γ-rays as a diagnostic of the origin of core radiation in low-luminosity active galactic nuclei

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ABSTRACT
The respective contribution of disc and jet components to the total emission in low-luminosity active galactic nuclei (LLAGNs) is an open question. This paper suggests that γ-rays emitted from electrons accelerated in jets could be a direct diagnostic tool for a jet component to the total emission. We demonstrate γ-ray flux from jets based on a synchrotron self-Compton model on the assumption that radio and X-rays are dominantly produced from jets in the case of a high state of a nearby LLAGN, NGC 4278. We also survey parameter space in the model. Observational properties of LLAGNs in radio and X-ray bands allow to constrain physical parameters in an emission region. The size of the emission region \( R \) is limited to \( 10^{16} \leq R \leq 10^{17.5} \) cm if the observed tight correlation between radio and X-ray emission originates from the same jet component. If the beaming factor of the emission region is close to the observed parsec scale jet of NGC 4278 and \( R \sim 10^{16} \) cm, the γ-rays may be detected by the Cherenkov Telescope Array and the jet domination can be tested in the near future.

Key words: galaxies: active – galaxies: individual: NGC 4278 – galaxies: jets – galaxies: nuclei – gamma-rays: galaxies.

1 INTRODUCTION
Active galactic nuclei (AGNs) are powerful objects in the Universe, which are thought to be powered by gravitational energy through the accretion of surrounding gas on to supermassive black holes (SMBHs) located at the centre of the accretion systems. Classically, the accretion paradigm has been applied to extremely powerful objects like quasars and radio galaxies for extragalactic objects. The Eddington ratio \( L_{\text{bol}}/L_{\text{Edd}} \) of these objects, where \( L_{\text{bol}} \) and \( L_{\text{Edd}} \) are the bolometric luminosity and Eddington luminosity, respectively, is \( \sim 10 \) per cent and thereby geometrically thin, optically thick disc models, the so-called standard discs (Shakura & Sunyaev 1973), have been successfully favoured. Recently, the idea that all the galaxies have SMBHs at their centres has been commonplace (Kormendy & Richstone 1995; Magorrian et al. 1998).

Optical spectroscopic surveys have revealed that a significant fraction of nearby galaxies have also active nuclei, but much less luminous than the powerful objects (\( < 10^{40} \) erg s\(^{-1}\) in nuclear H\(\alpha\) luminosity), called low-luminosity AGNs (LLAGNs) (Ho, Filippenko & Sargent 1997). LLAGNs can be furthermore spectroscopically classified into low-ionization nuclear emission region nuclei (LINERs), Seyfert galaxies and transition objects. Their Eddington ratios are much lower than the canonical value (\( \sim 10 \) per cent) appropriate for standard discs and could reach \( \sim 10^{-8} \) in some cases (e.g. Ho 2009). In addition to the low radiative efficiency, the correlation among radio luminosity, X-ray luminosity, and the mass of nuclear black holes (Merloni, Heinz & di Matteo 2003; Falcke, Körding & Markoff 2004) and the weak feature of the big blue bump (Ho 2008) indicates optically thin, radiatively inefficient accretion flows (RIAFs) in LLAGNs.

Advection-dominated accretion flow (ADAF) models (Narayan & Yi 1994, 1995; Abramowicz et al. 1995) are a kind of RIAFs and have been widely discussed to explain the spectral energy distribution (SED) of LLAGNs. ADAF models successfully explained most parts of the SED of Sagittarius A* which is a SMBH located at the centre of our Galaxy (Narayan, Yi & Mahadevan 1995; Mannoto, Mineshige & Kusunose 1997; Mahadevan 1998; Narayan et al. 1998).

ADAF models have been applied to nearby LLAGNs. In order to investigate the origin of radiation from the LLAGN core, radio and X-ray bands are often adopted to avoid possible contamination from stellar and dust emission. Follow-up observations of optically selected LLAGNs in radio bands have detected emission dominated with a compact core morphology (Ho & Ulvestad 2001; Nagar et al. 2002). Despite their low luminosity, a larger fraction of LLAGNs are radio-loud (Ho & Peng 2001; Terashima & Wilson 2003). Doi et al. (2005) detected a spectral bump in high-frequency radio (~submillimetre) bands which is a spectral feature of an ADAF component. However, observations have revealed (1–10 GHz) that ADAF components in radio bands are not enough to reproduce the total radio emission, which indicates the contribution of jets (Ulvestad & Ho 2001; Anderson, Ulvestad & Ho 2004; Wu & Cao 2005). These observations imply the coexistence of both disc and jet components in emission from LLAGNs.

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The respective contribution of disc and jet components from radio to X-ray bands is an open problem. Merloni et al. (2003) found correlation among radio luminosity, X-ray luminosity, and black hole mass and showed that an ADAF model can reproduce observational data better than a radiation model dominated by jets by comparing the data with theoretical models. On the other hand, Falcke et al. (2004) suggested that radiation is dominated by non-thermal emission from jets, by a similar analysis. The correlation between radio and X-ray luminosities has also implied the common non-thermal origin from jets for radio-loud LLAGNs (Balmaverde & Capetti 2006; Panessa et al. 2007). Note that Merloni et al. (2003) also mentioned that considering cooling processes of electrons can improve the reproducibility of the data in the jet model and synchrotron radiation from jets can be responsible up to X-rays. Furthermore, Nemmen et al. (2010) demonstrated theSED fittings of observed LLAGNs and showed that observed X-ray data can be reproduced by both disc-dominated and jet-dominated radiation models without inconsistency at present.

This study suggests that γ-rays emitted from electrons accelerated in jets can be a direct diagnostic tool for a jet component in radio to X-ray bands. When X-rays are produced by synchrotron radiation of the electrons, the synchrotron photons are also upscattered by the electrons through inverse-Compton scattering (ICS) into γ-rays. This is the so-called synchrotron self-Compton (SSC) scenario (Maraschi, Ghisellini & Celotti 1992; Bloom & Marscher 1996). This scenario is well established for the SED modellings of BL Lac objects (e.g. Aharonian et al. 2009; Anderhub et al. 2009). We focus on NGC 4278 as an example of an LLAGN and demonstrate expected γ-ray flux based on a SSC model on the assumption that non-thermal radiation from jets is dominated. We also survey parameter space in the model and constrain physical parameters required in jets.

NGC 4278 is a LLAGN with \( \xi = 0.002 \) and the distance of 16.7 Mpc (Tonry et al. 2001) for \( H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \), which is the Hubble constant. 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 (\( 2 \leq \theta \leq 4 \)), where \( \beta \) and \( \theta \) are the velocity in the unit of speed of light and the viewing angle of the jet, respectively (Giroletti, Taylor & Giovannini 2005). These observables lead to the relativistic beaming factor of the parsec scale jet of 2.6. In addition, a monthly time-scale variability by a factor of 3–5 has been observed in X-ray bands (Younes et al. 2010). In general, the time-scale of flux variability limits the size of an emission region.

This paper is laid out as follows. In Section 2, we describe a model of SED originating from electrons accelerated in relativistic jets. In Section 3, we fit the resultant SED to observed data below X-rays and estimate γ-ray flux. Moreover, combining observational results in radio and X-ray bands, we constrain the physical parameters of an emission region. Finally, we make some discussions and summarize this study in Section 4.

2 MODEL

Electrons are accelerated in a jet via particle acceleration mechanisms, that is, shock acceleration (Blandford & Eichler 1987) and emit synchrotron radiation by interactions with magnetic field. The synchrotron photons are also upscattered by the electrons through ICS. For simplicity, this electron acceleration region is modelled as a magnetized spherical blob with a radius of \( R \), which is moving with a Lorentz factor of \( \Gamma \) in a jet. Once we inject accelerated electrons into the blob, we discuss the interactions and emission from the blob following a SSC model. In this section, we introduce a model of a relativistic electron spectrum. The other details of our SSC model is described in Appendix A.

Although statistical particle acceleration mechanisms produce a power-law spectrum of electrons, the cooling processes of the electrons make a spectral break. Based on this picture and the approximation that electrons are continuously injected to the blob during the order of \( R/c \), electrons accelerated in the blob are assumed to have a broken power-law spectrum,

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

where \( n_0 \) and \( \gamma \) are the normalization factor of the number density of the electrons and the Lorentz factor of electrons, respectively. \( \gamma_{\text{min}}, \gamma_{\text{max}} \) and \( \gamma_{br} \) are the minimum of \( \gamma \), the maximum of \( \gamma \) and the Lorentz factor at a spectral break, respectively. We set \( \gamma_{\text{min}} = 1 \) throughout this paper. \( s_1 \) and \( s_2 \) are the spectral indices below and above \( \gamma_{br} \). For variable sources, an electron spectrum is expected to be time-dependent in reality, but the time profile of the electron injection is uncertain at present. A simple model is instantaneous injection approximation discussed in the literature (e.g. Dermer & Schlickeiser 1993, 2002). On the other hand, when particle acceleration at shocks in a jet is considered, the shocks propagate over a size of the outflowing plasma and can deposit energy continuously as mentioned in Dermer & Schlickeiser (1993). Thus, continuous injection approximation is also plausible in internal shock scenarios. It should be constrained by observations which injection approximation is closer to reality. In this paper, we adopt the continuous injection approximation and the electron spectrum described in equation (1).

\( \gamma_{\text{max}} \) can be estimated by comparing the time-scale to accelerate electrons and the shortest energy-loss time-scale. The former time-scale is

\[
\tau_{\text{acc}} = \frac{\theta_{\text{br}} R}{c} = 6 \times 10^7 \theta_{\text{br}}^2 \gamma R_{\text{br}}^2 \, \text{s},
\]

where \( R \) and \( c \) is the Larmor radius of an electron and the speed of light, respectively, \( \theta_{\text{br}} \) and \( \gamma_{\text{br}} \) are the angle and Lorentz factor at a spectral break, respectively. We take \( \theta_{\text{br}} \) to be a constant, which is equivalent to assuming the diffusion coefficient for accelerated particles to be proportional to the Bohm diffusion coefficient. \( \theta_{\text{br}} \geq 10 \) is a fairly conservative value, but \( \theta_{\text{br}} \sim 1 \) is also possible for relativistic shocks (Rachen & Meszaros 1998).

The accelerated electrons suffer from energy loss via synchrotron radiation and ICS. The former time-scale is

\[
\tau_{\text{syn}} = \frac{3m_e c}{4\pi\gamma U_B} = 8 \times 10^7 \gamma^{-1} R_{\text{br}}^{-2} \, \text{s},
\]

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 time-scale of ICS has a form similar to \( \tau_{\text{syn}} \) in the Thomson limit

\[
\tau_{\text{ics}} = \frac{3m_e c}{4\pi\gamma U_{\text{rad}}},
\]

where \( U_{\text{rad}} \) is the energy density of radiation. The shortest energy-loss time-scale is determined by comparing \( U_B \) and \( U_{\text{rad}} \). If \( U_{\text{rad}} \) is larger than \( U_B, \gamma_{\text{max}} \) and \( \gamma_{br} \) are estimated by adopting \( U_{\text{rad}} \). The flaring of blazars realizes \( U_{\text{rad}} > U_B \) in many cases. However, \( U_{\text{rad}} \) cannot be estimated before the calculation of SED. Returning to a kinetic equation of electrons to determine electron distribution, the equation is non-linear because the ICS energy-loss rate depends

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on the electron distribution. This non-linearity changes the resultant $\gamma$-ray spectrum (Schlickeiser 2009; Schlickeiser, Böttcher & Menzler 2010; Zacharias & Schlickeiser 2010). Since we do not know $U_{\text{rad}}$ initially on the spectral assumption of equation (1), first of all, we calculate SEDs on the assumption of $U_{\text{b}} > U_{\text{rad}}$, which means that the shortest time-scale is $\tau_{\text{syn}}$, and then check $U_{\text{rad}}$. Although this assumption will be satisfied in many cases, $U_{\text{b}} < U_{\text{rad}}$ could be realized when $R$ is small. Fortunately, such cases are not favoured by several observational aspects as discussed in Section 3. Consequently, $\gamma_{\text{max}}$ can be estimated by $\tau_{\text{esc}} = \tau_{\text{syn}}$ under this assumption as

$$\gamma_{\text{max}} = \left(\frac{6\pi e}{\theta_\gamma \sigma T B}\right)^{-1/2} = 4 \times 10^3 \theta_\gamma^{-2} \gamma^{-2/3} B^{-1/2}.$$

Note that this $\gamma_{\text{max}}$ always satisfies the Hillas criterion that $r_\gamma$ should be smaller than $R$ (Hillas 1984) in all the cases treated in this paper.

The cooling of electrons via synchrotron radiation and/or ICS makes a power-law index steeper by 1, $s_2 = s_1 + 1$ above characteristic energy $\gamma_{\text{esc}}$, assuming that accelerated electrons are continuously provided into the blob. Since the electrons lose energy during their staying in the blob, this characteristic energy can be estimated by $\gamma_{\text{syn}} < \gamma_{\text{esc}}$, where

$$\gamma_{\text{esc}} = \frac{2 \Gamma_0 \eta c^2}{\sigma T B^2} = 8 \times 10^3 \Gamma_0^{-1} B^{-1/2} \delta_{\text{b}}^{-2}.$$

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 modelled above. This model has five free parameters: $s_1(s_2), B, R, n_0$ and $\delta$, where $\delta = \left[\Gamma (1 - \beta \cos \theta) \right]^{-1}$ is the so-called the beaming factor of the blob. For convenience, we change a parameter $n_0$ into the ratio of electron energy density in the blob to $U_{\text{b}},$ $\eta = U_e / U_{\text{b}},$ where

$$U_{\text{e}} = m_e c^2 \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} d\gamma' \frac{d\nu}{d\gamma'}.$$

3 EXPECTED $\gamma$-RAYS

In order to estimate $\gamma$-ray flux by fitting a spectrum observed in radio to X-ray bands, we adopt data processed by Younes et al. (2010). A selection criterion of this data set is high angular resolution less than 10 arcsec to resolve radiation from the core of NGC 4278. The authors adopted the data of both Chandra and XMM–Newton obtained in different periods in X-ray bands and found a monthly time-scale variability in which flux is changed by a factor of 3–5. In this paper, we focus on a high state observed by XMM–Newton due to the following two reasons. The first reason is the existence of near-ultraviolet (near-UV) data simultaneously observed with the X-rays by an optical/UV monitor instrument onboard XMM–Newton. Simultaneous data for variable sources are generally a powerful tool to unveil the origin of emission from the sources. The second reason is that a high state expects larger $\gamma$-ray flux, which allows us to diagnose the origin of core radiation more easily. Since XMM–Newton, as well as Chandra, does not have angular resolution, it could not resolve two X-ray point sources close to the core resolved by Chandra. The authors estimated X-ray components other than the core as only 2 per cent by using Chandra data. The data could be well fitted by a power-law spectrum without any thermal component and confirmed that a spectral index in X-ray bands is not contaminated. The photon index defined in the X-ray spectrum in units of photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ was 2.05 $\pm$ 0.02. Assuming that the X-rays are synchrotron radiation from high-energy electrons above $\gamma_{\text{esc}}$, the spectral index of the electrons is $\delta_2 \sim 3.0$. The other optical data were processed from Hubble Space Telescope (HST) data, but they were not observed simultaneously.

In radio bands, we adopt data collected by Nagar, Wilson & Falcke (2001), Giroletti et al. (2005) and Jones, Wrobel & Shaffer (1984), which were also used and listed in Younes et al. (2010). The spectral index $\alpha_{\text{rad}}$ defined as $\nu L_\nu \propto \nu^{-\alpha_{\text{rad}}}$ in radio bands is $\sim 0.5$, where $L_\nu$ is the luminosity per unit frequency, which corresponds to $s_2 = 2.0$ because $s_1 = 2\alpha_{\text{rad}} + 1$ for synchrotron radiation. In order to produce SED in the overall energy range, we fit the observed data in radio and X-ray bands by the model. Flux variability in radio bands is assumed to be small, although the radio data are not simultaneous data to X-rays.

The size of an emission blob can be constrained by several discussions. The monthly time-scale variability in X-ray bands can limit the blob size as

$$R \leq \frac{c \Delta t_{\text{obs}}}{1 + \frac{\delta_2 - 3}{3}} = 3 \times 10^{17} \delta_1 \Delta t_{\text{obs}},$$

where $\delta_1 = \delta_2 / 3 + \delta_3$, $\Delta t_{\text{obs}} = 10^{-1}$ yr is the variability time-scale. Although flux variability by $\sim 10$ per cent in X-ray bands for 1.5 h is also reported in the term observed by XMM–Newton, the origin of this variability is not care here, but will be discussed later. On the other hand, assuming that X-rays are emitted from a blob in jets, it is difficult for its size to be smaller than the Schwarzschild radius of the central black hole, $r_{\text{sch}}$. Since the black hole mass of NGC 4278 is $M_{\text{BH}} \sim 3 \times 10^8 M_\odot$ (Wang & Zhang 2003; Chiaberge, Capetti & Macchetto 2005), the blob size is also limited as

$$R \geq r_{\text{sch}} = \frac{2 G M_{\text{BH}}}{c^2} = 9 \times 10^{13} M_\odot r_{\text{sch}},$$

where $M_{\odot, r_{\text{sch}}} = M_{\text{BH}} / 10^{8.5} M_\odot$, and $G$ and $M_\odot$ are the gravitational constant and the solar mass, respectively. Thus, we consider $10^{14} \lesssim R \leq 10^{17}$ cm below.

Fig. 1 shows SEDs calculated on the assumptions of $\delta = 2.6$ and $\theta_\gamma = 10^3$. The absorption of high-energy $\gamma$-rays by extragalactic background light is taken into account by using the model of Franceschini, Rodighiero & Vaccari (2008). The other parameters required for the spectral fits are listed in Table 1. Note that $\delta = 2.6$ was derived from a radio image of a parsec-scale jet (Giroletti et al. 2005), $\delta$ could be larger at inner jets (discussed afterwards) as radio observations have revealed mildly relativistic parsec-scale jets in blazars contrary to the requirement of $\delta \geq 10$ to reproduce $\gamma$-ray flux (Piner & Edwards 2004). The sensitivity limit of the Swift/Burst Alert Telescope (BAT) 54-month sky survey (Cusumano et al. 2010) 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) (5yr, 1 yr) (Atwood et al. 2009) and goal integral sensitivity of the Cherenkov Telescope Array (CTA) (5yr, 100 h) are shown (CTA Consortium 2010).

Fig. 1 demonstrates that a smaller blob predicts larger $\gamma$-ray flux. The case of a smaller blob requires larger number density of synchrotron photons, that is, seed photons for ICS, to reproduce the observed flux up to $\gamma$-rays, which leads to larger $\gamma$-ray flux.

To realize the increase in synchrotron photons, the strength of the magnetic field and/or the number of electrons in the blob should...
Figure 1. SEDs on the assumptions of $\delta = 2.6$ and $\theta_F = 10^2$. The other parameters are listed in Table 1. The sensitivity limit of the Swift/BAT 54-month sky survey (Cusumano et al. 2010) is also shown. In addition, the corresponding integral fluxes, $F(E)$, are shown with the integral sensitivity curves of the Fermi/LAT (5 yr, 1 yr) (Atwood et al. 2009) and CTA (5 yr, 100 h) (CTA Consortium 2010) in the small panel. The cases of $R = 10^{14}$ and $10^{15}$ cm are not favoured because of synchrotron self-absorption (see text).

Table 1. Physical parameters adopted in Figs 1 and 2. $\delta = 2.6$ is assumed in these figures.

| $R$ (cm) | $B$ (G) | $\eta$ |
|----------|---------|--------|
| $10^{14}$ | 3.72 | 140.0 |
| $10^{15}$ | 0.80 | 37.0 |
| $10^{16}$ | 0.165 | 10.0 |
| $10^{17}$ | 0.035 | 2.5 |

increase. However, only the number of electrons is essentially a free parameter, since the strength of the magnetic field is constrained to reproduce the observed data as follows. In order to fit the radio and X-ray data, a spectral break of synchrotron radiation should be at $\nu_{br} \sim 10^{15}$ Hz. Since the typical frequency of synchrotron photons generated from electrons with the energy of $\gamma$ is

$$\nu_e = \frac{0.29 \delta}{1 + \frac{3 \gamma^2 eB}{4\sigma m_e c}} = 4 \times 10^{15} \delta R_16^{-2} B_{-1}^{-3} \gamma^{-2} \text{ Hz}. \quad (11)$$

The requirement of $\nu_{br} \sim 10^{15}$ Hz means

$$R_16^2 B_{-1}^{-3} \sim 7 \times 10^{-3} \delta, \quad (12)$$

from equations (7) and (11). The values of magnetic field listed in Table 1 are roughly consistent with this estimation. In Table 1, $\eta$ is larger for a smaller blob, which means that more electrons are required for a smaller blob with respect to the increase in magnetic field. Also, the electron energy density is dominated compared to the energy density of magnetic field for $\delta = 2.6$. This is a similar situation to the emission region of blazars.

However, the small size of the blob has several problems. First, radiation energy density is dominated compared to the energy density of magnetic field in the blob in the cases of $R = 10^{14}$ and $10^{15}$ cm. In these cases, $\gamma_{\text{max}}$ and $\gamma_0$ are determined by ICS, which are unlikely to equations (5) and (7). 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 $U_B$ makes the spectral break frequency of synchrotron radiation lower. In order to keep $\nu_{br}$ to be $\sim 10^{15}$ Hz, $U_{\text{rad}}$ should be reduced by decreasing $n_e$ or $B$. Both these decrease the flux of synchrotron radiation. In the former case, $B$ is required to be larger to compensate the decrease in 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 $\sim 10^{11}$ and $\sim 10^{10}$ Hz for $R = 10^{14}$ and $10^{15}$ cm, respectively. In these cases, radio emission from the blob is not dominated 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 dominated (e.g. Aharonian et al. 2009; Anderhub et al. 2009). It is not clear at present whether this feature is 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 (Panessa et al. 2007). Based on this implication, $R \leq 10^{15.3}$ cm is not favoured for $\delta = 2.6$.

The integral fluxes for $R = 10^{16}$ and $10^{17}$ cm are lower than the integral sensitivity curve of the Fermi/LAT. This is consistent with the fact that NGC 4278 is not listed in Fermi/LAT 1 yr source catalogue (Abdo et al. 2010). Unfortunately, even 10-yr observations do not reach the prediction for $R = 10^{16}$ cm, assuming that the sensitivity curve of the Fermi/LAT is roughly scaled inversely proportional to the square root of the total observation time. The integral flux is also compared with the goal integral sensitivity of the CTA. The integral flux for $R = 10^{16}$ cm is above the CTA sensitivity at $\sim 100$ GeV. Thus, the CTA can test the jet domination of the total emission in this source in the case of $R \sim 10^{16}$ cm.

The simultaneous data in a near-UV band is not consistent with the synchrotron component of the SEDs, while the (non-simultaneous) data in optical bands are well fitted by the synchrotron component. Since a one-zone synchrotron model cannot satisfy both the near-UV point and a flat spectrum in X-ray bands at the same time, this near-UV radiation is thought to be the contribution from an accretion disc. In ADAF models, the ICS component of high-temperature thermal electrons in the disc can make a spectral peak at this band (e.g. Mammoto et al. 1997; Nemmen et al. 2010). The synchrotron component is not always dominated in all the bands below X-rays (see also Section 4 for possible contribution of the disc to X-rays).

In order to check the uncertainty of $\theta_F$, $\theta_F = 10^4$ is considered in Fig. 2. 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 in $\theta_F$, 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, which is decrease in the IC cross-section compared with the Thomson scattering. The detectability of the $\gamma$-rays by the CTA for $R = 10^{16}$ is not significantly changed. Note that both Figs 1 and 2 are consistent with the hard X-ray observations at present because of the sensitivity of the Swift/BAT for 54 months is larger than the expected flux. Future observations in hard X-rays, for example, NeXT (Takahashi et al. 2008), will constrain the maximum energy of electrons accelerated in the jets.

Finally, we discuss SEDs in the case of $\delta$ larger than 2.6. Fig. 3 shows SEDs calculated on the assumptions of $\delta = 10$ and $\theta_F = 10^4$. The other parameters are listed in Table 2. Since the high beaming 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 is more dominating compared to that of radiation even for $R = 10^{14}$ cm, but the cases of $R \leq 10^{15.5}$ cm are again not favoured due to synchrotron self-absorption. It is also more dominating compared to the electron energy density, contrary to the cases of Figs 1 and 2. The smaller energy densities of radiation and electrons lead to much smaller ICS components than those given in Fig. 1. Thus, even long-term observations by the Fermi/LAT and CTA could not confirm these $\gamma$-rays.

4 DISCUSSION AND SUMMARY
We have discussed possible $\gamma$-ray emission from jets in LLAGNs and have also constrained several physical parameters in our SSC model. The size of an emission region (blob) was limited to $10^{16} \leq R \leq 10^{17.5}$ cm by a monthly time-scale variability and synchrotron self-absorption. This range is consistent with the variability on a typical time-scale of a few days detected in LLAGNs (Anderson & Ulvestad 2005). On the other hand, we have, so far, neglected a small (~10 per cent) hour time-scale (~1.5 h) variability in X-ray bands reported by Younes et al. (2010). Here, we discuss the origin of this variability.

This indicates the size of an emission region as

$$R \leq \frac{6c \Delta t_{\text{obs}}}{1 + z} = 5 \times 10^{14} \delta_1 \Delta t_{\text{obs}, 1.5h} \text{ cm}, \tag{13}$$

where $\Delta t_{\text{obs}, 1.5h} = \Delta t_{\text{obs}}/1.5$ h is the time-scale of the flux variability. This size is comparable with the Schwarzschild radius of the central black hole for $\delta = 2.6$ and is ~2 $\times$ $10^{15}$ cm even for $\delta = 10$. These sizes are not favoured due to the limitation of $R$ if the X-rays are emitted from the blob. Thus, it is thought that X-ray radiation from an innermost part of an accretion disc contributes to this variability. Theoretically, ADAF models can predict X-rays via thermal bremsstrahlung of ions in an inner hot part of the disc (e.g. Mammoto et al. 1997; Nemmen et al. 2010). This implies that emission from the disc could contribute to the total X-rays by a small (but significant) fraction, even if a jet component is dominated from radio to X-ray bands, suggested by the correlation between radio and X-ray luminosities.

In this paper, a linear regime of synchrotron cooling of electrons, that is, synchrotron cooling under constant magnetic field, was considered. Recently, non-linear radiative cooling of electrons has been discussed (Schlickeiser & Lerche 2007, 2008). Non-linear models assume a constant equipartition parameter $\eta^{-1}$ based on the success of spectral modelling of the observed blazars. Since the synchrotron and inverse-Compton cooling rates of electrons depend on the energy density of relativistic electrons, an electron spectrum resulting from a solution of the kinetic equation of electrons is different from that derived from treatment in a linear regime even for a steady electron injection. Although whether equipartition is realized in jets of LLAGNs is not clear observationally at present, it is an intriguing topic to investigate common physical features between blazars (strong radio galaxies) and LLAGNs.

To summarize, we have discussed $\gamma$-ray emission from LLAGN jets in the framework of a SSC model on the assumption that 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 beaming factor as low as that of parsec-scale jets and $R \sim 10^{16}$ cm, the CTA may detect the $\gamma$-rays in the near future and test the jet domination of radiation from LLAGNs. Determination of the respective contribution of disc and jet components will give us a hint of a physical connection between a disc and relativistic jet in LLAGNs.

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APPENDIX A: SYNCHROTRON SELF-COMPTON MODEL

This appendix is dedicated to describe in detail the SSC model used in this paper. We consider a steady-state, that is, a time-independent model. In addition, it is assumed that electrons and resultant synchrotron photons are distributed isotropically and magnetic field is randomly oriented in the blob. Below, the energies of electrons $E_e$ and photons $E_{\gamma}$ are measured in the unit of the electron mass, that is, $\gamma = E_e/m_e c^2$ and $\epsilon_{\gamma} = E_{\gamma}/m_e c^2$.

The number density of photons in a blob frame, $dN_{\gamma}/d\epsilon$, is determined by a transport equation neglecting partial derivatives of time:

$$\frac{1}{t_{\gamma, \mathrm{esc}}} \frac{dN_{\gamma}}{d\epsilon} = \frac{d^2N_{\gamma, \mathrm{syn}}}{d\epsilon d\gamma} + \frac{d^2N_{\gamma, \mathrm{ICS}}}{d\epsilon d\gamma} (\epsilon),$$  \hspace{1cm} (A1)

where $t_{\gamma, \mathrm{esc}}$ is the escape time-scale of photons from a blob, $d^2N_{\gamma, \mathrm{syn}}/d\epsilon d\gamma$ and $d^2N_{\gamma, \mathrm{ICS}}/d\epsilon d\gamma$ are, respectively, the production rate of synchrotron photons and ICS photons per unit volume from the electron distribution assumed in equation (1). We assume an optically thin limit in this paper, that is, $t_{\gamma, \mathrm{esc}} \ll \tau/c$.

The production rate of synchrotron photons is calculated from the production rate of synchrotron photons from an electron in random magnetic field (Crusius & Schlickeiser 1986):

$$\frac{d^2N_{\gamma, \mathrm{syn}}}{d\gamma d\epsilon} (\epsilon) = \frac{3\sqrt{3}}{\pi} \sigma_{\gamma e} U_{B} g \epsilon^2 \left\{ K_{3/2}(g) K_{3/2}(g) - \frac{3}{5} g^2 \left[ K_{3/2}^2(g) - K_{1/2}^2(g) \right] \right\}, \hspace{1cm} (A2)$$

where

$$g = \frac{\epsilon}{3\gamma^2 m_e c^2}, \hspace{1cm} \sigma_{\gamma e} = \frac{2\pi \hbar c}{\gamma m_e c^2},$$  \hspace{1cm} (A3)

and $K_{\nu}(x)$ is the modified Bessel function of the order of $p$, $r_e$ and $\hbar$ are the classical electron radius and Planck constant, respectively. Synchrotron radiation is accompanied by absorption in which a photon interacts with a charge in magnetic field. The absorption coefficient of synchrotron self-absorption is described in standard textbooks (e.g. Rybicki & Lightman 1979) as

$$\alpha(\epsilon) = \frac{1}{8\pi \epsilon c} \left( \frac{2\pi \hbar c}{m_e c^2} \right)^3 \int_{\gamma_{\mathrm{min}}}^{\gamma_{\mathrm{max}}} d\gamma' \frac{d^2N_{\gamma, \mathrm{syn}}}{d\gamma d\epsilon} (\epsilon; \gamma') \frac{d}{d\gamma'} \left[ \frac{1}{\gamma^2} \frac{d}{d\gamma'} (\gamma') \right]. \hspace{1cm} (A4)$$

Thus, the production rate of synchrotron radiation is estimated as

$$\frac{d^2N_{\gamma, \mathrm{syn}}}{d\epsilon d\gamma} (\epsilon) = \int d\gamma' \frac{d\alpha(\epsilon)}{d\gamma'} \frac{d^2N_{\gamma, \mathrm{syn}}}{d\epsilon d\gamma} (\epsilon; \gamma') + \frac{d\alpha(\epsilon)}{d\epsilon} (\epsilon) \alpha(\epsilon). \hspace{1cm} (A5)$$

The production rate of ICS photons is estimated as follows:

$$\frac{d^2N_{\gamma, \mathrm{ICS}}}{d\epsilon d\gamma} (\epsilon) = -c \frac{dN_{\gamma, \mathrm{syn}}}{d\epsilon} (\epsilon) \int d\gamma' \frac{d\alpha(\epsilon)}{d\gamma'} R_{\mathrm{ICS}}(\gamma', \epsilon) + c \int d\gamma' \frac{d^2N_{\gamma, \mathrm{syn}}}{d\epsilon d\gamma} (\epsilon) \int d\gamma' \frac{d\alpha(\epsilon)}{d\gamma'} P_{\nu, \mathrm{ICS}}(\gamma', \epsilon), \hspace{1cm} (A6)$$

where $R_{\mathrm{ICS}}(\gamma', \epsilon)$ and $P_{\nu, \mathrm{ICS}}(\gamma', \epsilon)$ are

$$R_{\mathrm{ICS}}(\gamma', \epsilon) = \int_{-\gamma}^{1} d\mu \frac{1 - \beta \mu}{2} \sigma_{\gamma e} (\beta, \gamma', \epsilon) \hspace{1cm} (A7)$$

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\[ P_{\gamma,ICS}(\epsilon; \gamma, \epsilon') = \int_{-1}^{1} d\mu \frac{1 - \beta \mu}{2} \frac{d\sigma_{ICS}}{d\epsilon}(\epsilon; \gamma, \epsilon', \mu), \]  

(A8)

respectively, where \( \mu \) is the cosine of the angle between the momentums of incident photons and electrons. \( \sigma_{ICS} \) is the cross-section of ICS in the case when an electron with the energy of \( \gamma \) scatters a photon with the energy of \( \epsilon \) (Coppi & Blandford 1990):

\[ \sigma_{ICS}(\beta, \gamma, \epsilon) = \frac{3\sigma_T}{4x} \left( \frac{1 - 4}{x} - \frac{8}{x^2} \right) \log(1 + x) + \frac{1}{2} + \frac{8}{x} - \frac{1}{2(1 + x)^2} \],  

(A9)

where \( x = 2\gamma \epsilon / (1 - \beta \mu) \). \( d\sigma_{ICS} / d\epsilon \) is the differential cross-section of ICS in the case when a photon with the energy of \( \epsilon' \) is upscattered into the energy of \( \epsilon \) by an electron with the energy of \( \gamma \) (Lee 1998):

\[ \frac{d\sigma_{ICS}}{d\epsilon}(\epsilon; \gamma, \epsilon', \mu) = \frac{3\sigma_T}{4\gamma x} \left[ \frac{\gamma - \epsilon}{\gamma} + \frac{\gamma}{\gamma - \epsilon} \right. 
\left. - \frac{4}{x} \left( \frac{\epsilon}{\gamma - \epsilon} \right) + \frac{4}{x^2} \left( \frac{\epsilon}{\gamma - \epsilon} \right)^2 \right]. \]  

(A10)

Thus, \( R_{ICS}(\gamma, \epsilon) \) and \( P_{\gamma,ICS}(\epsilon; \gamma, \epsilon') \) can be interpreted as angle-averaged cross-sections.

After equations (A5) and (A6) are substituted, equation (A2) is an integral equation categorized to the Fredholm equation of the second kind. This equation can be numerically solved by the Nyström method (e.g. Press et al. 1992). Note that \( dn_{\gamma} / d\epsilon \) includes higher order ICS photons, whose seed photons are ICS photons. Finally, photon flux observed at the Earth is estimated as

\[ \frac{d^2N_{\gamma}}{dt_{\text{obs}} d\epsilon_{\text{obs}}} = \delta^2 \frac{V}{4\pi d_L^2 t_{\gamma, \text{esc}}} \frac{dn_{\gamma}}{d\epsilon} \left[ \frac{(1 + z)\epsilon_{\text{obs}}}{\delta} \right], \]  

(A11)

where \( \epsilon_{\text{obs}} = (1 + z)^{-1} \delta \epsilon \) and \( d_L \) is the luminosity distance of the source.