Cosmology from very high energy $\gamma$-rays

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ABSTRACT

In this work we study how the cosmological parameter, the Hubble constant $H_0$, can be constrained by observation of very high energy (VHE) $\gamma$-rays at the TeV scale. The VHE $\gamma$-rays experience attenuation by background radiation field through $e^+e^-$ pair production during the propagation in the intergalactic space. This effect is proportional to the distance that the VHE $\gamma$-rays go through. Therefore the absorption of TeV $\gamma$-rays can be taken as cosmological distance indicator to constrain the cosmological parameters. Two blazars Mrk 501 and 1ES 1101-232, which have relatively good spectra measurements by the atmospheric Cerenkov telescope, are studied to measure $H_0$. The mechanism measuring the Hubble constant adopted here is very different from the previous methods such as the observations of type Ia supernovae and the cosmic microwave background. However, at 2$\sigma$ level, our result is consistent with which given by other methods.

Subject headings: galaxies: distances and redshifts — BL Lacertae objects: individual (Mrk 501, 1ES 1101-232) — cosmological parameters — gamma-rays: general

1. Introduction

The modern cosmology achieves great progress in recent years. A concordance $\Lambda$CDM cosmology has been built thanks to the precise observations of the “distance indicators” type Ia supernovae (SNe Ia, Riess et al. 1998, 2004, Perlmutter et al. 1999) and the anisotropy of cosmic microwave background (CMB, de Bernardis et al. 2000, Spergel et al. 2003). There are also other cosmological probes such as the large scale structures (Tegmark et al. 2004), galaxy clusters (Allen et al. 2008), observational Hubble parameters (Simon et al. 2005) and the weak gravitational lensing (Munshi et al. 2008) further supporting this scenario. Different methods are roughly consistent with each other within the observation uncertainties. It is very important to develop
additional complementary observational evidence to test this model and measure the cosmological parameters.

It has been pointed out that the observations of VHE $\gamma$-rays at the energy scale of hundred GeV to TeV scale are possible to provide another independent constraint on the cosmological parameters (Salamon et al. 1994). Thanks to the rapid technical development of VHE $\gamma$-ray detection, especially the atmospheric Cerenkov telescopes, great progress of VHE $\gamma$-ray astronomy is achieved in recent years and a large number of VHE $\gamma$-ray sources are detected. Even $\gamma$-ray sources at cosmological distances, such as Mrk 501 at $z = 0.034$ and 1ES 1101-232 at $z = 0.186$ are observed. More importantly the spectra of these sources have been measured with relatively high precision, which provide us the possibility to untangle the effect of attenuation when $\gamma$-rays propagate in the intergalactic space.

The attenuation of VHE $\gamma$-rays is induced by the electron-positron pair production $\gamma + \gamma_{bk} \rightarrow e^+ e^-$ during its propagation in the background radiation field (Nikishov 1962; Gould & Schréder 1966, 1967). This process is actually complex. The observed spectra of extragalactic sources are related with several issues: the intrinsic spectra at sources, the cross section of $\gamma \gamma$ interaction, the intensity of the cosmic infrared background (CIB), and the physical distance the VHE $\gamma$-rays cross. Even before the first detection of the VHE $\gamma$-rays from distant extragalactic sources, the perspective to explore the CIB using the attenuation effect was proposed (Stecker et al. 1992). The discovery of the first extragalactic VHE $\gamma$-ray source, an active galactic nuclei (AGN) Mrk 421, was performed by Whipple in 1992 (Punch et al. 1992). Till now more than 20 extragalactic sources, most of which are AGNs, are discovered by ground-based observatories. The observations of these sources provide us valuable information in understanding the $\gamma$-ray production mechanism and give useful implication or constraint on the CIB intensity (e.g., Coppi & Aharonian 1999; Krawczynski et al. 2000; Renault et al. 2001; Aharonian et al. 2006). On the other hand, once the primary spectra and the CIB intensity are specified, the distance-redshift relation (accordingly the cosmological model parameters) of the sources can be derived from the absorption effect.

In this work we try to constrain the Hubble constant from the absorption effect of distant VHE $\gamma$ sources by the CIB. By a global fitting to the observational spectra of two TeV blazars, Mrk 501 and 1ES 1101-232, we get the Hubble constant with larger errors compared with other methods. In our work the $\Lambda$CDM universe with matter component $\Omega_M = 0.28$ and dark energy $\Omega_\Lambda = 0.72$ is adopted (Komatsu et al. 2008). We find that the best-fitting to the data of the two sources intend to give similar Hubble constant, although they have very different intrinsic spectra and redshifts. This is very encouraging that the attenuation may indeed give implications on the cosmological parameters. We noticed in a previous work Barrau et al. (2008) adopt the similar effect to derive

\[\text{See the VHE source web by Wagner,}\text{http://www.mppmu.mpg.de/~rwagner/sources/}\]
the lower limit of the Hubble constant from observation of Mrk 501. In their work, the direct measurements of CIB intensity was adopted and the intrinsic spectrum of the source was required to be concave.

The outline of this paper is as follows. Sec. 2 describes the absorption of VHE \( \gamma \) photons by CIB. In Sec. 3 we present an introduction to the observations of the two TeV blazars. The implication on Hubble constant is given in Sec. 4. Finally we give conclusion and some discussion in Sec. 5.

### 2. Absorption of TeV \( \gamma \)-rays in CIB

The fundamental process of the VHE \( \gamma \)-ray absorption is due to electron/positron pair production \( \gamma + \gamma_{\text{bk}} \rightarrow e^+ + e^- \). The threshold energy of the pair production is \( m_e^2/\epsilon \), with \( \epsilon \) the energy of the background radiation. For the CMB photon \( \epsilon \sim 10^{-3} \) eV, this absorption takes place for \( \gamma \)-rays with energy \( E \gtrsim 1 \) PeV. While for the TeV scale \( \gamma \)-rays that the current experiments can probe, the responsible soft photon is in the infrared band, i.e., CIB with \( \epsilon \sim 1 \) eV (\( \lambda \sim 1 \) \( \mu \)m). An approximate relation between energies of attenuated VHE \( \gamma \)-rays and the CIB photons is

\[
\frac{\lambda}{1\mu\text{m}} \sim 1.2 \frac{E}{1\text{TeV}}.
\]

The observed VHE \( \gamma \)-ray spectrum after attenuation is given by

\[
F_{\text{obs}} = e^{-\tau} F_{\text{int}},
\]

where \( \tau \) is the optical depth and \( F_{\text{int}} \) is the intrinsic spectrum at the source. For the CIB with number density \( n(\epsilon) \), the optical depth \( \tau \) is given as

\[
\tau(E) = \int dl \int d\cos \theta \frac{1 - \cos \theta}{2} \int d\epsilon n(\epsilon) \sigma(E, \epsilon, \cos \theta),
\]

where \( dl = c dt = \frac{c}{H_0 (1+z)} \frac{dz}{0.28(1+z)^{1.72}} \) is the differential path traversed by the VHE \( \gamma \)-rays, \( \theta \) is the angle between the momenta of VHE \( \gamma \)-ray and CIB photon. The cross section of pair production is

\[
\sigma(E, \epsilon, \cos \theta) = \sigma_T \cdot \frac{3m_e^2}{2s} \cdot \left[ \frac{p_e}{E_e} \left( 1 + \frac{4m_e^2}{s} \right) + \left( 1 + \frac{4m_e^2}{s} \left( 1 - \frac{2m_e^2}{s} \right) \right) \log \left( \frac{E_e + p_e}{m_e^2} \right) \right],
\]

where \( \sigma_T = \sigma_T(R, \epsilon, \cos \theta) \) is the Thompson cross section and \( s = E_e^2 + p_e^2 - m_e^2 \).
Fig. 1.— Attenuation factor of VHE $\gamma$-rays for sources Mrk 501 and 1ES 1101-232. The three curves for each source correspond to the “nominal” (middle curve), 25% higher (lower curve) and 25% lower (upper curve) CIB respectively. The Hubble constant in the calculation is adopted as $h = 0.7$.

with $\sigma_T = 6.65 \times 10^{-25}$ cm$^2$ the Thomson cross section, $s = 2E_\gamma(1 - \cos \theta)(1 + z)^2$ the center of momentum system (CMS) energy square, $E_\gamma = \sqrt{s}/2$ and $p_e = \sqrt{E_e^2 - m_e^2}$ the CMS energy and momentum of electrons.

From Eq. (3) we can see that the intensity of CIB is crucial in determining the effect of attenuation. The CIB is generated by stars and absorption/re-emission of star light by dust in galaxies. The status of measurements and models of CIB can be found in the review paper by Hauser & Dwek (2001). Because of the contamination of foreground from the solar system and the Galaxy, the determination of CIB has relative large uncertainty. Here we adopt the “nominal” model prediction of Aharonian (2001) (curve 1 of Fig. 1) which can give a good description of the measurements. Two other models (curves 2 and 3 in Fig. 1 of Aharonian (2001)) are regarded as the lower and upper limits of CIB intensity. The differences between these model predictions
can vary from several tens percent to several times at different energies. To simplify the uncertainties of CIB in our analysis we take the uncertainty of ±25% relative to the “nominal” model of [Aharonian (2001)] to represent the upper and lower limits. The CIB is denoted as \( n(\epsilon) = A\bar{n}(\epsilon) \), where \( \bar{n}(\epsilon) \) represents the best [Aharonian (2001)] model of CIB, \( A = 1 \pm 25\% \) is a normalization factor to represent the uncertainties, which is energy independent. This form of uncertainties greatly simplifies the process of global fitting.

The comoving density of CIB is adopted to be constant without redshift evolution, which is shown to be of little influence for the sources with redshift \( z \lesssim 0.2 \) [Aharonian et al. (2006)]. Using this CIB field, we calculate the attenuation factor \( e^{-\tau} \) of VHE \( \gamma \)-rays according to Eq. (3) for sources Mrk 501 (\( z = 0.034 \)) and 1ES 1101-232 (\( z = 0.186 \)), as shown in Fig. 1. It can be seen from this figure that the absorption for \( \gamma \)-rays increases rapidly for energies \( \gtrsim 10 \) TeV. It also shows that absorption of the nearby source Mrk 501 at energies \( \sim 20 \) TeV is comparable with the effect to the distant source 1ES 1101-232 at energies \( \sim \) TeV [Barrau et al. (2008)]. Therefore \( \gamma \)-rays with high energy (\( E \gtrsim 10 \) TeV) or high redshift (\( z \gtrsim 0.1 \)) will be very effective to study the attenuation process and CIB [Primack et al. (1999)].

3. TeV \( \gamma \)-ray Observations of the sources: Mrk 501 and 1ES 1101-232

Mrk 501 is a nearby (with redshift \( z = 0.034 \)) BL Lac type blazar, which is a kind of radio-loud AGN with relativistic jet being aligned along the line of sight. The first detection of VHE \( \gamma \)-ray emission from Mrk 501 was performed by Whipple in 1995 [Quinn et al. (1996)]. During the 1997 flares, Mrk 501 was observed by several experiment groups (Catanese et al. (1997); Samuelson et al. (1998); Aharonian et al. (1997); Djannati-Atai et al. (1999); Hayashida et al. (1998)). The energy up to \( \sim 20 \) TeV observed from Mrk 501 makes it a good candidate to study the absorption effect of high energy \( \gamma \)-rays in CIB [Coppi & Aharonian (1999)] and the possible Lorentz violation effect [Protheroe & Meyer (2000)]. In the current study, we use the reanalyzed HEGRA data in 1997 with improved energy resolution [Aharonian et al. (2001)]. The observational spectrum is shown in the left panel of Fig. 2.

The other source investigated here, 1ES 1101-232, is a distant blazar with redshift \( z = 0.186 \). TeV observation of 1ES 1101-232 was performed by H.E.S.S. in 2005 [Aharonian et al. (2006)]. It is shown that even though the measured maximum energy only reaches \( \sim 3 \) TeV, 1ES 1101-232 is still very effective to probe the intensity of CIB in the propagation path VHE \( \gamma \)-rays go through due to its large distance from us [Aharonian et al. (2006)]. The observational spectrum of 1ES 1101-232 is shown in the right panel of Fig. 2.

Actually these observations show harder spectra than expected. Considering the effects of
absorption of the VHE $\gamma$-rays from the normal CIB density and distance-redshift relation, the observed spectra means unnaturally hard intrinsic spectra at the sources. It can be clearly seen from the upper most points in Fig. 2, which are calculated using the usually adopted CIB and $h = 0.7$. For 1ES 1101-232, the corrected spectrum is $\sim E^{-0.1}$, which seems extremely hard when comparing with the expected one from shock acceleration (Malkov & O’C Drury 2001). The corrected spectrum of Mrk 501 can not be fitted with a single power law, however, it is also shown in Fig. 2 that the spectrum of high energy part is very flat.

This possible anomaly has led to quite a few discussions about possible new physics. It was proposed that the axion-$\gamma$ oscillation when the VHE $\gamma$-rays propagate in the intergalactic magnetic field makes the universe more transparent than naively expected (Simet et al. 2008). When $\gamma$-rays oscillate into axions they will not be absorbed by the CIB and keep the primary spectra unchanged (Hooper & Serpico 2007). It was also suggested that the possible Lorentz violation may be responsible for the hard $\gamma$-ray spectra (Protheroe & Meyer 2000). In this scenario the threshold energy of the interaction moves to higher energy and the absorption effect at the observed energy scales becomes weaker. Possible explanations of the hard spectra within astrophysics are also discussed (Aharonian et al. 2006, 2008). In Aharonian et al. (2006) the authors pointed out that if the CIB intensity is about half of the locally measured values the observed $\gamma$-ray spectra can be naturally explained. Aharonian et al. (2008) also suggested some special mechanism to produce very hard intrinsic spectra at the sources.
Since all these explanations are based on a standard cosmological model, we are considering that if these observations have implications on the cosmological model itself. In the following we will show that the best-fitting to the $\gamma$-ray data favors a larger value of the Hubble constant. In spite of the large uncertainties, our result is consistent with previous cosmological measurements at 2$\sigma$ level.

4. Implication on the Hubble constant

The $\gamma$-ray spectra from astrophysical sources are usually very well described by power law functions, which originated from the shock wave acceleration at the sources. Assuming the power law spectral index $\Gamma_{\text{int}}$ at source we get the observed spectrum $F_{\text{obs}} \propto E^{-\Gamma_{\text{int}}} e^{-A\tau_0/h}$ according to Eq. (3), where $\tau_0$ is the optical depth with $A = 1$ and $h = 1$. Using the observational data we can fit the parameters $\Gamma_{\text{int}}$, $A$ and $h$. It should be noted that parameters $A$ and $h$ are strongly coupled with each other, so it is unable to determined them simultaneously from the attenuation of VHE $\gamma$-ray spectra. We firstly fix $A = 1$, and fit the parameters $\Gamma_{\text{int}}$ and Hubble constant $h$. Then we will take the uncertainty of $A$ into account.

![Fig. 3.— 1, 2 and 3$\sigma$ confidence regions (from inner to outer) of parameters $\Gamma_{\text{int}}$ and $h$ for $A = 1$. Left: for Mrk 501; right: for 1ES 1101-232. The cross in each panel is the best-fitting value.](image)

The confidence regions in the $h$–$\Gamma$ plane are shown in Fig. 3. The best-fitting values and 1$\sigma$ errors of the parameters are compiled in Table 1. It is shown that for both sources, the best-fitting Hubble constant $h$ is close to 1, which is larger than the results from other cosmological measurements $h \approx 0.7$, such as from SNe Ia (Astier et al. 2006) and CMB anisotropy (Komatsu et al. 2008). A larger $h$ implies that smaller absorption is favored by the observations. Similar results are also found by the previous studies (e.g., Protheroe & Meyer 2000; Aharonian et al. 2006). We
also notice in Fig. 3 that since the statistical errors of Mrk 501 are much smaller than that of 1ES 1101-232 it also gives much better constraints on the parameters.

The best-fitting intrinsic spectrum is $\Gamma_{\text{int}} = 2.62$ for Mrk 501 and 0.93 for 1ES 1101-232. It seems that the intrinsic spectrum for 1ES 1101-232 is still too hard. Generally the intrinsic spectrum of blazars for both hadronic and leptonic scenarios from shock acceleration is expected to be $\Gamma_{\text{int}} \gtrsim 1.5$ (Malkov & O’C Drury 2001, Aharonian et al. 2006). If we apply a limit $\Gamma_{\text{int}} \gtrsim 1.5$, we find that the Hubble constant $h > 1.2$ at 68% confidence level from 1ES 1101-232. It should be noted that scenario with very hard $\gamma$-ray spectrum is also proposed recently (Aharonian et al. 2008).

It is also shown in Fig. 3 that there is degeneracy between the parameters $\Gamma_{\text{int}}$ and $h$, especially for the source 1ES 1101-232. This is because a harder $\Gamma_{\text{int}}$ means a stronger absorption, and leads to a smaller $h$ (or a larger $A$).

The reconstructed source spectra using the best-fitting parameters are shown by the medium points in Fig. 2. The thick lines in this figure represent the best-fitting power law intrinsic spectra. We can see that the reconstructed source spectra are well consistent with power law functions.

Fig. 4.— Same as Fig. 3 but with a prior $A = 1 \pm 0.25$.

Furthermore, we take the uncertainty of the CIB into account by employing a prior $A = 1 \pm 0.25$ when doing the global fitting. The fitting results of $\Gamma_{\text{int}}$ and $h$ are shown in Fig. 4. For Mrk 501, the best-fitting values are almost the same as the case $A = 1$ (Fig. 3), but the contours become larger after including the uncertainty of CIB. The fitted Hubble constant with 1$\sigma$ range is $h = 1.01^{+0.53}_{-0.40}$. While for 1ES 1101-232, the best-fitting values of the parameters differ significantly from the case $A = 1$ and have larger uncertainties, as shown in the right panel of Fig. 4.

Finally, we combine data of the two sources to fit the Hubble constant $h$. We show the $\chi^2$ values as functions of $h$ taking the prior $A = 1$ and $A = 1 \pm 0.25$ respectively in Fig. 5. The lines
\( \chi^2 = \chi^2_{\text{min}} + 1 \) and \( \chi^2 = \chi^2_{\text{min}} + 4 \) is plotted to show the 1\( \sigma \) (2\( \sigma \)) range of parameter \( h \). We find that \( h = 1.00^{+0.15}_{-0.14} \) for \( A = 1 \), \( h = 1.05^{+0.35}_{-0.19} \) for \( A = 1 \pm 0.25 \) at 1\( \sigma \) level respectively. We can see that after combining data of the two sources the best value of \( h \) is not sensitive to the uncertainties of CIB, although the error bar of \( h \) becomes larger.

5. Conclusion and discussion

In this work we constrain the cosmological parameters, especially the Hubble constant \( H_0 \), by observations of extragalactic VHE \( \gamma \)-ray sources at cosmological distances. The VHE \( \gamma \)-rays experience attenuation by background radiation field through \( e^+e^- \) pair production. This attenuation is proportional to the distance that the VHE \( \gamma \)-rays go through. Therefore the absorption of VHE \( \gamma \)-rays can be used to determine the distance of VHE \( \gamma \)-ray sources, accordingly to get constraints on the cosmological parameters.

By fitting the spectra of two blazars Mrk 501 and 1ES 1101-232 we get the best-fitting Hubble constant is \( H_0 \sim 100 \) km s\(^{-1}\) Mpc\(^{-1}\). A large Hubble constant implies that the absorption of VHE \( \gamma \)-rays is not as significant as we usually expected \cite{Protheroe_Meyer_2000, Aharonian_2006}. Since the observations of VHE \( \gamma \)-rays and CIB are still rough, the errors of the fitting parameters are also very large. The mechanism constraining the Hubble constant adopted here is very different from previous methods, however, our results are consistent with the recent combined analysis of...
CMB, SNe Ia and baryon acoustic oscillation data on Hubble constant $h = 0.701 \pm 0.026$ at 2$\sigma$ level (Komatsu et al. 2008).

In fact, for each single method measuring the Hubble constant there are relatively large uncertainties, including both the statistical and the systematic ones. The HST Key Project measured the Hubble constant from several secondary distance indicators using Cepheid as calibration (Freedman et al. 2001). They gave the results that $h = 0.71 \pm 0.06$ for SNe Ia, $h = 0.71 \pm 0.08$ for the Tully-Fisher relation of spiral galaxies, $h = 0.70 \pm 0.08$ for the surface brightness fluctuations of galaxies, $h = 0.72 \pm 0.11$ for Type II supernovae and $h = 0.82 \pm 0.11$ for the fundamental plane method of elliptical galaxies. The combined result of HST Key Project suggested $h = 0.72 \pm 0.08$. While after the CMB observations are involved, the result is greatly improved (Komatsu et al. 2008), as shown in Fig. 5. It shows that the cross check and combination of different methods are very helpful to find the right answer and improve the accuracy.

Before concluding we would like to briefly comment the simple assumptions adopted in our work. We assume the intrinsic spectrum to be a single power law. In fact the spectral energy distribution of many AGNs can be well described by the so-called synchrotron self-Compton (SSC) model. In the SSC scenario, the VHE $\gamma$-rays are produced through the inverse Compton (IC) scatterings between the electrons and synchrotron photons generated themselves. The VHE spectrum generally has an “IC peak” originates from the transition from Thomson regime to Klein-Nishima regime (Blumenthal & Gould 1970). However, if the energy range is narrow, e.g., within a decade of energy, it can be described approximately by a power law.

The CIB model and its uncertainties are also too simplified. Because of the contamination of foreground radiation, it is usually difficult to get reliable CIB from measurements. The galaxy evolution models to predict CIB also have large uncertainties (Hauser & Dwek 2001; Stecker et al. 2006). In Stecker et al. (2006) the results between the “baseline” and “fast” evolution models differ by about 20% $\sim$ 40%. While the results given by Primack et al. (2005) differ from Stecker et al. (2006) by a factor of 2 at some wavelengths.

Anyway we think the present work is only a prototype of such studies, since the observation of VHE $\gamma$ rays from extragalactic sources is achieved only in the recent years. This field is actually immature and at its early stage. With the next generation of space and ground-based instruments more extragalactic sources will be observed with high precision. Especially the space observatory Fermi\(^2\) (energy range from MeV to hundred GeV) can explore $\gamma$-ray sources to redshift $z \sim 1$, due to an estimate of the “$\gamma$-ray horizon” $\log(z) \sim 1 - 0.7 \log(E/1\text{GeV})$ (Hartmann 2007). The “$\gamma$-ray horizon” is the redshift corresponding to absorption depth $\tau \approx 1$ for energy $E$. With larger sample of data, higher precision of spectra and higher redshift sources from Fermi we can even explore

\(^2\)See the homepage of Fermi, \url{http://www-glast.stanford.edu}
more cosmological parameters besides the Hubble constant, such as the cosmological component or the equation of state of dark energy. The development of ground-based instruments also aims to lower threshold energy and improve sensitivities. We anticipate the field of VHE $\gamma$-ray will develop quickly in the near future. Our work shows that the VHE $\gamma$-rays may become an more important field, not only to astrophysics but also to the cosmology.

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Table 1. Fitting results for parameters

| Source     | $A = 1$ | $A = 1 \pm 0.25$ |
|------------|---------|------------------|
|            | $\Gamma_{\text{int}}$ | $h$ | $\Gamma_{\text{int}}$ | $h$ |
| Mrk 501    | $2.62^{+0.11}_{-0.10}$ | $0.98^{+0.28}_{-0.20}$ | $2.62^{+0.12}_{-0.10}$ | $1.01^{+0.53}_{-0.40}$ |
| 1ES 1101-232$^a$ | 0.93 | 1.09 | 2.15 | 2.80 |
| Combined   | —      | $1.00^{+0.15}_{-0.14}$ | —      | $1.05^{+0.35}_{-0.19}$ |

$^a$The fitting errors of parameters for this source are very large that not shown here.