PROCEEDINGS OF SCIENCE

Searching for the most distant blazars with the Fermi Gamma-ray Space Telescope

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We investigate the prospects for discovering blazars at very high-redshifts (z>3–6) with the *Fermi* Gamma-Ray Space Telescope (*Fermi*), employing a model for the evolving gamma-ray luminosity function (GLF) of the blazar population. Our previous GLF model is used as a basis, which features luminosity-dependent density evolution implied from X-ray data on active galactic nuclei, as well as the blazar sequence paradigm for their spectral energy distribution, and which is consistent with EGRET and current Fermi observations of blazars. Here we augment the high-redshift evolution of this model by utilizing the luminosity function of quasars from the Sloan Digital Sky Survey (SDSS), which is well-constrained up to $z \sim 5$. We find that Fermi may discover a few blazars up to $z \sim 6$ in the entire sky during its 5–year survey. We also discuss how such high-redshift blazar candidates may be efficiently selected in future Fermi data. We further discuss that the GeV gamma-ray spectra of such high-redshift blazars would be a probe of the early cosmic star formation history.

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1. Introduction

High-energy gamma-ray astronomy has progressed drastically after the launch of the Fermi Gamma-ray Space Telescope (*Fermi*). Its Large Area Telescope (LAT) is currently observing the entire gamma-ray sky in the 0.02 – 300 GeV range. The majority of extragalactic sources detected by *Fermi* are blazars, a subclass of active galactic nuclei (AGNs) dominated by broadband, non-thermal emission arising from relativistic jets oriented close to our line of sight. The *Fermi* 11 month catalog reports the detection of ~ 600 blazars up to $z \sim 3$ [1].

Before the *Fermi* era, the Energetic Gamma-Ray Experiment Telescope (EGRET) detected $\sim$50 blazars in total up to $z \sim 3$ [2]. Since *Fermi* has an order of magnitude better sensitivity and position accuracy compared to EGRET, it is naturally expected that *Fermi* will see much deeper into the universe in gamma-rays.

The purpose of this paper is to discuss expectations for the highest redshift blazars that *Fermi* may discover. This requires reasonable knowledge of their gamma-ray luminosity function (GLF). The blazar GLF has been discussed from different perspectives in many papers so far (see e.g. [3]). Inoue & Totani (2009; hereinafter IT09) [3] and Inoue, Totani & Mori (2010; hereinafter ITM09) [4] have recently developed a new model of the blazar GLF that accounts for the blazar spectral sequence as well as luminosity-dependent density evolution, and which is consistent with the EGRET and current *Fermi* data [4, 5]. However, the ITM10 GLF is uncertain for $z > 3$, because the current observed number of X-ray AGNs and gamma-ray blazars above $z \sim 3$ is insufficient to strongly constrain the model. On the other hand, the optical luminosity function (OLF) of AGNs has been well constrained up to $z \sim 5$ [6]. Therefore, here we consider a modified blazar GLF by combining the AGN XLF with the evolutionary constraints from the AGN OLF data.

Throughout this proceeding, we adopt the standard cosmological parameters of $(h, \Omega_M, \Omega_\Lambda)$ = (0.7,0.3,0.7).

2. High Redshift Evolution of the Blazar Gamma-ray Luminosity Function

2.1 Blazar Gamma-ray Luminosity Function

IT09 recently developed a model for the blazar GLF featuring the so-called luminosity-dependent density evolution (LDDE), based on the latest determination of the AGN XLF [7, 8]. Another novel aspect of IT09 is accounting for the blazar sequence of their spectral energy distribution (SED). The blazar sequence refers to the observed trend whereby the two characteristic frequencies at where the blazar SED peaks systematically decrease as the bolometric luminosity increases [9, 10]. The key parameters in the GLF model have been carefully determined to match the observed flux and redshift distribution of EGRET blazars by a likelihood analysis. Although the blazar sequence SED in IT09 was observationally constrained only up to the EGRET band of 30 GeV, this was extended to include the TeV band in ITM10, using published TeV blazar data. In this paper, we use the ITM10 GLF model as a baseline model.

2.2 Constraints on the High Redshift Evolution of Blazars

The ITM10 GLF model is based on data from EGRET blazars [2] and X-ray AGNs [7, 8], the highest redshifts for both samples being $z \sim 3$. To address the evolution at $z \geq 3$, additional obser-

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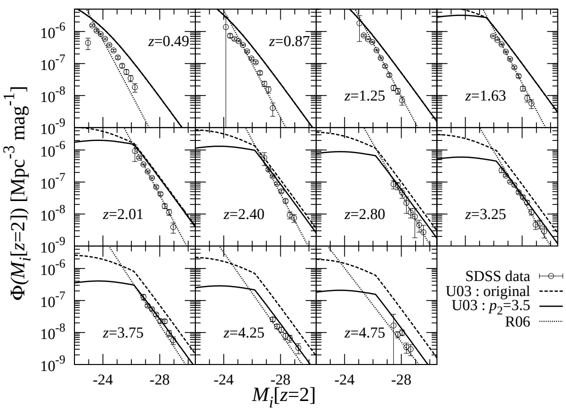

Figure 1: $M_i[z=2]$ luminosity function at each redshift as indicated in each panel. Circles indicate SDSS quasar OLF data [6]. Dashed, solid, and dotted curves show the U03 original XLF ($p_2 = 1.5$), modified U03 XLF ($p_2 = 3.5$), and R06 OLF, respectively.

vational constraints are necessary. Optical surveys such as the Sloan Digital Sky Survey (SDSS) has successfully identified quasars up to $z = 6.43$ [11], and the AGN OLF is well determined up to $z \sim 5$ (Richards et al 2006; hereinafter R06). Utilizing the R06 OLF, below we modify the high redshift evolution of our previous best-fit blazar GLF based on the AGN XLF of Ueda et al. (2003 [7]; hereafter U03) . The AGN XLF and OLF are merged following the procedures in §5.4 of [12] and §3, 4 in U03.

The power-law index p_2 in the U03 XLF characterizes the density evolution as a function of z at high redshift. Although $p_2 = 1.5$ was used in ITM10, here we modify this to $p_2 = 3.5$ in order to be consistent with the high-redshift R06 OLF data. Since p_2 does not affect the low-redshift evolution, the XLF is not significantly altered below $z \sim 3$. Fig. 1 shows the AGN OLF at each redshift as in terms of $M_i[z=2]$ in comparison with the R06 OLF data. With this AGN XLF, we reconstruct the blazar GLF with the ITM10 blazar sequence SED model, following the procedures of IT09.

The key parameters of our new blazar GLF model are $(q,\ \gamma_1, \kappa) = (4.42, 1.07, 1.92 \times 10^{-6})$, where q, the ratio between the bolometric jet luminosity and nuclear X-ray luminosity, γ_1, the faint-end slope index of the GLF, and κ, a normalization factor for the GLF (see Section. 3 of IT09 for details). Base on this model, we make predictions for the high-redshift blazars that *Fermi* may discover.

3. Predictions for high-redshift Fermi blazars

3.1 Expected Redshift Distribution of Fermi Blazars

Fig. 2 shows the expected cumulative redshift distribution of *Fermi* blazars above 100 MeV in the entire sky for a ∼5-year survey flux sensitivity limit of $F(> 100\text{MeV}) = 1 \times 10^{-9}$ photons/cm^2/s. Neglecting high-redshift optical constraints, *Fermi* may be able to detect blazars up to $z \sim 10$. Taking into account their high-redshift evolution implied from the AGN OLF, we expect that *Fermi* will find blazars up to $z \sim 6$ with the ∼5-year survey sensitivity.

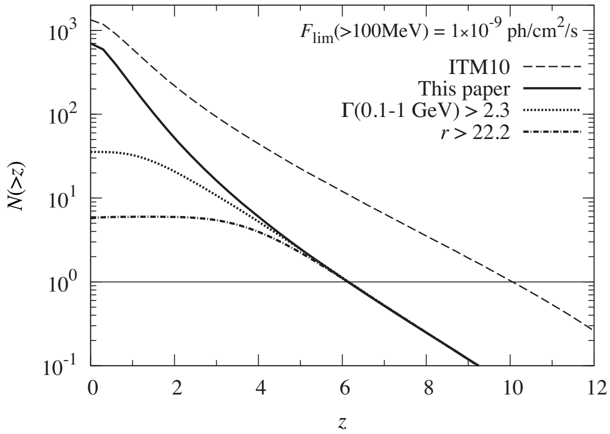

Figure 2: Expected cumulative redshift distribution of blazars detectable by *Fermi* above 100 MeV in the entire sky for a flux sensitivity limit $F(>100\text{MeV}) = 1\times10^{-9}\text{photons/cm}^2/\text{s}$. Solid and dashed curves correspond to whether or not AGN OLF constraints are taken into account. The dotted curve is for $\Gamma > 2.3$, and the dot-dashed curve is for $\Gamma > 2.3$ together with $r > 22.2$

3.2 Methods for selecting high-redshift blazar candidates

It is expected that *Fermi* will find more than 1,000 blazars [3]. Although $\sim 70\%$ of the *Fermi* blazars have confirmed redshifts, the other $\sim 30\%$ still do not [1]. This implies that the highest redshift blazars must be searched for among a large number of sources and distinguished from numerous unrelated ones. The following methods for their observational selection should be effective in searching for high-redshift blazars.

First, we select the sources whose fluxes are close to the *Fermi* sensitivity limit, as the high-redshift blazars are naturally expected to be faint. Furthermore, it should be useful to look those showing time variability, a characteristic trait of blazars.

Second, we choose the sources whose 0.1–1 GeV photon indices $\Gamma > 2.3$ to pick out luminous blazars with gamma-ray luminosities $L_\gamma > 10^{47}$ erg/s at 100 MeV, since high-redshift objects that are detectable should be luminous, and their spectral indices are expected to be soft according to the blazar sequence [9, 10].

Third, we identify the radio counterpart using deep radio survey catalogs, which should give us tighter constraints on the source location and identification. The radio fluxes of blazars at $z > 6$ expected from the blazar sequence are ~ 20 mJy. These are below the limiting sensitivity of radio-loud galaxy catalogs used for the current *Fermi* catalog. More useful for our purposes are the Faint Images of the Radio Sky at Twenty centimeters survey (FIRST) [13] and the NRAO VLA Sky Survey (NVSS) [14] catalogs, which go down to 1 mJy at 1.4 GHz, below the expected 1.4 GHz radio flux for blazars at $z > 6$. Within the *Fermi* localization uncertainty of $\sim 10'$ at Galactic latitudes $|b| > 10^\circ$, the expected radio source count is ~ 0.20 blazars. Therefore, identifying the radio counterpart should be essential.

Fourth, we select objects that are not detected in optical surveys such as the SDSS, in view of the unavoidable attenuation due to intergalactic HI for high-redshift sources. Since FIRST covers the SDSS survey area, a quarter of the entire sky, sources detected by the SDSS can be searched for their radio counterparts. Here we set the optical selection criterion to be $r > 22.2$ in AB magnitude, the r-band limiting magnitude of SDSS. We caution that the SDSS sensitivities in the i and z band would be insufficient for detecting blazars at $z > 3$ even in the absence of intergalactic absorption. Thus, the SDSS data by itself cannot be used for identifying high-redshift blazars, but will nevertheless be valuable for rejecting low-redshift contaminants.

The dotted and dot-dashed curves in Fig. 2 show cases where the above selection criteria have been imposed for the gamma-ray photon index and the optical magnitude. The expected total number of *Fermi* blazars would decrease to ~ 60 sources, of which $\sim$38% is expected to lie at $z > 5$, so this procedure should be effective in narrowing down high-redshift blazar candidates, albeit with some remaining low-redshift contamination. Finally, deeper optical and infrared follow-up observations of the candidate objects are warranted to accurately identify their respective counterparts and spectroscopically measure their actual redshifts. Note that for blazars in the southern sky, surveys such as that being undertaken by the South Pole Telescope at 1.4 and 2.0 mm with milli-Jansky sensitivities [15], as well as the VST ATLAS and VISTA surveys in the optical and near-infrared, should prove to be likewise valuable for their selection.

4. Probing the Cosmic Star Formation History at $z > 6$

It is well known that high energy γ-rays ($\gtrsim$20 GeV) propagating the universe are absorbed by the interaction with the extragalactic background light (EBL), also called as cosmic optical and infrared background [16 – 18]. Here GeV photons from high-redshift sources are also expected to suffer intergalactic absorption due to electron-positron pair production interactions but with the high redshift cosmic UV background radiation [18 – 20].

By using the semi-analytical galaxy formation model [21], we have estimated the gamma-ray optical depth from $z = 20$ to $z = 0$ [22]. In Figure. 3, we show the expected gamma-ray optical depth comparing with previous works [16, 20]. The resulting absorption features in the spectra of such sources could therefore be a key probe of the poorly-understood UV background radiation and provide valuable insight into the cosmic dark ages. Discovering high-redshift gamma-ray blazars or gamma-ray bursts will thus offer a new probe of the formation histories of early stars and galaxies.

5. Summary

We studied the prospects for detecting the highest-redshift blazars with *Fermi*, and how we may select such blazars from the numerous other expected *Fermi* sources. The high-redshift evolution of the blazar GLF was constrained from the observed AGN OLF, which is well determined up to $z \sim 5$. Thus we found that *Fermi* may discover some blazars up to $z \sim 6$ down to the $\sim$5-year survey flux sensitivity limit of $F(> 100\mathrm{MeV}) = 1 \times 10^{-9}$ photons/cm^2/s.

High-redshift blazar candidates may be selected through the criteria that the source (1) is faint and shows time variability, (2) has a soft spectrum with $\Gamma > 2.3$, corresponding to luminous blazars in the blazar sequence, (3) has a radio counterpart in deep survey catalogs such as FIRST, and (4) are not detected in the SDSS, which should remove low-redshift contamination. Then such sources must be followed up by optical and infrared telescopes.

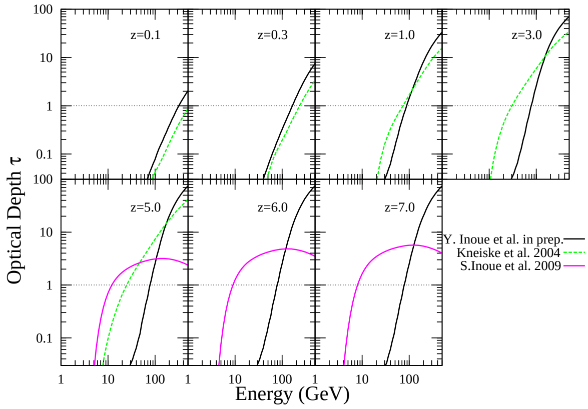

Figure 3: Optical depth of intergalactic absorption of high-energy gamma-rays for various source redshifts, as indicated in each panel. The black, green, and magenta curves correspond to the models of Y. Inoue et al. in prep. [22], Kneiske et al. (2004) [16], and S. Inoue et al. (2009) [20], respectively. The dotted line marks the level of the optical depth, $\tau = 1$.

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