 \pm 0.3$, $\Gamma_{obs} = 4.2 \pm 0.3$, and $\Gamma_{obs} = 4.1 \pm 0.3$, are very similar. The deviations of energy spectral index from the average value are less than 15%. Normalizing the flux at 300 GeV, we find that the change of flux at 300 GeV are not more than 30%. Uncertainty due to non-simultaneous observation is discussed. We calculate the relative error of upper limits of redshift caused by variability of energy index and flux at VHE range shown in the Table 1. For blazars the variability of index and flux should be simultaneous, separately discussing the errors caused by variability of index and flux in this work might be a simplified one. PG 1553+113 has 22 data points observed by HESS and MAGIC, we use a power-law spectrum to fit these points with the energy index $\Gamma_0 = 2.20$ and the flux $F_0 = 3.54 \times 10^{-11} cm^{-2} s^{-1} TeV^{-1}$ at 300 GeV. Based on Γ_0, F_0 and Fermi data, we calculate the upper limit Z_0 of redshift. We define $V_F = F/F_0$ and $V_I = \Gamma/\Gamma_0$ to show the variability of the energy index and flux. We fix the flux F_0 at 300 GeV and change the energy index shown by V_I, , then we obtain the upper limits Z and the relative errors $RE = |Z - Z_0|/Z_0$. We find that RE is less than 2% when Γ changes about 15%. Similarly we fix the energy index and change the flux described by V_F to calculate Z and RE. We find that RE is less than 12% when the flux at 300 GeV changes 30%.

With our obtained upper limits of redshifts, the de-absorbed intrinsic VHE spectra are hard. If the redshifs are real, the cascade emission will significantly contribute to the GeV spectrum. The GeV radiation is produced by $e^{\pm}$ pairs scattering the cosmic microwave background photons on the way from the source to us, where the $e^{\pm}$ are created by VHE photons interacting with the EBL. However, the GeV emission greatly depends on the EBL model and intergalactic magnetic field which has large uncertainty (Dai & Lu 2002; Fan et al. 2004; Yang et al. 2008). Detailed discussions are complicated and need further observations in the future.

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Table 1. Relative error of upper limits of redshift if the flux or energy index vary at VHE range for PG 1553+113

V_I	0.85	0.90	0.95	1.00	1.05	1.10	1.15
Z	0.76	0.76	0.76	0.76	0.74	0.74	0.74
RE	0%	0%	0%	0%	2%	2%	2%
V_F	0.7	0.8	0.9	1.0	1.1	1.2	1.3
Z	0.85	0.81	0.78	0.76	0.73	0.70	0.69
RE	12%	7%	4%	0%	4%	7%	9%

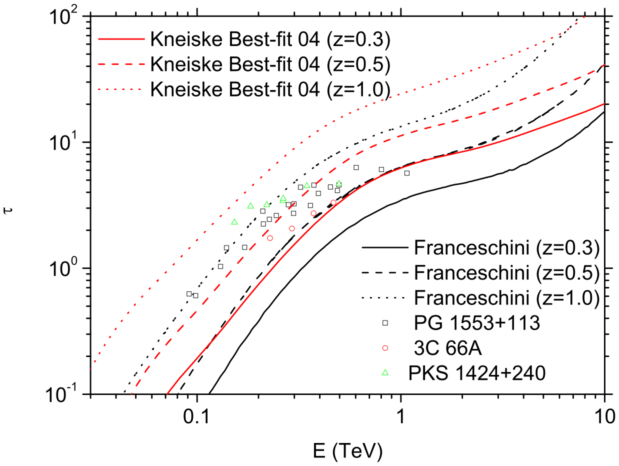

Fig. 2. Relation of derived τ with VHE bands. The open squares indicate PG 1553+113, the black circles represent 3C 66A, and the triangles are PKS 1424+240. The lines show the results of the EBL models respectively given by Franceschini et al. (2008)(black) and Kneiske et al. (2004) (red) under the redshifts of 0.3, 0.5 and 1.0.

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