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New prediction of extragalactic GeV γ-ray emission from radio lobes of young AGN jets

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ABSTRACT

We present a new prediction of GeV γ-ray emission from radio lobes of young AGN jets. In the previous work of Kino et al. (2007), MeV γ-ray bremsstrahlung emission was predicted from young cocoons/radio-lobes in the regime of no coolings. In this study, we include cooling effects of bremsstrahlung emission and adiabatic loss. With the initial conditions determined by observed young radio lobes, we solve a set of equations describing the expanding lobe evolution. Then we find that the lobes initially have electron temperature of $\sim$GeV, and they cool down to $\sim$MeV by the adiabatic loss. Correspondingly, the lobes initially yield bright bremsstrahlung luminosity in $\sim$GeV range and they fade out. We estimate these γ-ray emissions and show that nearby young radio lobes could be detected with Fermi Gamma-ray Space Telescope.

Key words: jets—galaxies: active—galaxies: gamma-rays—theory

1 INTRODUCTION

Jets in active galactic nuclei (AGNs) are one of the most powerful objects in the universe. AGNs with jets are known as radio-luminous sources and they have been called as radio-loud AGNs. There is increasing evidence that radio-loud AGNs significantly interact with ambient medium and the cosmological importance of radio-loud AGN feedbacks have been advocated (e.g., Best et al. 2007). Among a variety of radio-loud AGNs, a population with its linear size $LS < 1$ kpc has been called as compact symmetric objects (CSOs). The previous studies support a scenario in which CSOs propagate from $\sim$ 100 pc scales thrusting away an ambient medium and they grow up to Fanaroff-Riley type II radio galaxies (FR IIs) (e.g., Fanti et al. 1995; Readhead et al. 1996a, b; O'Dea & Baum 1997; Stanghellini et al. 1998; Snellen et al. 2000; Dallacasa et al. 2000; Orienti et al. 2007). CSOs are thus recognized as newly born AGN jets, and they are crucial sources to explore physics of radio-loud AGNs in their early days.

On the contrary to various radio observations, high-energy emission observations of CSOs had been sporadic (Siemiginowska 2008 for review). Recently, XMM-Newton observations begin to detect X-ray emissions from some of the CSOs although these are not very bright in X-ray (Guainazzi et al. 2006; Vink et al. 2006; O'Dea et al. 2006). Although a few authors recently indicate possible γ-ray emissions from CSOs (e.g., Stawarz et al. 2008), there is little observations of CSOs viewed in γ-rays. Hence γ-ray observations of CSOs may provide us new independent knowledges on the youth era of AGN jets.

Recently, Kino et al. (2007) (hereafter KKI07) showed a possibility of thermal MeV γ-ray bremsstrahlung emission from the young radio-loud AGNs. In KKI07, as a first step, they focused on the simplest case in which cooling effects are not significant. These sources roughly correspond to medium-size symmetric objects (MSOs) with 1 kpc $< LS <$ 10 kpc and FR II galaxies with $LS >$ 10 kpc. Since various cooling timescales in smaller sources tend to be shorter than the ones in larger sources, cooling effects in CSOs are expected to be more significant than the ones in MSOs and FR IIs. However little is known about the cooling processes in compact radio sources such as CSOs. In this study we will consistently solve a set of equations which describe young lobe expansions including the effects of bremsstrahlung emission and adiabatic loss together with initial conditions determined by observations.

The goals of this paper are (i) to solve a hydrodynamical evolution of expanding lobes with the cooling effects and (ii) to show a new prediction of γ-ray emission from the lobes based on the results of (i). In §2, we show a set of basic equations which describes an expanding radio lobe inflated by its internal energy. In §3, we show the resultant temperature evolution of radio lobes. New predictions of bright GeV γ-ray emissions from young radio lobes is presented in §4. Summary and discussion are given in §5.

2 MODEL OF RADIO LOBES

2.1 Basic equations

Let us consider the dynamics of sideways expansion for young radio lobes. We assume that the sideways expansion of radio lobe is caused by the internal pressure of the shocked jet matter. A breakdown of the internal pressure is an open question. The partial pressure of non-thermal electrons alone might be small to expand the radio lobes (e.g., Hardcastle and Worral 2000; Ito et al. 2008 and reference therein). Therefore the partial pressure of thermal particles may play an important role for lobe expansions. Here we focus on the case of thermally expanding lobes and we neglect the partial pressure of non-thermal electrons for simplicity.

The equation of motion and the energy equation, for expanding radio lobes, are respectively given by

$$\frac{d}{dt}\left(\frac{4\pi}{3}\rho_{\rm ext}R^3\dot{R}\right) = 4\pi R^2 P, \quad (1)$$

$$\frac{d}{dt}\left(\frac{4\pi}{3}R^3 U_{\rm th}\right) = L_{\rm j} - P\frac{d}{dt}\left(\frac{4\pi}{3}R^3\right) - \frac{4\pi}{3}R^3\epsilon_{\rm cool}, \quad (2)$$

where $\rho_{\rm ext}$ R, $\dot{R}=v$, P, $U_{\rm th}(=3P)$, and $L_{\rm j}$ are the mass density of external ambient medium, the radius, the expansion velocity, thermal pressure, the thermal energy density of relativistic particles of the lobe, and the total kinetic power of the jet, respectively. We denote the volume emissivity as $\epsilon_{\rm cool}$ and here we focus on the case of $\epsilon_{\rm cool}=\epsilon_{\rm brem}$ where $\epsilon_{\rm brem}$ is the bremsstrahlung one. In the case of relativistic jets, $L_{\rm j}$ is given by

$$L_{\rm j} = \Gamma_{\rm j}\dot{M}_{\rm j}c^2, \quad (3)$$

where $\Gamma_{\rm j}$, and $\dot{M}_{\rm j}$ are the bulk Lorentz factor of the relativistic jet, and mass outflow rate of the jet, respectively. The $L_{\rm j}$ is the ultimate source of the lobe expansion. The $L_{\rm j}$ is a free parameter in this model and it is assumed to be constant in time. Particular noteworthy compared with KKI07 is that we take cooling effects into account. The equation of state (EOS) and mass conservation in the lobe are, respectively,

$$P = (n_- + n_+)kT_\pm + n_p kT_p, \quad (4)$$

$$\frac{4\pi}{3}\rho R^3 = \dot{M}_{\rm j}t, \quad (5)$$

where n_-, n_+, and n_p are number densities of thermal electrons, thermal positrons and total protons in the lobe, respectively, and $\rho=(n_-+n_+)m_e+n_p m_p$, $T_\pm$, and T_p are total mass density and temperatures of $e^\pm$ pairs and protons, respectively. Merely for simplicity, we neglect protons i.e., $n_p\approx 0$ throughout this work. Although "which plasma component is dynamically dominated in AGN jets?" is still a matter of debate, previous works at least indicate the existence of copious amount of $e^\pm$ pairs in jets (Wardle et al. 1998; Reynolds et al. 1996; Sikora and Madejski 2000; Kino and Takahara 2004; Kataoka et al. 2008). Combining the above equations all together, we obtain the ordinary differential equation of

$$\frac{d^3R}{dt^3} + \frac{11\dot{R}\ddot{R}}{R} + \frac{12\dot{R}^3}{R^2} = \frac{3}{4\pi\rho_{\rm ext}R^4}\left(L_{\rm j} - \frac{4\pi R^3\epsilon_{\rm brem}}{3}\right). \quad (6)$$

Setting $\epsilon_{\rm brem}$ as for relativistic $e^\pm$ pairs (Eq. (22) in Svensson 1982), then we obtain

$$\frac{4\pi R^3\epsilon_{\rm brem}}{3} = 0.75\times 10^{11}\,\rho_{\rm ext}\dot{M}t(R\ddot{R}+3\dot{R}^2) \times \left[\ln\left(\frac{4.4\rho_{\rm ext}R^3(R\ddot{R}+3\dot{R}^2)}{9\dot{M}tc^2}\right)+\frac{5}{4}\right]\ {\rm erg\ s^{-1}}. \quad (7)$$

Given the initial values of R, $\dot{R}$, $\ddot{R}$ at an initial time t_0, we can solve the evolution of expanding lobes. The initial temperature can be obtained via $P=\rho_{\rm ext}(R\ddot{R}+3\dot{R}^2)/3$ and EOS.

The free paramter $L_{\rm j}$ can be normalized as

$$L_{\rm j} = 5.7\times 10^{44}\left(\frac{\Gamma_{\rm j}}{10}\right)\left(\frac{\dot{M}_{\rm j}}{10^{-3}\ {\rm M_\odot\ yr^{-1}}}\right)\ {\rm erg\ s^{-1}} \quad (8)$$

which is typical value for AGN jets. In this work, we will examine the range of 5.7×10^{43} erg s^{-1} $< L_{\rm j} <$ 5.7×10^{46} erg s^{-1}, the corresponding $\dot{M}_{\rm j}$ is 1×10^{-4} M$_\odot$ yr^{-1} $<$ $\dot{M}_{\rm j} < 1\times 10^{-1}$ M$_\odot$ yr^{-1}. The mass outflow rate $\dot{M}_{\rm j}$ is the essential parameter to determine $L_{\rm j}$.

2.2 Initial conditions of lobes and jets

Based on recent observations of CSOs (e.g., O'Dea 1998; Stanghellini et al 1998; Dallacasa 2000; Snellen et al. 2004), we set the initial conditions as follows. Since physical quantities diverge at $R=0$, certain initial conditions of the lobe at $t=t_0\neq 0$ are required for solving a set of equations. In this work, we treat the evolutions of physical quantities for $t\geqslant t_0$ and we do not consider $t<t_0$. The followings are two initial conditions (with subscript of 0) examined in this work;

$$R_0 = 100\ {\rm pc},\quad v_0=0.1c,\quad t_0=3.0\times 10^3\ {\rm yr}\quad (\text{Low } P_0),$$
$$R_0 = 300\ {\rm pc},\quad v_0=0.2c,\quad t_0=4.5\times 10^3\ {\rm yr}\quad (\text{High } P_0), \quad (9)$$

and we set $dv/dt|_{t=t_0}=0$. This size and velocity is typical ones for CSOs (e.g., Stanghellini et al. 1998; Dallacasa et al. 2000; Polatidis and Conway 2003; Gugliucci et al. 2005, 2007; Taylor et al. 2000; Nagai et al. 2006; Kawakatu et al. 2008). Note that $R_0\approx v_0t_0$ holds here. Since we here deal with small radio lobes, the external ambient medium is not intracluster medium (ICM) but interstellar medium (ISM). By using them, we further set the initial conditions as

$$P_0 = m_p n_{\rm ext}v_0^2,\quad kT_{\pm,0} = \frac{m_e P_0 V_0}{\dot{M}_{\rm j}t_0},\quad n_{-,0} = \frac{\dot{M}_{\rm j}t_0}{2m_eV_0}, \quad (10)$$

where $V_0=4\pi R_0^3/3$. Hereafter we set the number density of external ambient medium $n_{\rm ext}=1$ cm^{-3} which is typical for ISM (e.g., Readhead et al. 1996a and references within).

In principle, the upper limit of n_- can be constrained by the analysis of Faraday depolarization (Dreher et al. 1987). However, the strong Faraday depolarization observed in CSOs (Cotton et al. 2003) are likely to be caused by dense foreground matter such as narrow line region. Therefore n_- in radio lobes of CSOs has not been clearly constrained.

3 TEMPERATURE OF RADIO LOBES

Fig. 1 shows the evolution of $kT_\pm$ of expanding lobes which is obtained by solving Eq. (6) with the initial condition of the "Low-P_0" case. We examine various outflow rate of $\dot{M}_{\rm j} = 10^{-4}$ M$_\odot$ yr^{-1}, $\dot{M}_{\rm j} = 10^{-3}$ M$_\odot$ yr^{-1}, $\dot{M}_{\rm j} = 10^{-2}$ M$_\odot$ yr^{-1}, and $\dot{M}_{\rm j} = 10^{-1}$ M$_\odot$ yr^{-1}. Corresponding kinetic power of injected jet into the lobes are, respectively, $L_{\rm j} = 5.7\times 10^{42}$ erg s^{-1}, $L_{\rm j} = 5.7\times 10^{43}$ erg s^{-1}, $L_{\rm j} = 5.7\times 10^{44}$ erg s^{-1}, and $L_{\rm j} = 5.7\times 10^{45}$ erg s^{-1}. The initiall temperature of the lobe $kT_{\pm,0}$ in the case of the Low P_0 case can be analytically evaluated as

$$kT_{\pm,0} = 0.18 \text{ GeV} \left(\frac{\dot{M}_{\rm j}}{10^{-3}\text{ M}_\odot\text{yr}^{-1}}\right)^{-1} \left(\frac{P_0 V_0/t_0}{2.0\times 10^{46}\text{erg s}^{-1}}\right), \tag{11}$$

The resultant $kT_\pm$ evolutions obtained by Eq. (6) can be well approximated by the simple relation of $kT_\pm \approx kT_{\pm,0}(t/t_0)^{-1} + \Gamma_{\rm j} m_e c^2/3$ for $kT_{\pm,0} \geqslant \Gamma_{\rm j} m_e c^2/3$. In the early-phase, the first term $(t/t_0)^{-1}$ is dominant for the case examined here. Then $kT_\pm$ decreases proportional to t^{-1}. The agreement of this approximation is due to the negligible bremsstrahlung cooling and dominant adiabatic loss in the early-phase. We will show the reason in the next section. In the late phase, it is found that the temperature asymptotically approaches to $kT_\pm = \Gamma_{\rm j} m_e c^2/3 = 1(\Gamma_{\rm j}/10)$ MeV. This clearly coincides with the prediction of "MeV cocoon" by KKI07. This implies that the final temperature of lobes is determined only by $\Gamma_{\rm j}$ regardless of diverse cooling effects in the early phase. Fig. 2 shows the $kT_\pm$ evolution but for the "High-P_0" case. The initial temperature is given by

$$kT_{\pm,0} = 13 \text{ GeV} \left(\frac{\dot{M}_{\rm j}}{10^{-3}\text{ M}_\odot\text{yr}^{-1}}\right)^{-1} \left(\frac{P_0 V_0/t_0}{1.4\times 10^{48}\text{erg s}^{-1}}\right). \tag{12}$$

The behavior is essentially the same as Fig. 1. Adiabatic loss phases for the "High-P_0" case last longer than those for the "Low-P_0" case simply because of its higher $kT_{\pm,0}$.

Next, we show how $kT_{\pm,0}$ will change when we choose different initial conditions. The terms $\dot{M}_{\rm j}$ and P_0V_0/t_0 are the only ingredients which determine the initial temperature $kT_{\pm,0}$. The predicted $kT_{\pm,0}$ will increase by the increase of R_0, v_0, and $\rho_{\rm ext}$ according to $P_0V_0/t_0 \propto \rho_{\rm ext} R_0^2 v_0^3$, and vice versa. Therefore, in principle, $kT_{\pm,0}$ can become higher or lower than MeV/GeV ranges examined in Fig. 1. When $kT_{\pm,0}$ is order of keV, the predicted $kT_{\pm,0}$ is smaller than $\Gamma_{\rm j} m_e c^2/3 = 1(\Gamma_{\rm j}/10)$ MeV. Therefore, the lobe plasma is gradually heated by the jet injection and $kT_\pm$ asymptotically approaches to $\Gamma_{\rm j} m_e c^2/3 = 1(\Gamma_{\rm j}/10)$ MeV. However, the case of $\dot{M}_{\rm j} \sim 10$ M$_\odot$ yr^{-1} requires $L_{\rm j} \sim 10^{48}$ erg s^{-1} (see Eq. (8)) which tend to exceed the ones for very powerful AGN jets (e.g., Rawlings and Saunders 1991; Ito et al. 2008). Here we do not discuss this case further.

Lastly we comment on the formation of initial lobes. In order to accomplish the initial hot lobes at $t = t_0$, a heating process for $e^\pm$ pairs is needed at $t \leqslant t_0$. Theoretically, a mechanism of electron heating (and acceleration) in a collisionless shock is a matter of debate (e.g., Shimada and Hoshino 2000; Ohira and Takahara 2007). If pairs are effectively heated up by various kind of plasma instabilities via hotter protons (e.g., Lyubarsky 2006), it could be possible to attain $kT_{\pm,0} \sim kT_{p,0}$. It is beyond the scope of this paper to explore microscopic processes in the plasma. Instead, we have uniquely determined $T_{\pm,0}$ by using the quantities required from the observations and the assumption of thermal pair expansions. We have neglected the partial pressure of proton in P_0 merely for simplicity. However the neglect does not affect the main arguments in this work. Because the protons also simply cool down by the adiabatic loss for $t > t_0$. To form "High-P_0" lobe, very fast $\Gamma_{\rm j} \sim 50-100$ is required when assuming that hot protons with $kT_p = \Gamma_{\rm j} m_p c^2/3$ are the heating source of $e^\pm$ pairs. The required $\Gamma_{\rm j}$ is by a factor of $\sim 2-3$ larger than the fastest $\Gamma_{\rm j} \sim 30$ estimated from VLBI observations (Kellermann et al. 2004) and it is comparable to $\Gamma_{\rm j} \sim 50-100$ indicated by rapid variabilities of blazars (e.g., Begelman et al. 2008; Ghisellini and Tavecchio 2008). Since we take the oversimplified assumption of proton neglect, it is not possible any further to explore the hot lobe formation at $t < t_0$. We keep this as a subject for future investigation. It is worth to mention that youngest radio sources termed "high frequency peakers" (HFPs) with ages of $< 10^3$ yr have been recently observed (e.g., Orienti et al. 2007) and HFPs may give us substantial hints for the physics in $t \leqslant t_0$.

4 γ-RAY EMISSION FROM RADIO LOBES

Using Eqs. (10), (11), and (12), we can estimate the bolometric bremsstrahlung luminosity $L_{\rm brem,0} = \epsilon_{\rm brem,0} V_0$ at $t = t_0$ for the "Low P_0" case

$$L_{\rm brem,0} = 1.5\times 10^{41} \left(\frac{n_{-,0}}{2.7\times 10^{-2}\text{ cm}^{-3}}\right)^2 \left(\frac{V_0}{1.2\times 10^{62}\text{ cm}^3}\right) \left(\frac{kT_{\pm,0}}{0.18\text{ GeV}}\right) \left[1+\ln\left(0.17\frac{kT_{\pm,0}}{0.18\text{ GeV}}\right)\right] \text{ erg s}^{-1} \tag{13}$$

for $\dot{M} = 10^{-3}$ M$_\odot$ yr^{-1}. The lobe for the "High P_0" case with the same $\dot{M} = 10^{-3}$ M$_\odot$ yr^{-1} have hotter $e^\pm$ pairs and smaller $n_{-,0}$ in larger V_0. Then, the "High P_0"case leads to brighter $L_{\rm brem,0}$ of

$$L_{\rm brem,0} = 1.4\times 10^{42} \left(\frac{n_{-,0}}{1.5\times 10^{-3}\text{ cm}^{-3}}\right)^2 \left(\frac{V_0}{3.3\times 10^{63}\text{ cm}^3}\right) \left(\frac{kT_{\pm,0}}{13\text{ GeV}}\right) \left[1+\ln\left(0.10\frac{kT_{\pm,0}}{13\text{ GeV}}\right)\right] \text{ erg s}^{-1}. \tag{14}$$

Fig. 3 shows the bremsstrahlung spectra at $t = t_0$. Adopted $\dot{M}_{\rm j}$ are same as in Fig. 1. The source is located at the distance of 10^2 Mpc which corresponds to nearby observed CSO samples (e.g., Snellen et al. 2004). For these cases, the predicted spectra are brighter than the sensitivity of Fermi/LAT (http://www-glast.stanford.edu/). In other words, we predict radio lobes in CSOs as a new population of GeV-γ emitter in the universe. From Eqs. (13) and (14), we find that the increase of $\dot{M}_{\rm j}$ leads to the enhancement of $L_{\rm brem,0}$ since $L_{\rm brem,0} \propto \dot{M}_{\rm j}$ holds where we neglect the logalithm terms in (13) and (14). We can also say that lower $kT_{\pm,0}$ leads to brighter $L_{\rm brem,0}$ because $n_{\pm,0}^2 \propto \dot{M}_{\rm j}^2$ dominates $kT_{\pm,0} \propto \dot{M}_{\rm j}^{-1}$, and vice versa. Regarding the luminosity evolution, we obtain $L_{\rm brem} \propto kT_\pm n_\pm^2 V \propto n_\pm$ where we use the relation of $kT_\pm \propto t^{-1}$ and $nV \propto t$ for the early phase. We thus find that $L_{\rm brem}$ decrease with time and it will fade out because the lobe becomes dilute. This sort of negative luminosity evolution has been well known for synchrotron emission (Readhead et al. 1996b; Begelman 1996) and bremsstrahlung emission (KKI07). Once we obtain $L_{\rm brem,0}$, we can easily check that the radiative cooling

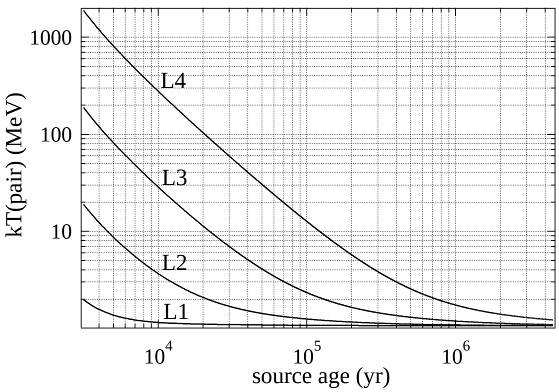

Figure 1. Evolution of $kT_{\pm}$ for the "Low-P_0" case which starts from the age of $t_0 = 3000$ yr. The examined cases are $\dot{M}_{\rm j}/(M_{\odot}\ {\rm yr}^{-1}) = 10^{-4}$, 10^{-3}, 10^{-2}, and 10^{-1} and they are labeled as L4, L3, L2, and L1, respectively. Corresponding kinetic power of the jet are, respectively, $L_{\rm j} = 5.7 \times 10^{42}$ erg s^{-1}, $L_{\rm j} = 5.7 \times 10^{43}$ erg s^{-1}, $L_{\rm j} = 5.7 \times 10^{44}$ erg s^{-1}, and $L_{\rm j} = 5.7 \times 10^{45}$ erg s^{-1}. The temperature decrease by the adiabatic loss are seen in the initial phase. Each case asymptotically goes to constant $kT_{\pm}$ phase which is predicted by KKI07. Bremsstrahlung cooling is found to be negligible.

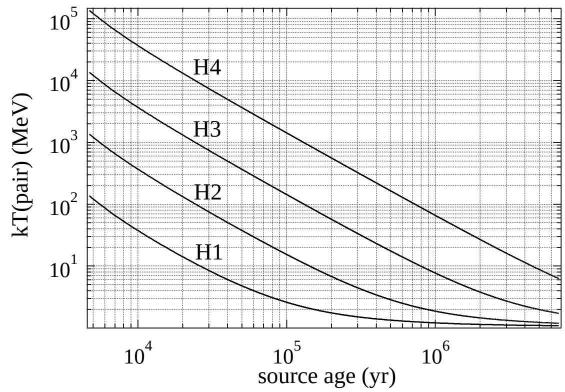

Figure 2. Evolution of $kT_{\pm}$ for the "High-P_0" case which starts from the age of $t_0 = 4500$ yr. We examine the cases of $\dot{M}_{\rm j}/(M_{\odot}\ {\rm yr}^{-1}) = 10^{-4}$, 10^{-3}, 10^{-2}, and 10^{-1} and they are labeled as H4, H3, H2, and H1, respectively. Correspondingly, kinetic power of injected jet into the lobes are, respectively, $L_{\rm j} = 5.7 \times 10^{42}$ erg s^{-1}, $L_{\rm j} = 5.7 \times 10^{43}$ erg s^{-1}, $L_{\rm j} = 5.7 \times 10^{44}$ erg s^{-1}, and $L_{\rm j} = 5.7 \times 10^{45}$ erg s^{-1}. Similar to the "Low-P_0" case, adiabatic loss is dominant in the initial phase and bremsstrahlung cooling is negligible.

is effective or not. Since $L_{\rm brem}$ decreases with time, the effect of bremsstrahlung is most significant at $t = t_0$. At the time, $L_{\rm brem,0} \ll L_{\rm j}$ holds where $L_{\rm j}$ is the source term of the internal energy flux injected in the lobe. Therefore we find that back-reaction of bremsstrahlung cooling is negligible and the behavior of $kT_{\pm}$ in Figs. 1 and 2 are governed by the adiabatic loss.

Lastly we discuss the change of $L_{\rm brem,0}$ for different choices of initial conditions. Two ingredients to determine $L_{\rm brem,0}$ are $n_{-,0}$ and $kT_{\pm,0}$ for given V_0. Concerning $kT_{\pm,0} \propto P_0 V_0/t_0$, the predicted $L_{\rm brem}$ increases as R_0, v_0, and $\rho_{\rm ext}$ becomes larger according to $kT_{\pm,0} \propto \rho_{\rm ext} R_0^2 v_0^3$, and vice versa. Hence it is worth to note that lobes with faster sideways expansions will shine brighter. Indeed there are some CSOs with $v_0 > 0.1c$ (Polatidis and Conway 2003; Gugliucci et al. 2005, 2007). The quantity $n_{-,0}$ is the important parameter, since $n_{-,0}$ dependence of $L_{\rm brem,0}$ is significant as $L_{\rm brem,0} \propto n_{-,0}^2$. For the estimate of $n_{-,0}$, we assumed the $e^{\pm}$ pair jet so far. If instead we assume the pure electron/proton jet for given $L_{\rm j}$ and $\Gamma_{\rm j}$, then $n_{-,0}$ decreases by a factor of m_e/m_p. Then $L_{\rm brem,0}$ decreases by a factor of $(m_e/m_p)^2$, and the predicted $L_{\rm brem,0}$ becomes much smaller than the Fermi/LAT sensitivity.

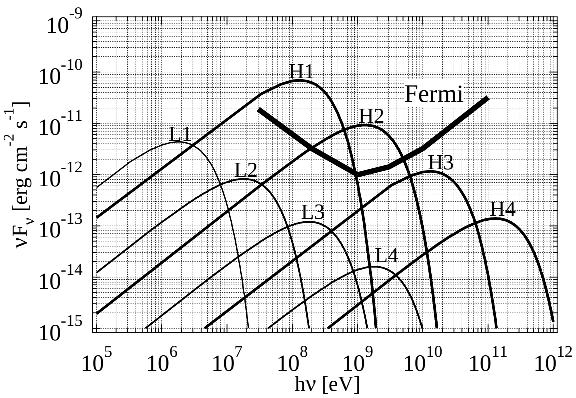

Figure 3. Predicted bremsstrahlung emission from young radio lobes at $t = t_0$ with the distance 10^2 Mpc. The spectra for "High-P_0 " case (H1, H2, H3, and H4) are brighter than the sensitivity of Fermi Gamma-ray Space Telescope while the spectra for "Low-P_0" case (L1, L2, L3, and L4) are less luminous for the detection.

5 SUMMARY AND DISCUSSION

We have investigated the temperature and luminosity evolutions of radio lobes of CSOs which expands by their own thermal pressure. In the previous work of KKI07, MeV γ-ray bremsstrahlung emission was predicted from young lobes in the regime of no coolings. In this work, we include cooling effects of bremsstrahlung emission and adiabatic loss. Below we summarize the main results of the present work.

(i) We examine the evolution of $kT_{\pm}$ together with the initial conditions determined by observed CSOs. By solving a set of equations describing the expanding lobe evolution, it is found that the lobes initially have electron temperature of $\sim$GeV for $\Gamma_{\rm j} \sim 10$, the lobes then cool down to MeV by the adiabatic loss. During the early phase, $kT_{\pm}$ is governed by the adiabatic loss alone. Since the adiabatic loss is more effective than bremsstrahlung cooling in any case. In the late phase, $kT_{\pm}$ asymptotically approaches to the constant temperature of $\Gamma_{\rm j} m_e c^2/3 = 1\ (\Gamma_{\rm j}/10)$ MeV which has been predicted in KKI07.

(ii) Thermal bremsstrahlung emission peaked about GeV-γ band is newly predicted in CSOs because $n_{\pm}$ and $kT_{\pm}$ in younger radio lobes are larger than those in older ones. These spectra can be brighter than the sensitivity of Fermi/LAT for nearby CSOs in the case of High-P_0 lobe. This means that young radio-lobes can be a new population of GeV-γ emitter in the universe. From Eq. (13) showing $L_{\rm brem,0}$, we see that the radio lobes with larger v_0 (i.e., faster expansions) and/or the one with larger n_- (i.e., larger $L_{\rm j}$) yield brighter emission for given R_0. As for a specific source, we stress the importance of young recurrent lobe 3C 84 (e.g., Asada et al. 2006). Since 3C 84 is located at the center of very nearby Perceus cluster ($z = 0.018$), a deep observation of the Fermi/LAT collabolated with radio obserbations on it will give us tight constraints on the physics of young radio lobes. Near future mission of the VLBI Space Observatory Programme 2 (VSOP-2) with unprecedented high angular resolution (Tsuboi et al. 2009) would play important roles for direct constraint on v_0 and R_0 of HFPs.

(iii) Stawarz et al. (2008) investigated a variety of non-thermal γ-ray emissions from lobes of CSOs. They claim that the predicted non-thermal emissions can be also detected by Fermi/LAT with an assumed certain electron acceleration efficiency. In GeV γ range, the dominant components are inverse-Compton scattered emissions of ultraviolet and infrared photons. It is worth to note that even though the luminosity of thermal bremsstrahlung and inverse-Compton ones are comparable, the spectrum shape thermal component is quite different from non-thermal spectra. Hence it is straightforward to distinguish whether the emission is thermal or non-thermal one.

(iv) The observations of Fermi/LAT will be tests for some unresolved questions of AGN jets. Suppose the case that we exactly know R_0, v_0, and $n_{\rm ext}$, and a source distance. If we observe the predicted thermal GeV-γ emission from CSOs, then it suppose the scenario in which CSOs have relativistic jets and their lobes thermally expand. If we do not detect it, it is attribute to lower $kT_\pm$ and/or smaller $n_\pm$. Possible reasons are as follows; (1) the jet is mainly made of e/p plasma with the same $L_{\rm j}$, (2) the jet consists of $e^\pm$ plasma on the whole but with smaller $L_{\rm j}$, (3) the lobe is expanded by energetic non-thermal particle and the actual $n_\pm$ is smaller, (4) the jet has non-relativistic speed which leads to the lower $kT_\pm$, (5) other cooling processes could make $kT_\pm$ lower. We remain them as our future investigations.

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