Extragalactic MeV $\gamma$-ray emission from cocoons of young radio galaxies

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ABSTRACT

Strong $\gamma$-ray emission from cocoons of young radio galaxies is newly predicted. Considering the process of adiabatic injection of the shock dissipation energy and mass of the relativistic jet in active nuclei (AGNs) into the cocoon, while assuming thermalizing electron plasma interactions, we find that the thermal electron temperature of the cocoon is typically predicted in $\sim$ MeV, which is determined only by the bulk Lorentz factor of the relativistic jet. Together with the time-dependent dynamics of the cocoon expansion, we find that young cocoons can yield thermal bremsstrahlung emissions at energies $\sim$ MeV.

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

1 INTRODUCTION

Relativistic jets in active galactic nuclei (AGNs) are widely believed to be the dissipation of kinetic energy of relativistic motion with a Lorentz factor of order $\sim$ 10 produced at the vicinity of a supermassive black hole at the galactic center (Begelman, Blandford and Rees 1984 for reviews). The jet in powerful radio loud AGNs (i.e., FR II radio sources) is slowed down via strong terminal shocks which are identified as hot spots. The shocked plasma then expands sideways and envelops the whole jet system and this is so-called a cocoon (Begelman and Cioffi 1989, hereafter BC89). The cocoon is a by-product of the interaction between AGN jets and surrounding intra-cluster medium (ICM). The internal energy of the shocked plasma continuously inflates this cocoon. Initially, the existence of the cocoon is theoretically predicted by Scheuer (1974).

The first clear evidence for an X-ray cavity was discovered in the center of the Perseus cluster of galaxies by Boehringer et al. (1993). The thermal ICM is displaced by the radio lobes which are composed of the remnants of the decelerated jet. Then the X-ray surface brightness in those regions is significantly decreased. These cavities correlate to the cocoons. Most of the X-ray cavities are associated with low power AGN jets (i.e., FR I radio sources). Recent X-ray observations of radio galaxies shows us a further evidences of these X-ray cavities (e.g., Fabian et al. 2000; Blanton et al. 2001). Another X-ray observational evidence of the cocoon is the non-thermal emission around radio lobes (e.g., Feigelson et al. 1995; Isobe et al. 2002; Croston et al. 2005). In some cases, those non-thermal emissions are associated with FR II radio sources. In any case, there is no direct evidence of thermal emissions coming from the dilute thermal plasma inside the cocoon.

In this paper, we propose that “a cocoon of a young radio galaxy” as a new population of $\gamma$-ray emitters in the universe. Up to now, little attention has been paid to the evolution of thermal temperature and number density of the cocoon. Recently we have investigated the evolution of its temperature and number densities by taking the proper account of mass and energy injections by the relativistic jet (Kino and Kawakatu 2005; Kawakatu and Kino 2006). We found that the cocoon remains constant temperature whilst the number density increases as a cocoon becomes younger. This leads to our new prediction of bright $\gamma$-ray emission from the young cocoon.

2 COCOON INFLATION BY DISSIPATIVE RELATIVISTIC JET

Here we consider the time-evolution of expanding cocoon inflated by the dissipation energy of the relativistic jet via terminal shocks. The adiabatic energy injection into the cocoon is assumed here. We will compare the source age $t$ and a cooling time scale and check the consistency at the last part of §2. Note that the injection process of kinetic energy and mass into the cocoon is “continuous” during $t$. It is different from the “impulsive” injection realized in gamma-ray bursts (GRBs) and supernovae.

The time-averaged mass and energy injections from the jet into the cocoon, which govern the cocoon pressure $P_c$,
and mass density $\rho_c$ are written as

$$\frac{\dot{\gamma}_c = \frac{P_e(t)}{\gamma_c - 1}}{t} \approx 2T_{\text{icm}}^2(t)A_j(t)$$  \hspace{1cm} (1)

$$\frac{\rho_c(t)V_c(t)}{t} \approx 2J_1(t)A_j(t)$$  \hspace{1cm} (2)

where $\dot{\gamma}_c$, $V_c$, $T_{\text{icm}}$, $J_1$, and $A_j$, are the adiabatic index of the plasma in the cocoon, the volume of the cocoon, the kinetic energy and mass flux of the jet, and the cross-sectional area of the jet, respectively. The total kinetic energy and mass flux of the jet are $T_{\text{icm}}^2 = \rho_c T_{\text{icm}}^2 v_j$, $J_1 = \rho_1 T_1 v_j$ where $\rho_j$, and $\Gamma$ are mass density and bulk Lorentz factor of the jet (Blandford and Rees 1974). Hereafter we set $v_c = 1$. The total kinetic power of the relativistic jet is defined as $L_j \equiv 2T_{\text{icm}}^2(t)A_j(t)$ and it is assumed to be constant in time. Although little attention has been payed to the mass injection Eq. (2) up to now, it is of great significance to take account of the Eq. (2) for deriving the cocoon temperatures. Hence we take up the the Eq. (2) to evaluate the temperatures of the cocoons. In contrast, the energy equation Eq. (1) has been widely utilized in the literatures of the AGN bubbles in various ways (e.g., BC89; Dunn and Fabian 2004).

The kinetic power dominance in the flow is postulated in this work in accordance with the observational indications (e.g., Leahy and Gizani 2001; Isohe et al. 2002; Croston et al. 2005). The jet is assumed to be cold since the hot plasma produced at the central engine usually cool down very quickly (e.g., Iwamoto and Takahara 2004). As for the mass and kinetic energy flux of powerful relativistic jets, numerical simulations tell us that no significant entrainment of the environmental matter takes place during the jet propagation (Scheck et al. 2002). According to this, the mass and kinetic energy flux of the jet are regarded as constant in time. Then, the conditions of $T_{\text{icm}}^2$ = const., $J_1$ = const. leads to the important relations of

$$\rho_1(t)A_j(t) = \text{const}, \quad \Gamma_j(t) = \text{const}.$$  \hspace{1cm} (3)

In fact, the constant $\Gamma_j$ agrees with the relativistic hydrodynamic simulations (e.g., Marti et al. 1997; Scheck et al. 2002). In order to evaluate $L_j$, we use the shock jump condition of $\Gamma_j^2 \rho_j = \beta^2_{\text{icm}} \rho_{\text{ICM}}$ (Kawakatu and Kino 2006) where $\beta_{\text{icm}}(= v_{\text{icm}}/c)$ and $\rho_{\text{ICM}}$ is the advance speed of the hot spot $\beta_{\text{icm}} = 10^{-2} \beta_{-2}$ (Liu et al. 1992; Scheuer 1995) and the mass density of ICM, respectively. Using, the jump condition, $L_j$ is given by

$$L_j = 2 \times 10^{45} R_{\text{icm}}^2 \beta_{-2}^2 n_{-2} \text{erg s}^{-1}$$  \hspace{1cm} (4)

where we use $A_j(t) = \pi R_{\text{icm}}^2(t)$, and the hot spot radius $R_{\text{icm}}$ is given by $R_{\text{icm}} = R_{\text{icm}}(10^7 \text{ yr})/1 \text{ kpc}$. As a fiducial case, we set the number density of surrounding ICM as $n_{\text{ICM}} = 10^{-2} \text{ cm}^{-3}$. The geometrical factors in Eqs. (1) and (2) are completely cancelled out. Actually, the $\Gamma_j$ dependence of Eq. (4) well coincide with the result of hydrodynamic simulations of relativistic outflows (Fig. 5 in Marti et al. 1997). One can naturally understand these properties by comparing the well-established properties such as supernovae and GRBs. Constant temperature in AGN jet can be realized by the “continuous” energy injection into the expanding cocoon whilst temperatures of astrophysical explosive sources such as gamma-ray bursts and supernovae would be decreased because of “impulsive” injection of the energy. Since the shock dissipation of the relativistic flow into non-relativistic one, in general, requires the energy conversion of whole kinetic energy density $\Gamma_j^2 \rho c^2$ into internal one (Piran 1999). Thus the resultant
temperatures are uniquely governed by $\Gamma_j$ and they remain to be constant in time. Similarly, in the studies of continuous stellar winds, the constant temperature has been predicted for a hot interior consist of the shocked wind (Weaver et al. 1977). Here we examine the time scale of the Coulomb interaction between protons and electrons. The time of energy transfer from the protons to electrons is given by $t_{\text{ep}} \approx (n_p \sigma_t c)^{-1}$ where $\sigma_t = 4 \pi (e^2/kT_e)^2 \ln \Lambda_e$ is the transport cross section for electron-proton collision. The coulomb logarithm is written as $\ln \Lambda_e \approx \ln (3kT_e \lambda_D/e^2)$ where $\lambda_D = (kT_e/\pi n_e e^2)^{1/2}$ is the Debye length (Totani 1998). A typical case of hot spots in AGN jets, we obtain $\ln \Lambda_e \approx 50$. Therefore, even using the maximal proton number density $n_p \approx n_e$, $t_{\text{ep}}$ satisfies

$$\frac{t_{\text{ep}}(t)}{t} \sim 5 \times 10^3 \Theta_{10}^{1/2} \bar{n}_e^{-1} \left( \frac{t}{10^3 \text{ yr}} \right)$$

where $\Theta_{10} \equiv kT_e/m_e c^2 = 10 \Theta_{10}$, and $n_e \equiv n_e (10^7 \text{ yr})/4 \times 10^{-5} \text{ cm}^{-3}$, are the electron temperature in unit of $m_e c^2$, and normalized number density of thermal electrons, respectively. As mentioned before, recent studies suggest the existence of large amount of $e^\pm$ pairs in AGN outflows which lead to much smaller $n_p$. Hence Eq. (10) shows the minimum value of $t_{\text{ep}}(t)/t$. Thus the energy transfer from protons to electrons is inefficient by the Coulomb coupling unless the cocoon is much younger than $t \sim 10^4 \text{ yr}$.

Next we evaluate the time scale of thermal bremsstrahlung cooling in the cocoons. It is well known that thermal bremsstrahlung is inefficient for the dilute plasma since its emissivity shows that thermal bremsstrahlung is inefficient for the dilute plasma since its emissivity shows that thermal bremsstrahlung is inefficient for the dilute plasma. As mentioned before, recent studies suggest the existence of large amount of $e^\pm$ pairs in AGN outflows which lead to much smaller $n_p$. Hence Eq. (10) shows the minimum value of $t_{\text{ep}}(t)/t$. Thus the energy transfer from protons to electrons is inefficient by the Coulomb coupling unless the cocoon is much younger than $t \sim 10^4 \text{ yr}$.

$$\frac{t_{\text{brems}}(t)}{t} \approx 5 \times 10^4 \Theta_{10}^{1/2} \bar{n}_e^{-1} \left( \frac{t}{10^3 \text{ yr}} \right)$$

where $\Theta_{10} \equiv kT_e/m_e c^2 = 10 \Theta_{10}$, and $n_e \equiv n_e (10^7 \text{ yr})/4 \times 10^{-5} \text{ cm}^{-3}$, are the electron temperature in unit of $m_e c^2$, and normalized number density of thermal electrons, respectively. As mentioned before, recent studies suggest the existence of large amount of $e^\pm$ pairs in AGN outflows which lead to much smaller $n_p$. Hence Eq. (10) shows the minimum value of $t_{\text{ep}}(t)/t$. Thus the energy transfer from protons to electrons is inefficient by the Coulomb coupling unless the cocoon is much younger than $t \sim 10^4 \text{ yr}$.

3 EMISSIONS FROM A YOUNG COCOON

3.1 Thermal MeV bremsstrahlung emission

The time-dependence of the thermal bremsstrahlung luminosity $L_{\text{brems}}$ is given by $L_{\text{brems}}(t) \propto n_e^2(t) T_e^{5/2} V_e(t) \propto t^{-1}$ based on the cocoon expansion shown in the previous section. Here it is clear that a younger cocoons are brighter bremsstrahlung emitters than older cocoons. In a similar way, brighter synchrotron luminosity has been expected for younger radio galaxies (Readhead et al. 1996; Begelman 1996). With relativistic thermal bremsstrahlung emissivity (Rybicki and Lightman 1979), the luminosity of the optically thin thermal bremsstrahlung emission $\nu L_{\nu}$ at energies $\sim 1 \text{ MeV}$ is estimated as

$$L_{\text{brems}}(t) \approx 2 \times 10^{40} \bar{n}_e^2 R^2 \Theta_{10}^{3/2} \left( \frac{t}{10^3 \text{ yr}} \right)^{-1} \text{ erg s}^{-1}.$$ (12)

Here we omit the redshift ($z$) factor merely for simplicity. Eq. (12) explains the reasons why for the no detection of the thermal emission from older cocoons. One is simply because it is not very bright. The other is because the predicted energy range is $\sim 1 \text{ MeV}$, the MeV–γ astronomy is still immature and it is sometimes called as “sensitivity gap” compared with the energy range below 10 keV and above GeV ranges (Takahashi et al. 2004).

For example, the bremsstrahlung emission from the cocoon located at a typical distance of $D = 10^7 \text{ Mpc}$ (O’Dea and Baum 1998) is examined here. In Fig. 1, we show the predicted values of $\nu F_\nu$ for the cocoons with $t = 10^7 \text{ yr}$ and $t = 10^4 \text{ yr}$.

$$\frac{t_{\text{brems}}(t)}{t} \approx 5 \times 10^4 \Theta_{10}^{1/2} \bar{n}_e^{-1} \left( \frac{t}{10^3 \text{ yr}} \right)$$

actually holds. Therefore most of the shock dissipation energy is deposited into the cocoon without suffering strong radiative cooling and our treatment of adiabatic energy injection in Eq. (11) is verified for $t < t_{\text{brems}}(t)$. We limit our attention on this case in the present work.

On the thermalizations of electrons and protons, it is worth to refer the recent studies with the particle-in-cell (PIC) simulations, since we only examine the simple case of the classical Coulomb interaction. PIC simulations begin to shed light on the complicated microscopic dynamics with in the relativistic collisionless shock. Using one-dimensional PIC simulations, Shimada and Hoshino (2000) revealed that the collision and merging processes among the coherent waves are accompanied by the strong thermalization of electrons. The results of three-dimensional PIC simulations (Nishikawa et al. 2003; Frederiksen et al. 2004) also tell us that electron populations are quickly thermalized whilst ion population tend to retain distinct bulk speed and thermalize slowly. In the result of Shimada and Hoshino (2000), (Fig. 4 in their paper), we see that the proton energy is transferred to the electrons, then the electrons are heated-up by protons. To sum up, PIC simulations imply the quick thermalization of electron populations by plasma waves and their associated instabilities such as the two-stream instability. Therefore, our estimate of $T_e$ would correspond to the lower limit of $T_e$. It is not the purpose of this paper to derive more realistic $T_e$ in detail.

In MeV energy band, a proposed mission of detector SGD on board the NeXt satellite with the eye up to $\sim 0.6 \text{ MeV}$ (Takahashi et al. 2004) could detect the thermal MeV emission from those located slightly closer and/or younger with smaller Lorentz factor. Lastly, other future
mission, Advanced Compton Telescope (ACT), is worth to be noticed. The sensitivity of ACT is expected to be a significantly improved compared with INTEGRAL one [http://heseweb.hr.navy.nil/gamma/detector/3C/3C-sens.htm](http://heseweb.hr.navy.nil/gamma/detector/3C/3C-sens.htm). Although they focus on the super-nova science (Milne et al. 2002) for the moment, the ACT would be a promising tool also for the young cocoon science.

At a glance, one may think it hard to distinguish overlapping emissions from the core of the AGN with limited spacial angular resolution of current satellites. Time variabilities of observed spectra is the key to distinguish them. It is obvious that the cocoon emission is constant in time whilst various emissions from the core of AGN should be highly variable. Hence steady emissions are convincingly originated in cocoons. Furthermore, the averaged spectral index of AGN core emissions at X-ray band (Koratkar and Blaes 1999; Kawaguchi et al. 2001) are softer than the bremsstrahlung emission discussed in the present work. Hence the difference of the spectral index is also a useful tool to figure out the origin of the emission.

### 3.2 Non-thermal emissions

Non-thermal emission from AGN jets is another key ingredient to investigate their physics. Non-thermal synchrotron emission from the radio lobes due to the relativistic electrons is well known characteristic of AGN jets (Miley 1980; Bridle and Perley 1984). Recently, inverse-Compton (IC) emissions from large scale jets have been also intensively explored both theoretically and observationally (e.g., Celotti and Fabian 2004; Croston et al. 2005).

The properties of IC emissions from young cocoons is discussed here. For this purpose, we firstly consider the properties of the synchrotron emission. The magnetic flux conservation is assumed here during the jet propagation which is given by

\[ B_{\text{hs}}(t) R_{\text{hs}}^2(t) = \text{const.} \quad (1 \leq Y \leq 2) \]

where \( Y \) is a parameter expressing the configuration of the magnetic field in the hot spot. The magnetic flux from the central engine is assumed to be constant in time. The case of constant \( Y = 1 \) shows the purely toroidal-dominated magnetic field whilst \( Y = 2 \) is relevant to the purely poloidal-dominated magnetic field. Using \( Y \), the time dependence of the synchrotron luminosity at the hot spot \( L_{\text{hs, syn}}(t) \) may be given by

\[ L_{\text{hs, syn}}(t) \propto R_{\text{hs}}^2(t) \gamma^2 B_{\text{hs}}(t) n_e^\gamma \propto t^{2Y - 4} \]

where we assume that the number density of the non-thermal electrons \( n_e^\gamma \) is proportional to \( n_e \), and \( \gamma \) is constant in time because the synchrotron cooling time tend to be longer than the sound crossing time at the hot spot (e.g., KT04). Taking the observational fact of the large number of the CSOs in spite of their young age, the larger synchrotron luminosity is required for younger sources (Bagelman 1996; Readhead et al. 1996). Qualitatively, the model well reproduce this observational properties of young radio galaxies.

To evaluate IC emission of the cocoon, it may be useful to define the quantities of \( f_{\text{usc}}(t) \equiv U_{\text{usc}}(t)/U_{\text{syn}}(t) \) and \( f_{\text{IC}/\text{CMB}}(t) \equiv U_{\text{IC}/\text{CMB}}(t)/U_{\text{syn}}(t) \), where \( U_{\text{syn}}, U_{\text{usc}}, \text{and } U_{\text{IC}/\text{CMB}} \) are the energy densities of synchrotron photons, those of synchrotron-self Compton (SSC), and those of IC scattering of the Cosmic-Microwave Background (CMB), respectively. Photons with larger density is the dominant seed photons for IC scattering. We denote that the IC luminosities for synchrotron photons and the CMB as \( L_{\text{usc}} \) and \( L_{\text{IC}/\text{CMB}} \), respectively.

For \( f_{\text{usc}}(t) < f_{\text{IC}/\text{CMB}}(t) \sim t^{2Y} \) which implies that younger cocoon produce less IC/CMB photons in contrast to the case of bremsstrahlung ones. It is of great importance to examine whether the predicted frequency of IC/CMB emission overlapping in MeV band or not. According to the standard diffusive shock acceleration, the acceleration time scale is estimated as \( t_{\text{acc}} = (2\pi\gamma m_e c^2)/(\epsilon B_{\text{hs}}) \) where \( \epsilon \) is the parameter characterizing the mean free path for the scattering (e.g., Drury 1983). The maximum Lorentz factor of electrons \( \gamma \) can be obtained by the equating \( t_{\text{acc}} \) to the synchrotron cooling time \( t_{\text{syn}} = (6\pi m_e c^2)/(\sigma_T c B_{\text{hs}}^2) \). This shows the \( B_{\text{hs}} \) dependence of \( \gamma \) as

\[ \gamma(t) \propto B_{\text{hs}}^{1/2}(t). \] (13)

Assuming that the strength of magnetic field in the cocoon \( B(t) \) is proportional to the one in the hot spot, the maximum frequency of the IC/ICM emission \( \nu_{\text{IC}/\text{CMB}} \propto \gamma^2 \nu_{\text{IC}} \) can be estimated as

\[ \nu_{\text{IC}/\text{CMB}}(t) \sim 1 \times 10^{19} \gamma^2 \left( \frac{t}{10^9 \text{ yr}} \right)^Y \text{ Hz}, \] (14)

where we denote \( B(t) \propto B_{\text{hs}}(t) \propto R_{\text{hs}}^2(t) \propto t^{-Y}, \gamma(t) = 10^{2Y/3}(t/10^9 \text{ yr})^{2Y/3}, \) and \( \gamma_4 = \gamma/10^4 \). The typical value of \( \gamma \) is adopted from Blandford (1990). From this, one can find that \( \nu_{\text{IC}/\text{CMB}}(t) \) of young cocoons much smaller than 1 MeV = 2 × 10^{20} Hz.

In the case of \( U_{\text{syn}}(t) > U_{\text{CMB}} \), the behaviour of \( U_{\text{syn}}(t) \) is given by \( L_{\text{syn}}(t) \propto c^2 \Delta^2(t) U_{\text{syn}}(t) \propto \nu_{\text{syn}}(t) V_c(t) \). From this we obtain \( U_{\text{syn}}(t) \propto U_{\text{hs}}(t)^{-1} \). The model predicts that \( f_{\text{usc}}(t) \propto t^{-1} \) in time and younger cocoon yields more SSC photons. Using this, \( L_{\text{usc}} \) can be estimated as \( L_{\text{usc}}(t) \propto t^{-2Y} \). The maximum frequency of the SSC emission \( \nu_{\text{ssc}} \) can be evaluated with Eq. (13). \( \nu_{\text{ssc}} \sim \gamma^2 \nu_{\text{syn}} \sim 1 \times 10^6 \gamma^4 B \text{ Hz} \).
can be evaluated as
\[ \nu_{\text{esc}}(t) \sim 1 \times 10^{17\cdot\gamma_5} B_{-5} \left( \frac{t}{10^7 \text{ yr}} \right)^{\circ} \text{Hz} \] (15)

where we use Eq. (13) and the typical value of \( B \) is set as \( B(t) = 10^{-5} B_{-5} (t/10^7 \text{ yr})^{-\circ} \) G based on Blandford (1990). Thus, it is found that non-thermal emissions from younger cocoon reside in much lower energy band than MeV.

4 SUMMARY

We have investigated the luminosity evolutions of AGN cocoons together with the dynamical evolution of expanding cocoon. Below we summarize the main results of the present work.

- We newly predict the bremsstrahlung emission peaked at MeV-\( \gamma \) band as a result of standard shock dissipation of relativistic jets in AGNs. The temperatures of cocoon is governed only by the bulk Lorentz factor of the jet \( \Gamma \). The electron temperature \( T_e \) relevant to observed emissions is typically predicted in the range of MeV for \( \Gamma \sim 10 \). Constant temperatures of plasma in the cocoon can be realized because of the continuous energy injection by the jet with constant \( \Gamma \). It should be emphasized that the constant behaviour of AGN cocoon temperatures is different from the well known cases of gamma-ray bursts and supernovae. In these sources, the temperatures decrease in time because the energy injection time scales are much shorter than their ages. Since larger number densities of thermal electrons are predicted for younger cocoons, brighter thermal bremsstrahlung emission than that of older cocoon is naturally expected.

- Additionally, non-thermal IC emissions from young cocoons are also investigated. Importantly, in contrast to the case of MeV thermal emission, the typical frequency of SSC and IC/CMB emissions are predicted to be decreased for younger cocoon, since the maximum Lorentz factor of relativistic electrons are decreased. Therefore the typical frequencies of IC from a younger cocoon are at much lower than MeV ranges.

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