Possible $\gamma$-ray Signals from Low-luminosity Active Galactic Nuclei

Hajime Takami
Max Planck Institute for Physics, Föhringer Ring 6, 80805 Munich, Germany
E-mail: takami@mpp.mpg.de

Abstract. Although it has been believed that both emission from an accretion disk and from a jet contributes to the spectral energy distribution of a low-luminosity active galactic nucleus (LLAGN), the respective contribution of them is still an open question. $\gamma$-ray signals from LLAGNs can constrain a jet component because a jet component is expected to associate with $\gamma$-rays by emission mechanisms similar to powerful blazars and radio galaxies, and then play an important role to understand the physics of disk-jet connection. Here, we demonstrate the $\gamma$-ray signals on the assumption that a jet component dominates in X-ray bands, and discuss possible parameter sets on an emission region and the detectability of the $\gamma$-rays. In some reasonable cases, Cherenkov Telescope Array can detect $\gamma$-rays from a nearby LLAGN.

1. Introduction
An active galactic nucleus (AGN) is a powerful object in the Universe, which is powered by gravitational energy through the accretion of surrounding gas onto a supermassive black hole (SMBH) located at the center of the accretion system. The accretion paradigm has been extensively applied to extremely powerful objects such as quasars and radio galaxies for extragalactic objects, but recently the idea that all the galaxies have their own SMBHs at their centers has been commonplace [1] and optical spectroscopic surveys have revealed that a significant fraction of nearby galaxies have active nuclei which are much less luminous than the powerful objects ($< 10^{40}$ erg s$^{-1}$ in nuclear H$\alpha$ luminosity; low-luminosity AGNs (LLAGNs)) [2]. The Eddington ratio of LLAGNs are much lower than the canonical value ($\sim 10$ per cent) and reach $\sim 10^{-8}$ in some cases [3].

The low radiative efficiency and the weak feature of the big blue bump [4] indicate optically thin, radiatively inefficient accretion flows (RIAFs) in LLAGNs. Advection-dominated accretion flow (ADAF) models [5, 6], which are a kind of RIAF models, have successfully reproduced the spectral energy distribution (SED) of Sagittarius A* which is a SMBH located at the center of our Galaxy [7, 8, 9]. Recently, ADAF models have been applied to nearby LLAGNs to investigate the physics of the accretion disk of LLAGNs. However, it is a difficult task to measure radiation from the core of a LLAGN because very good angular resolution is required to avoid possible contamination from stellar and dust emission. This fact prevents us from obtaining good multi-wavelength SED and from understanding the nature of LLAGNs. Radio observations are a powerful tool, they have revealed a compact core morphology [10, 11] and have implied the existence of an ADAF component [12]. Recent observations have revealed that a ADAF component is not enough to reproduce total radio emission from a core, which
indicates the contribution of jets [13, 14, 15]. These observations imply the coexistence of both disk and jet components in emission from LLAGNs. Recently, Ref. [16] demonstrated the SED modeling of several observed LLAGNs by using both the components and showed that observed X-ray data can be reproduced by either disk-dominated or jet-dominated radiation models without inconsistency because of sparse observational data. The respective contribution of them is connected with the understanding of the nature of the accretion disk of LLAGNs.

A possible solution to understand the origin of the X-rays from LLAGNs is to observe γ-rays. If the X-rays are the synchrotron radiation of relativistic electrons in a jet, the electrons upscatter the synchrotron photons (synchrotron self-compton) or ambient photons (external compton) and produce γ-rays, similarly to the cases of blazars and/or radio galaxies. Thus, γ-rays can be a hint of the jet component of radiation from LLAGNs.

Another motivation to consider γ-rays from LLAGNs is the commonality of γ-ray emission mechanisms among AGNs. Recent progress on Imaging Atmospheric Cherenkov Telescopes (IACTs) have detected a lot of very-high-energy (VHE) γ-ray emitted blazars and radio galaxies. Many BL Lac objects have been detected in VHE energies, which are associated with Fanaroff-Riley I galaxies based on a unification hypothesis [17], and their accretion disks are thought to be RIAFs. Thus, accretion physics is similar between VHE-detected BL Lac objects and LLAGNs. How common are γ-ray emission mechanisms among AGNs?

In this paper, we demonstrate possible γ-ray signals from a LLAGN, NGC 4278, as a representative on the assumption that a jet component dominates in X-ray bands by fitting observed SED in the framework of a synchrotron self-compton (SSC) model. We also discuss the detectability of the γ-ray signals by γ-ray observatories.

2. Model

We consider an one-zone SSC model for LLAGNs. Electrons are accelerated in a jet via particle acceleration mechanisms, such as shock acceleration [18], and are assumed to have a smoothed broken power-law spectrum,

\[ \frac{dn_e}{d\gamma} = n_0\gamma^{-s_1} \left( 1 + \frac{\gamma}{\gamma_{\text{br}}} \right)^{s_1-s_2} (\gamma_{\text{min}} \leq \gamma \leq \gamma_{\text{max}}), \]  

(1)

where \( n_0 \), \( \gamma \), \( \gamma_{\text{min}} \), \( \gamma_{\text{max}} \), and \( \gamma_{\text{br}} \) are the normalization factor of the electron number density in an emission blob, the Lorentz factor of electrons, the minimum of \( \gamma \), the maximum of \( \gamma \), and \( \gamma \) at a spectral break, respectively. \( \gamma_{\text{br}} \) and \( \gamma_{\text{max}} \) are determined by the cooling time-scale of electrons as discussed below, while \( \gamma_{\text{min}} \) is fixed at 1.

\( \gamma_{\text{max}} \) can be estimated by comparing the time-scale to accelerate electrons with the shortest energy-loss time-scale. The acceleration time-scale is \( \tau_{\text{acc}} = \theta_F r_g/c = 6 \times 10^2 \theta_F x \gamma^2 B_{-1}^{-1} \) s, where \( r_g \) and \( c \) is the Larmor radius of an electron and the speed of light, respectively. \( \theta_F = \theta_F / 10^2 \), \( \gamma = \gamma / 10^2 \), and \( B_{-1} = B / 10^{-1} \) G. We take \( \theta_F \) to be a constant, which is equivalent to assuming the diffusion coefficient for accelerated particles to be proportional to the Bohm diffusion coefficient. \( \theta_F \geq 10 \) is a fairly conservative value, but \( \theta_F \sim 1 \) is also possible for mildly relativistic shocks [19].

The accelerated electrons suffer from energy-loss via synchrotron radiation and inverse compton scattering (ICS). The cooling time-scale of synchrotron radiation is \( \tau_{\text{syn}} = 3 m_e c / 4 \sigma_T \gamma U_B = 8 \times 10^2 \gamma^{2-1} B_{-1}^{-2} \) s, where \( m_e \), \( \sigma_T \), and \( U_B = B^2 / 8 \pi \) are the electron mass, the cross-section of Thomson scattering and the energy density of magnetic field, respectively. The cooling time-scale of ICS has the same form, but \( U_B \) is replaced by \( U_{\text{rad}} \) in the Thomson regime, which is the energy density of radiation. A process with larger energy density dominantly contributes to the energy-loss of electrons. Practically, we don’t know \( U_{\text{rad}} \) until finishing calculations. Thus, firstly we calculate SED on the assumption that \( U_B \) is dominant, and then check \( U_{\text{rad}} \) in the cases of the small size of an emission blob, \( U_{\text{rad}} \) could be larger than \( U_B \), but
these cases are not favored by several observational aspects as seen afterwards. Consequently, $\gamma_{\text{max}}$ can be estimated by $\tau_{\text{acc}} = \tau_{\text{syn}}$,

$$\gamma_{\text{max}} = \left( \frac{6\pi e}{\theta_F \sigma_T B} \right)^{-1/2} = 4 \times 10^7 \theta_F^{-2} B^{-1}^{-1/2}. \quad (2)$$

Note that this $\gamma_{\text{max}}$ always satisfies the Hillas criterion that $r_g$ should be smaller than $R$ [20] in all the cases treated in this paper.

The cooling of electrons via synchrotron radiation makes a power-law index steeper by 1, where $\tau_{\text{syn}} < \tau_{\text{esc}}$, where $\tau_{\text{esc}} = 3R/c = 1 \times 10^6 R_{16} / c$, is the time-scale to escape electrons from the blob. Here, we assume that electrons escape from the blob by the velocity of $c/3$, which corresponds to the velocity of downstream fluid in a shock system under the strong shock limit of a relativistic shock. Thus,

$$\gamma_{\text{br}} = \frac{2\pi m_e c^2}{\sigma_T R B^2} = 8 \times 10^4 R_{16}^{-1} B^{-1}^{-2}. \quad (3)$$

We estimate the SEDs of a jet component of NGC 4278 in the overall energy range based on the SSC model under the electron spectrum modeled above. This model has five free parameters: $s_1(s_2)$, $B$, $R$, $n_0$, and $\delta$, where $\delta = [\Gamma(1 - \beta \cos \theta)]^{-1}$ is so-called Doppler factor of the blob. For convenience, we change a parameter $n_0$ into the ratio of electron energy density in the blob to $U_B$, $\eta = U_e/U_B$, where

$$U_e = m_e c^2 \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} d\gamma \gamma^2 \frac{dn_e}{d\gamma}. \quad (4)$$

Here, $\gamma_{\text{min}}$ is assumed to be 1.

In order to demonstrate $\gamma$-ray spectra of LLAGNs, this study focuses on a high state of NGC 4278. This object is a LLAGN located at 16.7 Mpc from the Earth [21]. This source is sometimes categorized as a LINER or a radio-loud LLAGN. Recent observations in radio bands have revealed a two-sided relativistic parsec scale jet ($\beta \sim 0.75$) closely aligned to the line of sight ($2^\circ \leq \theta \leq 4^\circ$), where $\beta$ and $\theta$ are the velocity in the unit of speed of light and the viewing angle of the jet, respectively [22]. These observables lead to the relativistic Doppler factor of the parsec scale jet of 2.6, which is much smaller than that of $\gamma$-ray blazars. In addition, there are several observational results with good resolution in optical and X-ray bands.

The size of an emission blob $R$ can be constrained by several discussions. Monthly time-scale variability in X-ray bands [23] limits the blob size as

$$R \leq \frac{\delta c \Delta t_{\text{obs}}}{1 + z} = 3 \times 10^{17} \delta_3 \Delta t_{\text{obs}, -1} \text{ cm}, \quad (5)$$

where $\delta_3 = \delta/3$ and $\Delta t_{\text{obs}, -1} = \Delta t_{\text{obs}}/10^{-1}$ yr is the variability time-scale. On the other hand, the emission blob is natural not to be smaller than the Schwarzschild radius of the central black hole. Since the black hole mass of this object is $M_{\text{BH}} \sim 3 \times 10^8 M_\odot$ [24, 25], the blob size is also limited as

$$R \geq \frac{2G M_{\text{BH}}}{c^2} = 9 \times 10^{13} M_{\odot, 8.5} \text{ cm}, \quad (6)$$

where $M_{\odot, 8.5} = M_{\text{BH}}/10^{8.5} M_\odot$, and $G$ and $M_\odot$ are the gravitational constant and the solar mass, respectively. Thus, we consider $10^{14} \leq R \leq 10^{17}$ cm throughout the paper.
these cases, radio emission from the blob does not dominate at the blob is not dominant (e.g., Refs. [30, 31]). It is not clear at present whether this feature is frequency, which is $\nu_{\text{break}}$ due to synchrotron self-absorption. A smaller is not reduced because ICS is proportional to $n_e$. Although of synchrotron radiation, but this leads to a break frequency lower than that calculated in Fig. 1. $B$ the spectral break frequency of synchrotron radiation be lower. In order to keep observed data self-consistently on the assumption of are not valid. However, even including the effects of ICS, the model cannot reproduce the observed $F(>|E|)$, are shown with the integral sensitivity curves of the Fermi/LAT (5$\sigma$, 1 yr) [27] and CTA (5$\sigma$, 100 h) [28] in the small panel.

3. Possible $\gamma$-ray Spectrum

Fig. 1 shows SEDs calculated on the assumptions of $\delta = 2.6$, and $\theta_F = 10^2$ (left) and $\theta_F = 10^4$ (right). $s_2 \sim 3$ is implied in the X-ray data. The absorption of high-energy $\gamma$-rays by extragalactic background light is taken into account by using a model of Ref. [29]. The other parameters used to fit observed data are listed in Table 1. $\delta = 2.6$ corresponds to a Doppler factor of radio jets estimated from radio images [22]. The sensitivity limit of the Fermi/Burst Alert Telescope (BAT) 54-month sky survey [26] is also shown. In the small panel inside the figure, integral fluxes corresponding to the SEDs with the integral sensitivity curve of the Fermi/Large Area Telescope (LAT) (5$\sigma$, 1 yr) [27] and the integral sensitivity goal of the Cherenkov Telescope Array (CTA) (5$\sigma$, 100 h) are shown [28].

The left panel demonstrates that a smaller blob predicts larger $\gamma$-ray flux. Since the case of a smaller blob requires the larger number density of synchrotron photons, which are seed photons for ICS, to reproduce the observed flux up to X-rays, larger $\gamma$-ray flux is realized.

However, the small size of the blob has several problems. Firstly, radiation energy density dominates compared to the energy density of magnetic field in the blob in the cases of $R = 10^{14}$ and $R = 10^{15}$ cm. In these cases, since $\gamma_{\text{max}}$ and $\gamma_{\text{br}}$ are determined by ICS, Eqs.2 and 3 are not valid. However, even including the effects of ICS, the model cannot reproduce the observed data self-consistently on the assumption of $\delta = 2.6$. $U_{\text{rad}}$ much larger than $U_{\text{B}}$ makes the spectral break frequency of synchrotron radiation be lower. In order to keep $\nu_{\text{br}}$ to be $\sim 10^{15}$ Hz, $U_{\text{rad}}$ should be reduced by decreasing $n_e$ or $B$. Both of these decreases the flux of synchrotron radiation. In the former case, $B$ is required to be larger to compensate the decrease of synchrotron radiation, but this leads to a break frequency lower than that calculated in Fig. 1. Although $\eta$ needs to be larger to reproduce the observed data in the latter case, the total $U_{\text{rad}}$ is not reduced because ICS flux is proportional to $n_e^{-2}$. The second reason is another spectral break due to synchrotron self-absorption. A smaller $R$ produces the spectral break at a higher frequency, which is $\sim 10^{14}$ Hz and $\sim 10^{10}$ Hz for $R = 10^{14}$ and $R = 10^{15}$ cm, respectively. In these cases, radio emission from the blob does not dominate at $\sim 5$ GHz. For well-observed blazars, radio emission at 5 GHz is already optically thick and therefore radio emission from the blob is not dominant (e.g., Refs. [30, 31]). It is not clear at present whether this feature is
Table 1. Parameters required for spectral fits in Figs. 1 ($\delta = 2.6$; left) and 2 ($\delta = 10$; right).

| $R$ [cm] | $B$ [G] | $\eta$ | $B$ [G] | $\eta$ |
|----------|---------|--------|---------|--------|
| $10^{14}$ | 3.72    | 140.0  | 5.86    | 0.25   |
| $10^{15}$ | 0.80    | 37.0   | 1.26    | 0.06   |
| $10^{16}$ | 0.165   | 10.0   | 0.272   | 0.014  |
| $10^{17}$ | 0.035   | 2.5    | 0.058   | 0.003  |

common in radio-loud LLAGNs. However, the tight correlation between radio luminosity at 5 GHz and X-ray luminosity implies that the origin of these radiations is the same [32]. Based on this implication, $R \leq 10^{15.5}$ cm is not favored for $\delta = 2.6$.

The integral flux for $R = 10^{16}$ and $10^{17}$ cm are lower than the integral sensitivity curve of Fermi LAT. This is consistent with the fact that NGC 4278 is not listed in Fermi LAT 1yr source catalog [33]. Unfortunately, even 10 years observations do not reach the prediction for $R = 10^{16}$ cm, assuming that the sensitivity curve of Fermi LAT is roughly scaled inversely proportional to the square root of the total observation time. The integral flux is also compared with the integral sensitivity goal of CTA. The integral flux for $R = 10^{16}$ cm is above the CTA sensitivity at $\sim 100$ GeV. Thus, CTA can test the jet dominance of the total emission in this source in the case of $R \sim 10^{16}$ cm.

In order to check the uncertainty of $\theta_F$, $\theta = 10^4$ are considered in the right panel. Since the cases of $R = 10^{14}$ and $10^{15}$ cm were ruled out, only SEDs for $R = 10^{16}$ and $10^{17}$ cm are shown in the figure. Following the change of $\theta_F$, the spectral edge of synchrotron radiation is shifted to lower energy by a factor of $10^2$. Also, the maximum energy of $\gamma$-rays decreases, but this effect is smaller than the synchrotron edge because of the Klein-Nishina effect. Thus, the detectability of the $\gamma$-rays by CTA for $R = 10^{16}$ is not largely changed.

Finally, we discuss SEDs in the case of $\delta$ larger than 2.6. Fig.2 shows SEDs calculated on the assumptions of $\delta = 10$ and $\theta_F = 10^4$. The other parameters are listed in Table 1. Since the high Doppler factor boosts the flux of radiation, the energy density of radiation much lower than that in the case of Fig.1 is enough to reproduce the observed flux up to X-rays. Thus, the energy density of magnetic field in the blob dominates compared to that of radiation even for $R = 10^{14}$ cm, but the cases of $R \leq 10^{15.5}$ cm are not favored due to synchrotron self-absorption again. The smaller energy densities of radiation and electrons leads to much smaller ICS components than those in Fig.1. Thus, even long-term observations by Fermi LAT and CTA could not confirm these $\gamma$-rays.

4. Summary

We have discussed $\gamma$-ray emission from LLAGN jets in the framework of a SSC model on the assumption of radio and X-rays are dominantly produced from jets. The $\gamma$-rays are a direct probe of a jet component in radio to X-ray bands without contamination from the other components, although the predicted flux is not large. Several observational results allowed us to constrain physical parameters in the emission region in jets. In the case of a Doppler factor as low as that of parsec scale jets and $R \sim 10^{16}$ cm, CTA may detect the $\gamma$-rays in the near future and test the jet dominance of radiation from LLAGNs. The determination of the respective contribution of disk and jet components will gives us a hint of a physical connection between a disk and relativistic jet in LLAGNs. For more details on this articles, see Ref. [34].

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Figure 2. Same as the right panel of Fig. 1, but the cases of $\delta = 10$ and $\theta_F = 10^4$.

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