Prospects for a Very High-Energy Blazar Survey by the Next-Generation Cherenkov Telescopes

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Abstract

The prospects for future blazar surveys by next-generation very-high-energy (VHE) gamma-ray telescopes, such as Advanced Gamma-ray Imaging System (AGIS) and Cherenkov Telescope Array (CTA), are investigated using the latest model of blazar luminosity function and its evolution, which is in good agreement with the flux and redshift distribution of observed blazars as well as the extragalactic gamma-ray background. We extend and improve the template of spectral energy distributions (SEDs) based on the blazar SED sequence paradigm, to make it reliable also in the VHE bands (above 100 GeV) by comparing with the existing VHE blazar data. Assuming the planned CTA sensitivities, a blind survey using a total survey time of ~100 hr could detect ~3 VHE blazars, with larger expected numbers for wider/shallower surveys. We also discuss a following-up of Fermi blazars. The detectability of VHE blazars in the plane of the Fermi flux and redshift is presented, which would be useful for future survey planning. Prospects and strategies are discussed to constrain the extragalactic background light (EBL) by using the absorption feature of brightest blazar spectra, as well as cut-offs in the redshift distribution. We will be able to get useful constraints on EBL by VHE blazars at different redshifts ranging 0.3–1 TeV corresponding to $z = 0.10–0.36$.

Key words: galaxies: active — galaxies: jet — gamma rays: theory

1. Introduction

Very high-energy (VHE; above 100 GeV) gamma-ray astronomy has now been firmly established by observations of the state-of-the-art imaging atmospheric Cherenkov Telescopes (IACTs), such as H.E.S.S., MAGIC, and VERITAS (see de Angelis et al. 2008; Mori 2009, for reviews). Further progress is anticipated in the near future by the planned next-generation IACTs, such as Cherenkov Telescope Array (CTA) and Advanced Gamma-ray Imaging System (AGIS). The sensitivities of all-sky monitoring VHE gamma-ray experiments are also expected to be improved by future projects, such as the High Altitude Water Cherenkov Experiment (HAWC) and the Tibet-III/MD experiment.

Current IACTs have already found ~100 VHE sources, including ~25 blazars. Blazars, a class of active galactic nuclei (AGNs), are the dominant population in the extragalactic gamma-ray sky. Almost all of the extragalactic sources detected by EGRET (Energetic Gamma-Ray Experiment Telescope) aboard the Compton Gamma Ray Observatory are blazars (Hartman et al. 1999). Moreover, 3 months bright source and 11 months catalog by the Fermi gamma-ray space telescope (Fermi) have recently also showed that most of the extragalactic sources are blazars (Abdo et al. 2009a, 2009c, 2010, 2010a), and we expect that more than 1000 blazars will be detected by Fermi in the near future (e.g., Narumoto & Totani 2006; Dermer 2007; Inoue & Totani 2009). The number of VHE blazars is expected to dramatically increase with the improved next-generation IACT sensitivity. Therefore, it would be possible to do a statistical study of VHE blazars in the CTA/AGIS era, which would provide a crucial key to understand AGN populations and high-energy phenomena around super-massive black holes in AGNs and jets.

The purpose of this paper is to consider the prospect of future blazar surveys by IACTs, especially for the statistical power of future VHE blazar samples that can be obtained by realistic observing times of next-generation IACTs. For this purpose, the blazar gamma-ray luminosity function (GLF) and spectral energy distribution (SED) are needed. The blazar GLF has been studied in detail in many papers (Padovani et al. 1993; Stecker et al. 1995; Salamon & Stecker 1994; Chiang & Mukherjee 1998; Mücke & Pohl 2000; Narumoto & Totani 2006; Dermer 2007; Inoue & Totani 2009). Inoue and Totani (2009) (hereafter IT09) have recently presented a new blazar GLF while taking into account the blazar SED sequence (see subsection 2.1), which is in nice agreement with the CGRO/EGRET and Fermi/LAT data. We utilized this IT09 model to predict the expected number and distributions of physical quantities of VHE blazars in future IACT surveys. Since the SED model of IT09 was constrained only at photon energies under GeV, we constructed a new blazar SED template by modifying that used in IT09 in accordance with the available VHE blazar data. By using our updated blazar sequence and GLF model, it has been possible for us to make predictions for future VHE gamma-ray observations, which is the most reliable based on available observed data.

Extragalactic background light (EBL) in the optical and...
infrared bands contains information about the history of star-formation activity in the universe, and knowing EBL quantitatively is an important step to understand galaxy formation in the cosmological context. However, it is hard to measure the EBL spectrum directly, mainly because of a difficulty in subtracting the foreground emission (see Hauser & Dwek 2001, for reviews). VHE observations provide a completely independent constraint on EBL, since VHE gamma-ray photons propagating the universe are absorbed via electron-positron pair creation with the EBL photons (Gould & Schrédler 1966; Jelley 1966). Some useful limits have already been obtained by VHE blazar observations (Aharonian et al. 2006a; MAGIC Collaboration, Albert, et al. 2008), up to the redshift of \( z = 0.536 \) by using 3C279 data. The next-generation IACTs will shed further light on this issue, and we discuss the prospect about this as a particular application of our study.

This paper is organized as follows. We introduce our updated blazar SED template and GLF model, as well as the model of VHE gamma-ray absorptions by EBL in section 2. In section 3, we make predictions for the expected number and statistics of future VHE blazar surveys assuming some observing modes. We discuss the prospect for determining EBL by VHE blazars in section 4. Summary is given in section 5. Throughout this paper, we adopt the standard cosmological parameters of \((h, \Omega_M, \Omega_{\Lambda}) = (0.7, 0.3, 0.7)\).

## 2. Model Description

### 2.1. Blazar Gamma-Ray Spectrum and Luminosity Function

IT09 has recently developed a blazar GLF model based on the latest determination of the X-ray luminosity function of AGNs (Ueda et al. 2003; Hasinger et al. 2005), featuring a so-called luminosity dependent density evolution (LDDE). Another new feature of IT09 is taking into account the blazar SED sequence. The blazar sequence is a feature seen in the mean SED of blazars that the synchrotron and inverse Compton (IC) peak photon energies decrease as the bolometric luminosity increases [Fossati et al. (1997); Kubo et al. (1998); Fossati et al. (1998); Donato et al. (2001); Ghisellini et al. (2009), but see also Padovani et al. (2007)]. The key parameters in GLF have been carefully determined to match the observed flux and redshift distribution of EGRET blazars by a likelihood analysis. Recently, the predicted extragalactic gamma-ray background (EGBR) spectrum by IT09, including non-blazar AGNs contributing to MeV bands (Inoue et al. 2008), has been found to be in excellent agreement with the new determination of the EGBR spectrum reported by Fermi (Abdo et al. 2010b; Inoue et al. 2010).

The gamma-ray SED of the blazar sequence model used in IT09 is constrained only by the EGRET data whose energy range is 30 MeV–30 GeV. Figures 1 and 2 show multi-wavelength SEDs and the radio-to-gamma-ray luminosity relation of VHE blazars, respectively. To avoid the absorption effect by EBL at high redshift, we have selected 12 VHE blazars below \( z = 0.14 \) where the optical depth for 1 TeV photon is \( \lesssim 1 \). We have obtained SED data from published papers for VHE gamma-ray data (see the caption of figure 1) and from the NASA/IPAC Extragalactic Database (NED) for other wavelength data. By comparing with the observed data of VHE blazars, we have updated our blazar SED sequence model to properly reproduce the typical VHE flux of observed blazars. A source of systematic uncertainty in this procedure is the variability of blazars; generally, blazars show rapid and violent variability, and hence it is difficult to accurately estimate the VHE luminosity averaged over a long time. Here, we simply collected published VHE flux data from the literature, except for those of observations aiming at blazars during flares.

As shown in figures 1 and 2, the sequence model of IT09 tends to overestimate the VHE luminosity, but the new formulation reproduces a rough mean of the VHE luminosities, though there is still significant scatter around the mean. Furthermore, the IT09 model shows a kink in the radio-VHE gamma-ray luminosity correlation, because of a mathematical problem of the connection between different luminosity ranges. This kink has also been removed in the new formulation. The new formulation of our updated blazar SED sequence templates is presented in Appendix in detail. We use this sequence template as the best model currently available to predict the statistics of VHE blazars based on the luminosity function determined at lower photon energy bands.

We have also reconstructed the blazar GLF model based on our modified blazar sequence formulation. We set minimum and maximum gamma-ray luminosities of blazars as \( 10^{43} \text{erg s}^{-1} \) and \( 10^{38} \text{erg s}^{-1} \) in \( 10^2 \lambda_0 \), at rest-frame 100 MeV as in IT09. Since the modification in SED is mostly in the VHE energy band, the predictions for other wavelength, including the GeV energy band for Fermi, hardly change from IT09. For example, the expected Fermi blazar count is \( \sim 720 \) and \( \sim 750 \) in the entire sky for our model and IT09, respectively, where we set the Fermi sensitivity as \( 3 \times 10^{-9} \text{photons cm}^{-2} \text{s}^{-1} \) at \( > 100 \text{MeV} \), corresponding to the 1-year sky-survey sensitivity (Atwood et al. 2009). Since Fermi 11-months AGN catalog has already detected 596 blazars and 72 unidentified extragalactic gamma-ray sources at high Galactic latitude (\( |b| > 10^\circ \)), our source count prediction is also consistent with the number of Fermi blazars.

The key parameters of the blazar GLF are \((q, \gamma_1, \kappa) = (4.50, 1.10, 1.42 \times 10^{-6})\), where \( q \) is the ratio between the bolometric jet luminosity and the disk X-ray luminosity, \( \gamma_1 \) the faint-end slope index of GLF, and \( \kappa \) a normalization factor of GLF (see section 3 of IT09 for details). Now we can predict the abundance and statistics of blazars in any photon energy bands including VHE gamma-ray.

### 2.2. EBL Models

When we try to make some predictions for an extragalactic VHE blazar survey, EBL modeling is crucial. A number of models have been proposed by many authors (e.g., Salamon & Stecker 1998; Totani & Takeuchi 2002; Kneiske et al. 2002; Kneiske et al. 2004; Primack et al. 2005; Stecker et al. 2006; Mazin & Raue 2007; Raue & Mazin 2008). Figure 3...
Fig. 1. SEDs (in isotropic equivalent luminosity) of VHE blazars at $z \leq 0.14$. The VHE data points are taken from the literature: Mrk 421 (Albert et al. 2007c), Mrk 501 (Albert et al. 2007d), 1ES 2344+514 (Albert et al. 2007b), Mrk 180 (Albert et al. 2006a), 1ES 1959+650 (Albert et al. 2006b), the BL Lac (Albert et al. 2007a), PKS 2005+489 (Aharonian et al. 2005a), RGB J0152+017 (Aharonian et al. 2008), PKS 2155–304 (Aharonian et al. 2005b), 1ES 0806+524 (Acciari et al. 2009), H 1426+428 (Aharonian et al. 2002), and 1ES 0229+200 (Aharonian et al. 2007). Note that VHE data are deabsorbed by the EBL model of Totani and Takeuchi (2002). The data points at energy bands other than VHE are taken from NED. Solid and dashed curves correspond to blazar sequence models by this paper and IT09, respectively.

Fig. 2. Gamma-ray and 5 GHz radio luminosity relations in $\nu L_{\nu}$. The VHE luminosities in the left and right panels are at 300 GeV and 1 TeV, respectively. Data points are the same as those of 12 blazars in figure 1, except for H 1426+428 and 1ES 0229+200 in the left panel, and the BL Lac and 1ES 0806+524 in the right panel, because of non-detections in the corresponding energy bands. Gamma-ray luminosity is deabsorbed using the optical depth model of Totani and Takeuchi (2002) for intergalactic absorption. The solid and dashed curves correspond to the blazar sequence models by this paper and IT09, respectively.

shows optical depth models of Totani and Takeuchi (2002: TT02), Kneiske et al. (2004: K04), and Raue and Mazin (2008: RM08). Since MR07 constrained the EBL optical depth from VHE blazars observations, we present their model below $z = 0.6$. Here, we use the optical depth of TT02 as the standard in this paper, because it is in good agreement with MR07, which is consistent with VHE blazar observations at low redshift, and it extends beyond $z \sim 1$ by galaxy evolution modeling that is consistent with galaxy counts and EBL observations in both optical and infrared bands (TT02). K04 predicted about twice higher optical depth than TT02, and the expected number of VHE blazars will decrease from our predictions below, when we adopt K04.

3. Predictions for the Upcoming CTA Era

We consider two modes of future surveys for VHE blazars. One is a blank field sky survey. This is a natural outcome for the nearly all-sky monitoring types of VHE observatories (such as the HAWC and Tibet experiments). For IACTs, various survey designs are possible for a fixed amount of the total observation time, changing the survey area and exposure time for one field of view (FoV) [e.g., the Galactic Plane by H.E.S.S.}
Fig. 3. Optical depth of intergalactic absorption of high-energy gamma-rays for various source redshifts, as indicated in each panel. The solid, dashed, and dot-dashed curves correspond to the models of Totani and Takeuchi (2002: TT02), Kneiske et al. (2004: K04), and Raue and Mazin (2008: RM08), respectively. The dotted line marks the level of the optical depth, $\tau = 1$.

(Aharonian et al. 2006b). The other is follow-up surveys for targets selected at other wavelengths. We particularly consider a follow-up survey of Fermi blazars by CTA.

The sensitivity of VHE detectors is often given in terms of the integrated photon flux (total photon flux above a given photon energy). However, a comparison with theoretical predictions is more easily made in terms of the energy flux, like $vF_\gamma$. In this paper, we express the VHE sensitivity in terms of $vF_\gamma = E^2dF_\gamma/dE$, where $E$ is the gamma-ray energy and $dF_\gamma/dE$ the differential photon flux. The sensitivities in the integrated photon flux of H.E.S.S.$^3$, CTA,$^4$ Tibet-III/MD,$^5$ and HAWC$^6$ are converted into $vF_\gamma$, assuming a gamma-ray spectrum of $dF_\gamma/dE \propto E^{-2.5}$, although the spectral index varies from source to source in reality. We also assume that the sensitivity limit scales as $\propto T^{-1/2}$, where $T$ is the exposure time.

Table I summarizes the 5$\sigma$ CTA sensitivities in several energy bands for some sets of the observing time. The sensitivity of CTA will be about one order of magnitude better than that of the current IACTs, and the photon energy range will also become about one order of magnitude wider.

### Table 1. CTA $vF_\gamma$ sensitivity in units of $10^{-13}$ erg cm$^{-2}$ s$^{-1}$.

| Energy   | 2 hr | 10 hr | 50 hr |
|----------|------|-------|-------|
| 30 GeV   | 45   | 20    | 9.0   |
| 100 GeV  | 25   | 11    | 5.0   |
| 300 GeV  | 5.0  | 2.2   | 1.0   |
| 1 TeV    | 3.0  | 1.3   | 0.6   |
| 10 TeV   | 10   | 4.5   | 2.0   |

$^a$ These sensitivities are converted into $vF_\gamma$ basis from those in integrated photon flux of 5$\sigma$, 50 hr observation (http://www.cta-observatory.org/). Sources are assumed to have a power law differential photon spectrum of $dF_\gamma/dE \propto E^{-2.5}$.

3.1. Blank Field Surveys

A blank field survey is the most fundamental mode of observing the sky in a waveband, and free from biases about the pre-selection, except for the flux limit of the survey. A catalog of objects obtained by such a survey is important for a statistical study, such as constructing a luminosity function. For
Fig. 4. Cumulative source counts as a function of the gamma-ray flux (in $E^2 dF/dE$) of VHE blazars. The five panels correspond to different photon energies, as indicated in the panels. The solid curves are predictions by our blazar GLF model. The dotted curves are the same as the solid curves, but for blazars that are detected by Fermi with a sensitivity of $F_{\text{lim}} = 3 \times 10^{-9}$ photons cm$^{-2}$ s$^{-1}$ for photon flux above 100 MeV. The intergalactic absorption by EBL is taken into account for the solid and dotted curve, but not in the dashed and dot-dashed curve. The 5-yr detection limits of H.E.S.S. and CTA for 50-hr observation and those of HAWC and Tibet-III/MD for 1-year observation are also shown. The dotted curve in the panel of 10 TeV is shifted upward artificially by a factor of 1.2 for the purpose of presentation, because the solid and dotted curves totally overlap with each other. The horizontal thin solid line is the total expected number of Fermi blazars with the Fermi sensitivity given above.

For example, the Galactic-plane survey by H.E.S.S. made a breakthrough in Galactic high-energy astronomy by discovering various gamma-ray emitting objects (Aharonian et al. 2006b). Figure 4 shows the cumulative source counts per 1 square degree, i.e., the surface number density of blazars brighter than a given threshold flux, predicted by our blazar GLF model in five energy bands of 30 GeV, 100 GeV, 300 GeV, 1 TeV, and 10 TeV as indicated in the panels. The expected counts in the case of no intergalactic absorption are also shown.

First we examine the expected number of blazars detectable by HAWC or Tibet-III/MD experiments. These experiments cover photon energies higher than $\sim 1$ TeV, and the 1-yr, 5-σ sensitivities of these two telescopes are indicated in the 1 and 10 TeV panels of figure 4. The expected number of blazars by a HAWC search at 1 TeV is about four in 4π steradian, and there may be a chance to detect some bright blazars by HAWC. On the other hand, the expected number is less than one at 10 TeV.

Next we consider a blind survey in a fixed survey area, $A_{\text{survey}}$, by multiple CTA pointing observations. The 50-hr, 5-σ sensitivities of CTA are shown in figure 4. As an example, we consider a total survey time of $T_{\text{survey}} = 100$ hr, and hence the observation time per field-of-view becomes $T_{\text{FoV}} = T_{\text{survey}} (A_{\text{FoV}} / A_{\text{survey}})$. Here, we assume the CTA FoV to be $A_{\text{FoV}} = 20 \text{deg}^2$ (Aharonian et al. 2006b). Assuming that the flux sensitivity limit simply scales as $\propto T_{\text{FoV}}^{-1/2}$, we find that the expected numbers of blazars are 0.17, 0.56, 0.89, 2.3, and 3.3 for the assumed survey areas of $A_{\text{survey}} = 40, 200, 400, 2000$, and $4000 \text{deg}^2$, respectively, in the energy band of 300 GeV. The expected numbers in the other energy bands are summarized in table 2. These results mean that a wider and shallower sky survey is better for a fixed total survey time. However, the expected number of detectable blazars in a blind survey is at most a few in the case of $T_{\text{survey}} = 100$ hr, which is insufficient for a detailed statistical study, such as the luminosity function. The typical total observable time for IACTs is 1000 hours in a year; a more ambitious survey using $\geq 1000$ hr may be required to construct a sufficiently large sample. Another important implication is that the contamination of extragalactic objects will be small in the Galactic plane survey by CTA.

It should be kept in mind that there are considerable
Fig. 5. Differential redshift distribution of VHE blazars in a blind survey down to several values of flux sensitivity. Here, the 5-σ sensitivity is indicated by the corresponding observation time per field (see table 1 for the sensitivities in physical units). Thick and thin curves are predictions when the intergalactic absorption is taken into account or not, respectively.

Table 2. Expected blazar counts for the 100-hour CTA blank field survey

| Energy  | $A_{\text{survey}}$ [deg$^2$] |
|---------|-------------------------------|
|         | 40  | 200  | 400  | 2000 | 4000 |
| 30 GeV  | 0.26 | 0.59 | 0.80 | 1.4  | 1.7  |
| 100 GeV | 0.22 | 0.52 | 0.72 | 1.3  | 1.6  |
| 300 GeV | 0.17 | 0.56 | 0.89 | 2.3  | 3.3  |
| 1 TeV   | 0.05 | 0.14 | 0.23 | 0.61 | 0.92 |
| 10 TeV  | 0.002| 0.004| 0.007| 0.02 | 0.03 |

uncertainties in the numbers predicted above. The use of the blazar SED sequence is the key to convert the blazar luminosity function in the GeV band into the VHE band, but the validity of the blazar sequence is still a matter of debate. Furthermore, VHE SED of our new sequence model is constrained by only 12 VHE blazars. We did not consider the time variability of blazars, because it is difficult to formulate the variability. The luminosity function model parameters have been determined only by about 50 EGRET blazars, but a much larger statistics by Fermi will soon allow us a more accurate determination of the parameters of the blazar sequence and GLF.

Finally, our model includes only the known blazar population. A completely different extragalactic population may be found by such a blind survey, which is probably the most exciting possibility and a strong motivation for the survey.

Figure 5 shows the expected differential redshift distribution for several flux limits. Again, the cases of no intergalactic absorption are also plotted, and the effect of EBL absorption eliminating high redshift blazars is clearly seen. Therefore, the number and highest redshift of VHE blazars would not dramatically increase even with the CTA sensitivity.

3.2. Following up Fermi Blazars

Since a blind survey for VHE blazars seems not to be easy, or to require a large amount of observing time, even with the CTA sensitivities, we consider another strategy to find new VHE blazars, i.e., following up blazars detected at other wavelengths. The results of the three-month bright source and 11-month AGN catalog by Fermi have already been published (Abdo et al. 2009a, 2009c, 2010), including 596 sources identified as blazars. It is expected that Fermi will eventually discover $\geq 1000$ blazars in future surveys (Dermer 2007; Inoue & Totani 2009). Very recently Abdo et al. (2009b) have reported that Fermi detected GeV gamma-rays from 21 blazars that have been detected in TeV bands. Therefore, following up Fermi blazars would be one of the most promising ways to increase VHE blazar samples.
Fig. 6. Source counts of Fermi blazars that are detectable by CTA, as a function of flux in the Fermi band (>100 MeV). Five panels are for five photon energy bands of CTA, and three different curves are for the different CTA flux sensitivities for each blazar that are the same as those in figure 5. See table 1 for the sensitivity limits in physical units. The dotted curves are for all Fermi blazars regardless of the detectability by CTA. Thick curves take into account the intergalactic absorption, while thin curves do not.

Figure 4 also shows the expected cumulative source counts of blazars that will be detected by Fermi, where we set the Fermi sensitivity as $3 \times 10^{-9}$ photons cm$^{-2}$ s$^{-1}$ at >100 MeV for one-year survey (Atwood et al. 2009). We adopt this value for the Fermi sensitivity throughout this paper unless otherwise stated. Taking the sensitivity of 50 hr observation by CTA (indicated in the figure), the expected number of detectable blazars is not much different (within a factor of about two) from that of a blind search.

Although $\sim$1000 blazars will be detected by Fermi in all sky, a simple systematic follow-up of all these blazars will not be practical for CTA. In a realistic future observation, we should set an appropriate threshold flux and redshift range of Fermi blazars to efficiently select the follow-up targets for CTA. Figure 6 shows the number of blazars detectable by CTA as a function of the Fermi GeV flux, for three different sensitivities of CTA observations. This figure tells us that the fraction of Fermi blazars detectable by CTA becomes smaller for higher photon energy bands due to the sensitivity and intergalactic absorption, indicating that a follow-up survey may become inefficient if only the flux information is utilized.

Since $\sim$70% of Fermi blazars have already been measured concerning their redshifts (Abdo et al. 2010a), it is expected that a significant fraction of Fermi blazars will have redshift information. Therefore, the redshift information may also be useful to select Fermi blazars as the targets for CTA observations, though using redshift information might introduce a further bias in the resulting sample. Figure 7 shows the region in the Fermi flux versus the redshift plane for blazars than can be detected by CTA for three different sensitivities. We denote $z_\gamma$ (depending on observed gamma-ray energy $E_\gamma$) as the redshift at which the absorption optical depth becomes $\tau(z_\gamma, E_\gamma) = 1$. It should be noted that, even for the same Fermi flux, higher-$z$ blazars are more difficult to detect in the VHE bands. This is not only due to the effect of intergalactic absorption; another effect is that VHE flux becomes relatively smaller compared with the Fermi band at larger distances, because of the larger absolute luminosity and the assumed SED sequence. If the SED sequence is valid, one must be careful to discriminate between these two effects in future analyses.

These two figures will be useful to design the follow-up strategy of Fermi blazars by CTA (e.g., the Fermi flux and redshift thresholds for CTA targets). The spectral index in the Fermi band may also be useful for efficient target selection. A variety of target selection strategies are possible, and the best observing strategy must be determined according to the scientific purposes.
4. On the Determination of the EBL

We now consider how to measure EBL by future VHE observations of blazars by CTA, as a particular application of our result. An obvious approach is to use the brightest blazars and to measure their VHE spectra precisely, to measure the intergalactic absorption feature, and hence EBL. The improved CTA sensitivity would allow us to measure the absorption features over a wider range of the photon energy and, correspondingly, the redshift. The optical depth to a source at redshift \( z \) is an integration of EBL from redshift zero to \( z \) along the photon path, and the optical depth is mainly contributed by EBL photons whose frequency satisfies the relation \( E / c^2 \sim m_e c^2 \). Therefore, EBL measurements by blazars having a variety of redshifts would give us information about the evolution of EBL as well as the spectrum.

Another possible approach to measure EBL is using a break in the redshift distribution by intergalactic absorption. Although this approach would require a larger sample than using a single VHE spectrum of bright blazars, the uncertainty concerning the intrinsic spectrum could be minimized by looking at a statistical signature in the redshift distribution. Here, we quantitatively discuss the feasibilities of these two approaches, which are expected to be complementary to each other.

4.1. Absorption Features in Brightest Blazar Spectra

Figure 8 shows the blazar source counts as a function of the VHE flux around \( z/\langle z \rangle \) in the entire sky for four energies of 100 GeV, 300 GeV, 1 TeV, and 10 TeV, in the case of following up Fermi blazars with the intergalactic absorption taken into account. The values of \( z/\langle z \rangle \) are 1.5, 0.36, 0.10, and 0.035 for each energy, respectively. The flux of the brightest blazars available at the four photon energy bands are \( \langle \nu L_\nu \rangle / (\langle \nu L_\nu \rangle - 10^{39} \text{ erg cm}^{-2} \text{ s}^{-1}) \) (the fluxes at which the expected number becomes order unity in this figure).

First, we set the required signal-to-noise to be \( 5 \sigma \) per logarithmic energy bin width of \( \Delta E / E = 1 \) to detect the absorption feature. This corresponds to \( 7.2 \sigma \) detection for the integrated flux. From estimates of the brightest blazar flux, the required observing times to achieve this \( S/N \) are 450, 0.36, 0.003, and 40 hours for the four energy bands, respectively. The photon energy resolution of CTA may become as good as \( \Delta E / E = 0.1 \), and if we require \( S/N = 5 \) per this spectral resolution, the required significance for the integrated flux becomes \( 19 \sigma \). Then, the required observing times become
Fig. 8. Source counts of VHE blazars as a function of the VHE flux in the four energy bands indicated in the figure, assuming a follow-up of Fermi blazars down to a flux threshold of $F(> 100 \text{ MeV}) = 3 \times 10^{-9} \text{ photons cm}^{-2} \text{s}^{-1}$. Here, the redshift range is limited to around the expected break by EBL absorption: $z_f/2 < z < 2 z_f$. The intergalactic absorption is taken into account. The horizontal dotted line marks the level of one blazar in the entire sky.

Fig. 9. Redshift distribution of blazars detectable in the 300 GeV band, for the case of following up Fermi blazars down to the Fermi flux threshold of $F(> 100 \text{ MeV}) = 3 \times 10^{-9} \text{ photons cm}^{-2} \text{s}^{-1}$. Three different curves are for different CTA sensitivity limits, as indicated in the figure in terms of the exposure time. (See table 1 for the sensitivity.) Thin and thick curves correspond to unabsorbed cases and absorbed cases, respectively. Redshift distribution of Fermi blazars is also shown as black solid line.

3000, 2.4, 0.02, and 270 hours for the four energy bands, respectively. These results indicate that we will have bright blazars at various redshift ranges of 0.01–1.5 to measure EBL with a reasonable amount of observing time. Especially, we will be able to obtain high-resolution spectra of bright blazars with a reasonable observing time between 0.3–1 TeV (corresponding to $z = 0.10–0.36$).

4.2. Cut-Offs in Redshift Distributions

Next, we consider the break signature in the redshift distribution. Here, we suppose that the redshifts of the majority of Fermi blazars are already known at the time of future VHE observations, which seems to be a reasonable assumption, as discussed in the previous section. Suppose a VHE photon energy, $E_γ$, and a corresponding $z_f$. We expect a strong break at around $z_f$ in the redshift distribution of Fermi blazars that are detectable by the VHE photon energy band around $E_γ$, and such a break should give a strong constraint on EBL. Such a break is demonstrated in Figure 9, where we show the redshift distribution of Fermi blazars whose Fermi flux is brighter than $F(> 100 \text{ MeV}) = 3 \times 10^{-9} \text{ photons cm}^{-2} \text{s}^{-1}$, and which are detectable at the 300 GeV band with several different CTA sensitivities. Most Fermi blazars at $z < 0.3$ can be detected by CTA, while sharp cut-offs appear, as expected, at redshifts significantly lower than in the cases ignoring intergalactic absorption.

The key question for this approach is whether there are a sufficient number of blazars to construct a statistically large enough sample to see the break. This available number should change with the supposed redshift (or VHE photon energy). Figure 10 gives an answer to this question; it shows blazar counts as a function of the Fermi flux, for Fermi blazars at around $z \sim z_f$ in three VHE photon energy bands. In this figure, we show the source counts of blazars that can be detected with several different CTA sensitivities, as well as the original Fermi source counts. Then, we can estimate the number of targets to be observed and the detection rate at the VHE bands for a given Fermi threshold flux and VHE sensitivities. We did not show panels for 30 and 100 GeV because the expected break redshift by intergalactic absorption is comparable with, or larger than, the redshift limit coming from CTA sensitivity with a reasonable amount of observing time (see figure 7).

From this result, it seems to be difficult to construct a statistically large ($\geq 10$) sample at 10 TeV. However, in the 300 GeV and 1 TeV bands, we will be able to construct a sample of a few tens of blazars with 30 and 30 hours of the total observational time by following up Fermi blazars down to $F(> 100 \text{ MeV}) = 3 \times 10^{-9} \text{ photons cm}^{-2} \text{s}^{-1}$, respectively. Here, we assumed that all samples are $5\sigma$ detection in the integral flux, and the minimum observational time for each blazar is 0.5 hours. If we require $10\sigma$ detection for each blazar at these VHE sensitivities, the total observation time necessary for this survey becomes 200 and 100 hours, respectively. Therefore, this statistical approach seems to be feasible in the VHE energy range of 0.3–1 TeV, which is complementary to EBL measurements using the spectral break of bright blazars.

It should be noted that the location and shape of the break in the redshift distribution depends not only on EBL, but also the VHE luminosity function of blazars, which may induce some systematic uncertainties in the EBL measurement by this approach. However, we should be able to construct luminosity distribution of VHE blazars that is not affected by intergalactic absorption by using blazars slightly below $z_f$. We do not expect a strong cosmological evolution of the VHE luminosity function of blazars in a small range of redshift around $z_f$, and we can apply the VHE luminosity distribution below $z_f$ to derive the optical depth of intergalactic absorption, without invoking uncertain theoretical modeling.
5. Summary

In this paper, we estimated the expected source counts and redshift distribution of VHE blazars for the next-generation IACTs, such as CTA and AGIS missions based on the latest blazar GLF model of Inoue and Totani (2009). For this purpose, we developed a new SED sequence formula of blazars while taking into account the latest VHE data, though the previous sequence formulae were constructed using only data at photon energies below the EGRET/Fermi energy band. The parameters of our blazar GLF were also refined with this new SED formula, by fitting to the GeV blazar data. Our modeling does not include time variabilities of VHE blazars, and blazars at flaring states would be more easily detected than estimated here.

We made predictions for future VHE blazar survey in two observing modes: one was a blind survey in a blank field, and the other was a following up survey of Fermi blazars. We found that CTA will detect a few VHE blazars by a blind survey using a total survey time of 100 hours. Therefore, a large amount of observing time ($\gtrsim 1000$hr) is required to construct a statistically large sample of blazars selected only by VHE bands. However, this suggests that blazar contamination in the Galactic plane survey should not be significant, even in the era of the next-generation IACTs. We also found that future all-sky gamma-ray detectors, such as HAWC and Tibet-III/MD, will detect only a few VHE blazars in one year survey in the entire sky. The survey design for a follow-up survey of Fermi blazars should be dependent on the scientific purposes. Here, we presented a plot for regions in the Fermi flux versus the redshift plane where the Fermi blazars can be detected by VHE observations for several different sensitivities.

As a particular example of Fermi blazar follow-up surveys, we considered a survey for the purpose of determinings of EBL by VHE observation. CTA can observe VHE blazars that are sufficiently bright to obtain detailed spectra with a high S/N in the redshift range of $z \sim 0.10$–0.36, corresponding to the absorption cut-off energy of 1–0.3 TeV, and hence we can constrain not only the EBL flux, but also its spectra and/or redshift evolution. It will also be possible to construct a statistically large sample ($\gtrsim 30$) of blazars at $z \sim 0.10$–0.36 to constrain EBL by the sharp break in the redshift distribution. This approach could avoid, or minimize, any uncertainty about the intrinsic blazar spectra, and hence could be complementary to using a few spectra of the brightest blazars.

This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract...
Appendix 1. The New Blazar SED Sequence Templates

We introduce some modifications on the inverse Compton (IC) component of the blazar SED sequence model of IT09 to make it in better agreement with VHE blazars data. We define $\psi(x) = \log_{10}[vL_v/(\text{erg s}^{-1})]$ with $x = \log_{10}(v/\text{Hz})$ ($v$ in rest-frame). The empirical SED sequence model of blazars is the sum of the synchrotron [$\psi_s(x)$] and IC [$\psi_c(x)$] emissions. Each component is described by the combination of a linear and a parabolic function at low and high photon frequencies, respectively. We take $\psi_R \equiv \log_{10}[L_R/(\text{erg s}^{-1})]$ as a reference of the blazar luminosity, where $L_R$ is the $vL_v$ luminosity in the radio band ($v_R = 5\,\text{GHz}$ or $x_R = 9.698$).

Here, we only describe the modified points from the IT09 blazar sequence model. The peak frequency of the IC component, $v_c$, is determined by the relation to that of the synchrotron component, $v_s$, where $v_s$ has been determined as a function of $v_R$ as in IT09. This relation has been changed into the following equation:

$$v_c/v_s = \begin{cases} 5 \times 10^8 & (\psi_R < 43.0) \\ 5 \times 10^8(10^{\psi_R-43.0})^{-0.1} & (\psi_R \geq 43.0) \end{cases}, \quad (A1)$$

instead of the fixed value $v_c/v_s = 5 \times 10^8$ used by IT09. The parabolic part of the IC component, $\psi_{c2}$, is modified as follows:

$$\psi_{c2}(x) = \begin{cases} -(x-x_c)/\sigma^2 + \psi_{c,p} & (x < x_c) \\ -1.5[(x-x_c)/\sigma]^2 + \psi_{c,p} & (x \geq x_c) \end{cases}, \quad (A2)$$

from equation (A6) of IT09. Note that the shape of the parabolic part is now different for the synchrotron and IC components. Such a difference is possible by several effects, e.g., an external photon field for target photons of IC, internal absorption of high-energy gamma-rays by pair production, or the Klein–Nishina effect. Finally, the peak luminosity of the IC component, $\psi_{c,p}$, is changed into the following form:

$$\psi_{c,p} = -0.014(\psi_R - 36.2)(\psi_R - 44.6)(\psi_R - 55.0) + 47.7. \quad (A3)$$

from equation (A13) of IT09.

Figure 11 shows the blazar sequence SED of IT09 and of this paper.

References

Abdo, A. A., et al. 2009a, ApJ, 700, 597
Abdo, A. A., et al. 2009b, ApJ, 707, 1310
Abdo, A. A., et al. 2009c, ApJS, 183, 46
Abdo, A. A., et al. 2010a, ApJ, 715, 429
Abdo, A. A., et al. 2010b, Phys. Rev. Lett., 104, 101101
Acciari, V. et al. 2009, ApJ, 690, L126
Aharonian, F. et al. 2002, A&A, 384, L23
Aharonian, F. et al. 2005a, A&A, 436, L17
Aharonian, F. et al. 2005b, A&A, 430, 865
Aharonian, F. et al. 2006a, Nature, 440, 1018
Aharonian, F. et al. 2006b, ApJ, 636, 777
Aharonian, F. et al. 2007, A&A, 475, L9
Aharonian, F. et al. 2008, A&A, 481, L103
Albert, J., et al. 2006a, ApJ, 648, L105
Albert, J., et al. 2006b, ApJ, 639, 761
Albert, J., et al. 2007a, ApJ, 666, L17
Albert, J., et al. 2007b, ApJ, 662, 892
Albert, J., et al. 2007c, ApJ, 663, 125
Albert, J., et al. 2007d, ApJ, 669, 862
Atwood, W. B., et al. 2009, ApJ, 697, 1071

Chiang, J., Fichtel, C. E., von Montigny, C., Nolan, P. L., & Petrov, V. 1995, ApJ, 452, 156
Chiang, J., & Mukherjee, R. 1998, ApJ, 496, 752
de Angelis, A., Mansutti, O., & Persic, M. 2008, Nuovo Cimento Rivista Serie, 31, 187
Dermer, C. D. 2007, ApJ, 659, 958
Donato, D., Ghisellini, G., Tagliaferri, G., & Fossati, G. 2001, A&A, 375, 739
Fossati, G., Celotti, A., Ghisellini, G., & Maraschi, L. 1997, MNRAS, 289, 136
Fossati, G., Maraschi, L., Celotti, A., Comastri, A., & Ghisellini, G. 1998, MNRAS, 299, 433
Ghisellini, G., Maraschi, L., & Tavecchio, F. 2009, MNRAS, 396, L105
Gould, R. J., & Schréder, G. 1966, Phys. Rev. Lett., 16, 252
Hartman, R. C., et al. 1999, ApJS, 123, 79
Hasinger, G., Miyaji, T., & Schmidt, M. 2005, A&A, 441, 417
Hauser, M. G., & Dwek, E. 2001, ARA&A, 39, 249
Inoue, Y., & Totani, T. 2009, ApJ, 702, 523 (IT09)
Inoue, Y., Totani, T., Inoue, S., Kobayashi, M. A. R., Kataoka, J., & Sato, R. 2010, in Proc. 2009 Fermi Symposium, arXiv:1001.0103
Inoue, Y., Totani, T., & Ueda, Y. 2008, ApJ, 672, L5
Jelley, J. V. 1966, Phys. Rev. Lett., 16, 479
Kneiske, T. M., Bretz, T., Mannheim, K., & Hartmann, D. H. 2004, A&A, 413, 807 (K04)
Kneiske, T. M., Mannheim, K., & Hartmann, D. H. 2002, A&A, 386, 1
Kubo, H., Takahashi, T., Madejski, G., Tashiro, M., Makino, F., Inoue, S., & Takahara, F. 1998, ApJ, 504, 693
MAGIC Collaboration, Albert, J., et al. 2008, Science, 320, 1752
Mazin, D., & Raue, M. 2007, A&A, 471, 439
Mori, M., Shooshtary, N. A., Tohyama, T., & Maekawa, S. 2009, J. Phys. Soc. Jpn., 78, Suppl. A, 78
Mücke, A., & Pohl, M. 2000, MNRAS, 312, 177
Narumoto, T., & Totani, T. 2006, ApJ, 643, 81
Padovani, P., Ghisellini, G., Fabian, A. C., & Celotti, A. 1993, MNRAS, 260, L21
Padovani, P., Giommi, P., Landt, H., & Perlman, E. S. 2007, ApJ, 662, 182
Primack, J. R., Bullock, J. S., & Somerville, R. S. 2005, in AIP Conf. Proc., 745, High Energy Gamma-Ray Astronomy, ed. F. A. Aharonian, H. J. Völk, & D. Horns, (New York: AIP) 23
Raue, M., & Mazin, D. 2008, Int. J. Mod. Phys. D, 17, 1515 (RM08)
Salamon, M. H., & Stecker, F. W. 1994, ApJ, 430, L21
Salamon, M. H., & Stecker, F. W. 1998, ApJ, 493, 547
Stecker, F. W., Malkan, M. A., & Scully, S. T. 2006, ApJ, 648, 774
Stecker, F. W., & Salamon, M. H. 1996, ApJ, 464, 600
Stecker, F. W., Salamon, M. H., & Malkan, M. A. 1993, ApJ, 410, L71
Totani, T., & Takeuchi, T. T. 2002, ApJ, 570, 470 (TT02)
Ueda, Y., Akiyama, M., Ohta, K., & Miyaji, T. 2003, ApJ, 598, 886