Mon. Not. R. Astron. Soc. **376,** 1630–1634 (2007) doi:10.1111/j.1365-2966.2007.11354.x

Extragalactic MeV γ-ray emission from cocoons of young radio galaxies

M. Kino,[1]★ N. Kawakatu[2] and H. Ito[3]

[1]*Department of Earth and Space Science, Osaka University, 560-0043 Toyonaka, Japan*
[2]*National Astronomical Observatory of Japan, 181-8588 Mitaka, Japan*
[3]*Department of Science & Engineering, Waseda University, Tokyo 169-8555, Japan*

Accepted 2006 November 28. Received 2006 November 1; in original form 2006 August 2

ABSTRACT

Strong γ-ray emission from cocoons of young radio galaxies is predicted for the first time. Considering the process of adiabatic injection of the shock dissipation energy and mass of the relativistic jet in active nuclei into the cocoon, while assuming thermalizing electron plasma interactions, we find that the thermal electron temperature of the cocoon is typically predicted to be of the order of $\sim$ MeV, and 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: galaxies: active – galaxies: jets – 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 the order of $\sim$10 produced in the vicinity of a supermassive black hole at the galactic centre (see Begelman, Blandford & Rees 1984, for reviews). The jet in powerful radio-loud AGNs [i.e. Fanaroff–Riley type II (FR II) radio sources] is slowed down via strong terminal shocks which are identified as hotspots. The shocked plasma then expands sideways and envelops the whole jet system, and this is a so-called cocoon (Begelman & Cioffi 1989, hereafter BC89). The cocoon is a by-product of the interaction between AGN jets and the surrounding intracluster medium (ICM). The internal energy of the shocked plasma continuously inflates this cocoon. Initially, the existence of the cocoon was theoretically predicted by Scheuer (1974).

The first clear evidence for an X-ray cavity was discovered in the centre 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 correspond 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 show us further evidence of these X-ray cavities (e.g. Fabian et al. 2000; Blanton et al. 2001). Additional 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 'the cocoons of young radio galaxies' as a new population of γ-ray emitters in the Universe. Until now, little attention has been paid to the evolution of the thermal temperature and number density of the cocoon. Recently we have investigated the evolution of the temperature and number density by taking into proper account mass and energy injections by the relativistic jet (Kino & Kawakatu 2005; Kawakatu & Kino 2006). We have found that the cocoon remains at constant temperature whilst the number density increases as a cocoon becomes younger. This leads to our new prediction of bright γ-ray emission from the young cocoon.

2 COCOON INFLATION BY A DISSIPATIVE RELATIVISTIC JET

Here we consider the time evolution of an expanding cocoon inflated by the dissipation energy of the relativistic jet via terminal shocks. 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 end of Section 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 γ-ray bursts and supernovae.

The time-averaged mass and energy injections from the jet into the cocoon, which govern the cocoon pressure $P_{\rm c}$ and mass density $\rho_{\rm c}$, are written as

$$\frac{\hat{\gamma}_{\rm c}}{\hat{\gamma}_{\rm c}-1}\frac{P_{\rm c}(t)V_{\rm c}(t)}{t} \approx 2T_{\rm j}^{01}(t)A_{\rm j}(t), \tag{1}$$

$$\frac{\rho_{\rm c}(t)V_{\rm c}(t)}{t} \approx 2J_{\rm j}(t)A_{\rm j}(t), \tag{2}$$

where $\hat{\gamma}_{\rm c}$, $V_{\rm c}$, $T_{\rm j}^{01}$, $J_{\rm j}$ and $A_{\rm j}$ 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.

★E-mail: kino@vega.ess.sci.osaka-u.ac.jp

© 2007 The Authors. Journal compilation © 2007 RAS

The total kinetic energy and mass flux of the jet are $T_{\rm j}^{01} = \rho_{\rm j} c^2 \Gamma_{\rm j}^2 v_{\rm j}$ and $J_{\rm j} = \rho_{\rm j}\Gamma_{\rm j} v_{\rm j}$ where $\rho_{\rm j}$ and $\Gamma_{\rm j}$ are the mass density and bulk Lorentz factor of the jet (Blandford & Rees 1974). Hereafter we set $v_{\rm j} = c$. The total kinetic power of the relativistic jet is defined as $L_{\rm j} \equiv 2\,T_{\rm j}^{01}\,(t)\,A_{\rm j}(t)$ and it is assumed to be constant in time. Although little attention has been paid to the mass injection equation (2) up to now, it is of great significance to take account of equation (2) for derivation of the cocoon temperatures. Hence we use equation (2) to evaluate the temperatures of the cocoons. In contrast, the energy equation (1) has been widely utilized in the literature of AGN bubbles in various ways (e.g. BC89; Dunn & Fabian 2004).

The kinetic power dominance in the flow is postulated in this work in accordance with observational indications (e.g. Leahy & Gizani 2001; Isobe et al. 2002; Croston et al. 2005). The jet is assumed to be cold since the hot plasma produced at the central engine usually cools down very quickly (e.g. Iwamoto & Takahara 2002). 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 $T_{\rm j}^{01} =$ constant and $J_{\rm j} =$ constant lead to the important relations

$$\rho_{\rm j}(t) A_{\rm j}(t) = \text{constant}, \quad \Gamma_{\rm j}(t) = \text{constant}. \tag{3}$$

In fact, the constant $\Gamma_{\rm j}$ agrees with relativistic hydrodynamic simulations (e.g. Martí et al. 1997; Scheck et al. 2002). In order to evaluate $L_{\rm j}$, we use the shock jump condition of $\Gamma_{\rm j}^2 \rho_{\rm j} = \beta_{\rm hs}^2 \rho_{\rm ICM}$ (Kawakatu & Kino 2006), where $\beta_{\rm hs}(= v_{\rm hs}/c)$ and $\rho_{\rm ICM}$ are the advance speed of the hotspot $\beta_{\rm hs} = 10^{-2}\beta_{-2}$ (Liu, Pooley & Riley 1992; Scheuer 1995) and the mass density of the ICM, respectively. Using the jump condition, $L_{\rm j}$ is given by

$$L_{\rm j} = 2 \times 10^{45} R_{\rm kpc}^2 \beta_{-2}^2 n_{-2}\ \text{erg s}^{-1}, \tag{4}$$

where we use $A_{\rm j}(t) = \pi R_{\rm hs}^2\,(t)$, and the hotspot radius $R_{\rm hs}$ is given by $R_{\rm kpc} = R_{\rm hs}(10^7\,\text{yr})/1\,\text{kpc}$. As a fiducial case, we set the number density of the surrounding ICM as $n_{\rm ICM}(d) = \rho_{\rm ICM}(d)/m_{\rm p} = 10^{-2}\,\text{cm}^{-3}\,n_{-2}(d/30\,\text{kpc})^{-2}$, where d is the distance from the centre of the ICM, and $m_{\rm p}$ is the proton mass. Since the change of the index from -2 does not change the essential physics discussed in this work, we focus on this case for simplicity. Since $L_{\rm j}$ is the ultimate source of the phenomena associated with the cocoon, all of the emission powers that will appear in Section 3 should be less than $L_{\rm j}$.

The total number density of electrons in the cocoon $n_{\rm e}(t)$ is governed by the cocoon geometry and its plasma content. For convenience, we define the ratio of 'the volume swept up by the unshocked relativistic jet' to 'the volume of the cocoon' as $\mathcal{A}(t)$. Hereafter we denote $V_{\rm c}(t) = 2(\pi/3)\mathcal{R}^2 Z_{\rm hs}^3(t)$, $Z_{\rm hs}$ [which satisfies $Z_{\rm hs}(t) = \beta_{\rm hs} ct$], $R_{\rm c}$ and $\mathcal{R} \equiv R_{\rm c}/Z_{\rm hs} < 1$ as the cocoon volume, the distance from the central engine to the hotspot, the radius of the cocoon body and the aspect-ratio of the cocoon, respectively (e.g. BC89; Kino & Kawakatu 2005). Postulating that $\mathcal{R}$ and $Z_{\rm hs}/R_{\rm hs}$ are constant in time, $\mathcal{A}(t)$ is evaluated as

$$\mathcal{A}(t) \equiv \frac{2A_{\rm j}(t) v_{\rm j} t}{V_{\rm c}(t)} \approx 0.4\,\mathcal{R}^{-2} R_{\rm kpc}^2 Z_{30}^{-2} \beta_{-2}^{-1}, \tag{5}$$

where $Z_{30} = Z_{\rm hs}(10^7\,\text{yr})/30\,\text{kpc}$. Note that, in this case, the time dependence of $\mathcal{A}$ is removed since $V_{\rm c} \propto t^{-3}$ and $A_{\rm j} \propto t^2$. We stress that this case satisfies the observational indication of $v_{\rm hs} =$ constant (e.g. Conway 2002). Equation (5) tells us that $\mathcal{A}$ is of the order of unity. Actually it is seen in some numerical simulations (e.g. in fig. 2 of Scheck et al. 2002). The cocoon mass density $\rho_{\rm c}(t)$ is controlled by the mass injection by the jet and it can be expressed as

$$\begin{aligned}\rho_{\rm c}(t) &\approx \Gamma_{\rm j}\rho_{\rm j}(t)\mathcal{A} \\ &= \beta_{\rm hs}^2 \Gamma_{\rm j}^{-1} \rho_{\rm ICM}[Z_{\rm hs}(t)]\mathcal{A},\end{aligned} \tag{6}$$

where we use the shock condition of $\Gamma_{\rm j}^2 \rho_{\rm j} = \beta_{\rm hs}^2 \rho_{\rm ICM}$. Adopting properties typical of FR II sources(Miley 1980; Begelman et al. 1984; Bridle & Perley 1984), we obtain

$$n_{\rm e}(t) \approx 4 \times 10^{-5} \bar{\mathcal{A}} n_{-2} \Gamma_{10} \beta_{-2}^2 \left(\frac{t}{10^7\,\text{yr}}\right)^{-2} \text{cm}^{-3}, \tag{7}$$

where $\Gamma = 10\,\Gamma_{10}$, and $\bar{\mathcal{A}} = \mathcal{A}/0.4$. Here we assume that the mass density of the $\text{e}^\pm$ pair plasma is heavier than that of an electron–proton one, and then we adopt $\rho_{\rm c} \approx 2m_{\rm e}n_{\rm e}$ in the light of previous works (Reynolds et al. 1996; Wardle et al. 1998; Sikora & Madejski 2000; Kino & Takahara 2004). However, the mixture ratio of $\text{e}^\pm$ pair and electron–proton plasmas is still open. If we assume completely pure electron–proton content in the jet, too small a value of $n_{\rm e}$ is required and it conflicts with that of non-thermal electrons (Kino & Takahara 2004).

Let us estimate the electron (and positron) temperature ($T_{\rm e}$) and proton temperature ($T_{\rm p}$). From equations (1) and (2) together with the equation of state

$$P_{\rm c} \approx 2n_{\rm e}kT_{\rm e}, \tag{8}$$

we can directly derive the temperatures as

$$kT_{\rm e} \approx 1\Gamma_{10}\,\text{MeV}, \quad kT_{\rm p} \approx 2\Gamma_{10}\,\text{GeV}, \tag{9}$$

where we adopt the two-temperature condition of $kT_{\rm e} \approx (m_{\rm e}/m_{\rm p})kT_{\rm p}$. It should be stressed that the temperatures are governed only by $\Gamma_{\rm j}$. It is also worth noting that the geometrical factors in equations (1) and (2) are completely cancelled out. Actually, the $\Gamma_{\rm j}$ dependence of equation (9) coincides well with the result of hydrodynamic simulations of relativistic outflows (fig. 5 in Martí et al. 1997). One can naturally understand these properties by comparing well-established properties such as those of supernovae and γ-ray bursts. A constant temperature in the AGN jet can be realized by 'continuous' energy injection into the expanding cocoon, whilst temperatures of astrophysical explosive sources such as γ-ray bursts and supernovae would be decreased because of 'impulsive' injection of the energy. This is because the shock dissipation of a relativistic flow into a non-relativistic one, in general, requires the energy conversion of the whole kinetic energy density $\Gamma_{\rm j}\rho_{\rm j}c^2$ into internal energy (Piran 1999). Thus the resultant temperatures are uniquely governed by $\Gamma_{\rm j}$ and they remain constant in time. Similarly, in studies of continuous stellar winds, a constant temperature has been predicted for a hot interior consisting of the shocked wind (Weaver et al. 1977).

Here we examine the time-scale of the Coulomb interaction between protons and electrons. The time-scale of energy transfer from the protons to the electrons is given by $t_{\rm ep} \approx (n_{\rm p}\sigma_{\rm t}c)^{-1}$, where $\sigma_{\rm t} = 4\pi(e^2/kT_{\rm e})^2 \ln\Lambda_{\rm c}$ is the transport cross-section for electron–proton collision. The Coulomb logarithm is written as $\ln\Lambda_{\rm c} \approx \ln\,(3kT_{\rm e}\lambda_{\rm D}/e^2)$ where $\lambda_{\rm D} = (kT_{\rm e}/4\pi n_{\rm e}e^2)^{1/2}$ is the Debye length (Totani 1998). For a typical case of hotspots in AGN jets, we obtain $\ln\Lambda_{\rm c} \sim 50$. Therefore, even using the maximal proton number density $n_{\rm p} \approx n_{\rm e}$, $t_{\rm ep}$ satisfies

$$\frac{t_{\rm ep}(t)}{t} \sim 5 \times 10^3\ \Theta_{10}^2 \bar{n}_{\rm e}^{-1} \left(\frac{t}{10^7\,\text{yr}}\right), \tag{10}$$

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

Next we evaluate the time-scale of thermal bremsstrahlung cooling in the cocoons. It is well known that thermal bremsstrahlung is inefficient for dilute plasma since its emissivity shows $\propto n_e^2(t)$ where $n_e(t)$ is the electron number density in the cocoon. For shock-heated electrons with a temperature of $\Theta_e \approx \Gamma_j$, the cooling time of the bremsstrahlung per unit volume is estimated as $t_{brem} \approx \Gamma m_e c^2 n_e/\epsilon_{brem}$ where the bremsstrahlung emissivity in the relativistic regime is $\epsilon_{brem} = 1.3 \times 10^{-22}\, \Theta_e^{1/2}\, n_e^2\, (1 + 2.6\Theta_e)\, \mathrm{erg\,cm^{-3}\,s^{-1}}$ with a Gaunt factor of 1.2 (Rybicki & Lightman 1979). The condition of $t_{brem}(t) > t$,

$$\frac{t_{brem}(t)}{t} \approx 5 \times 10^4\, \Theta_{10}^{-1/2} \bar{n}_e^{-1} \left(\frac{t}{10^7\ \mathrm{yr}}\right), \tag{11}$$

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 equation (1) is verified for $t < t_{brem}(t)$. We limit our attention to this case in the present work.

On the thermalizations of electrons and protons, it is worth referring to recent studies with 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 within the relativistic collisionless shock. Using one-dimensional PIC simulations, Shimada & Hoshino (2000) revealed that the collision and merging processes among coherent waves are accompanied by 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 the ion population tends to retain a distinct bulk speed and thermalize slowly. In the result of Shimada & 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 a more realistic T_e in detail.

3 EMISSIONS FROM A YOUNG COCOON

3.1 Thermal MeV bremsstrahlung emission

The time dependence of the thermal bremsstrahlung luminosity L_{brem} is given by $L_{brem}(t) \propto n_e^2(t) T_e^{3/2} V_c(t) \propto t^{-1}$ based on the cocoon expansion shown in the previous section. Hence it is clear that younger cocoons are brighter bremsstrahlung emitters than older cocoons. In a similar way, a higher synchrotron luminosity has been expected for younger radio galaxies (Readhead et al. 1996; Begelman 1996). With a relativistic thermal bremsstrahlung emissivity (Rybicki & Lightman 1979), the luminosity of the optically thin thermal bremsstrahlung emission νL_ν at energies $\sim$1 MeV is estimated as

$$L_{brem}(t) \approx 2 \times 10^{40}\, \bar{n}_e^2 \mathcal{R}^2 \Theta_{10}^{3/2} \left(\frac{t}{10^7\ \mathrm{yr}}\right)^{-1}\ \mathrm{erg\ s^{-1}}. \tag{12}$$

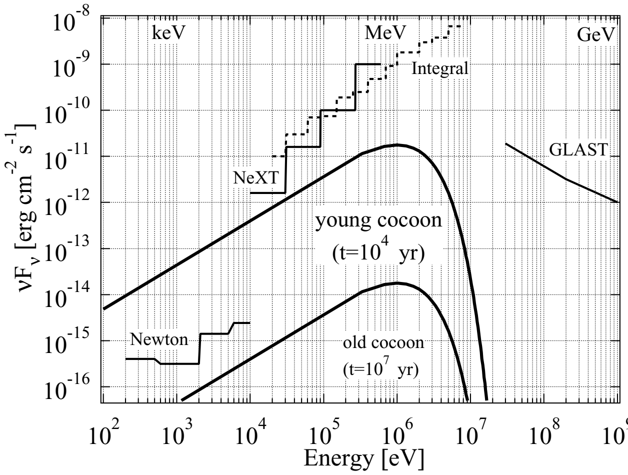

Figure 1. Model prediction of MeV-peaked thermal bremsstrahlung emission from cocoons located at $D = 10^3$ Mpc. The predicted emission from a young cocoon is bright enough to detect in the X-ray band, whilst that from an old cocoon is much fainter than the detection limits (Hasinger et al. 2001; Roques et al. 2003; Takahashi et al. 2004).

Here we omit the redshift (z) factor merely for simplicity. Equation (12) explains the reasons for the non-detection of the thermal emission from older cocoons. One reason is simply that it is not very bright. The other reason is that the predicted energy range is $\sim$1 MeV: MeV γ-astronomy is still immature and it is sometimes called a 'sensitivity gap' compared with the energy range below 10 keV and the ranges above a GeV (Takahashi et al. 2004).

For example, the bremsstrahlung emission from a cocoon located at a typical distance of $D = 10^3$ Mpc (O'Dea & Baum 1997) is examined here. In Fig. 1, we show the predicted values of νF_ν for cocoons with $t = 10^7$ and 10^4 yr. The cocoons with $t = 10^7$ yr have $\nu F_\nu \sim 10^{-14}\, \mathrm{erg\,cm^{-2}\,s^{-1}}$. The detection threshold of the spectrometer on board the *INTEGRAL* satellite (SPI) is about $\nu F_\nu \sim 10^{-9}\, \mathrm{erg\,cm^{-2}\,s^{-1}}$ at $\sim$1 MeV. For a young cocoon with $t = 10^4$ yr, the predicted luminosity is $\sim 10^3$ times larger than that for cocoons with $t = 10^7$ yr: $\nu F_\nu \sim 10^{-11}\, \mathrm{erg\,cm^{-2}\,s^{-1}}$. This is still less than the threshold of *INTEGRAL*. This may be the reason why there has been no clear detection of MeV emission from young cocoons up to now. Fig. 1 shows that the *XMM–Newton* satellite can detect the low-energy part of the thermal bremsstrahlung from young cocoons in principle. Hence some of the extragalactic unidentified X-ray sources could be attributed to the low-energy tail of the bremsstrahlung emissions. Interestingly, a recent observation by *XMM–Newton* reveals that the spectrum of the young radio-loud AGN B1358 + 624 actually shows the power-law slope close to the bremsstrahlung one (Vink et al. 2006).

In the MeV energy band, a proposed mission of the Soft Gamma-Ray Detector (SGD) on board the *NeXT* satellite with the sensitivity extended to the sub-MeV region (Takahashi et al. 2004) could detect thermal MeV emission from sources located slightly closer and/or younger with a smaller Lorentz factor. Lastly, another future mission, the *Advanced Compton Telescope* (*ACT*), is worth noting. The sensitivity of the *ACT* is expected to be significantly improved compared with *INTEGRAL* (http://heseweb.nrl.navy.mil/gamma/detector/3C/3C_sens.htm). Although it is focusing on supernova science (Milne et al. 2002) for the moment, the *ACT* would be a promising tool also for the science of young cocoons.

At a glance, one may think that it would be hard to distinguish overlapping emissions from the core of the AGN with the limited spatial angular resolution of current satellites. The time variability of observed spectra is the key to distinguishing them. It is obvious that the cocoon emission is constant in time whilst various emissions from the core of AGNs should be highly variable. Hence steady emissions convincingly originate in cocoons. Furthermore, the averaged spectral index of AGN core emissions in the X-ray band (Koratkar & Blaes 1999; Kawaguchi, Shimura & Mineshige 2001) is 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 relativistic electrons is a well-known characteristic of AGN jets (Miley 1980; Bridle & Perley 1984). Recently, inverse Compton (IC) emissions from large-scale jets have been also intensively explored both theoretically and observationally (e.g. Celotti & Fabian 2004; Croston et al. 2005).

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

$$B_{\rm hs}(t)R_{\rm hs}^{Y}(t) = \text{constant} \quad (1 \leqslant Y \leqslant 2),$$

where Y is a parameter expressing the configuration of the magnetic field in the hotspot. 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 hotspot $L_{\rm hs,syn}(t)$ may be given by $L_{\rm hs,syn}(t) \propto R_{\rm hs}^3(t)\gamma^2 B_{\rm hs}^2(t) n_{\rm e}^{\rm NT}(\gamma, t) \propto t^{-2Y+1}$, where we assume that the number density of the non-thermal electrons $n_{\rm e}^{\rm NT}(\gamma, t)$ is proportional to $n_{\rm e}(t)$, and γ is constant in time because the synchrotron cooling time tends to be longer than the sound crossing time at the hotspot (e.g. Kino & Takahara 2004). Taking the observational fact of the large number of compact symmetric object (CSOs) in spite of their young age, a larger synchrotron luminosity is required for younger sources (Begelman 1996; Readhead et al. 1996). Qualitatively, the model well reproduces these observational properties of young radio galaxies.

To evaluate the IC emission of the cocoon, it may be useful to define the quantities $f_{\rm ssc}(t) \equiv U_{\rm ssc}(t)/U_{\rm syn}(t)$ and $f_{\rm IC/CMB}(t) \equiv U_{\rm IC/CMB}(t)/U_{\rm syn}(t)$, where $U_{\rm syn}$, $U_{\rm ssc}$ and $U_{\rm IC/CMB}$ are the energy densities of synchrotron photons, synchrotron self-Compton (SSC) emission and IC scattering of the cosmic microwave background (CMB), respectively. Photons with larger density are the dominant seed photons for IC scattering. We denote the IC luminosities for synchrotron photons and the CMB as $L_{\rm ssc}$ and $L_{\rm IC/CMB}$, respectively.

For $U_{\rm ssc}(t) < U_{\rm CMB}$, we see that $f_{\rm IC/CMB}(t) \propto t^{2Y}$ which implies that younger cocoons 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 overlaps in the MeV band or not. According to standard diffusive shock acceleration, the acceleration time-scale is estimated as $t_{\rm acc} = (2\pi\, \gamma m_{\rm e}\, c\xi)/(eB_{\rm hs})$, where ξ is the parameter characterizing the mean free path for the scattering (e.g. Drury 1983). The maximum Lorentz factor of electrons γ can be obtained by equating $t_{\rm acc}$ to the synchrotron cooling time $t_{\rm syn} = (6\pi m_{\rm e}\, c^2)/(\sigma_{\rm T}\, \gamma c B_{\rm hs}^2)$. This shows the $B_{\rm hs}$ dependence of γ as

$$\gamma(t) \propto B_{\rm hs}^{-1/2}(t). \tag{13}$$

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

$$\nu_{\rm IC/CMB}(t) \sim 1 \times 10^{19} \gamma_4^2 \left(\frac{t}{10^7\ {\rm yr}}\right)^{Y}\ {\rm Hz}, \tag{14}$$

where we denote $B(t) \propto B_{\rm hs}(t) \propto R_{\rm hs}^{-Y}(t) \propto t^{-Y}$, $\gamma(t) = 10^4 \gamma_4 (t/10^7\ {\rm yr})^{Y/2}$ and $\gamma_4 = \gamma/10^4$. The typical value of γ is adopted from Blandford (1990). From this, one can find that $\nu_{\rm IC/CMB}(t)$ of young cocoons is much smaller than $1\ {\rm MeV} = 2 \times 10^{20}$ Hz.

In the case of $U_{\rm syn}(t) > U_{\rm CMB}$, the behaviour of $U_{\rm syn}(t)$ is given by $L_{\rm syn}(t) \propto cZ_{\rm hs}^2(t) U_{\rm syn}(t) \propto \epsilon_{\rm syn}(t) V_{\rm c}(t)$. From this we obtain $U_{\rm syn}(t) \propto U_{\rm B}(t) t^{-1}$. The model predicts that $f_{\rm ssc}(t) \propto t^{-1}$ in time and a younger cocoon yields more SSC photons. Using this, $L_{\rm ssc}$ can be estimated as $L_{\rm ssc}(t) \propto t^{-2Y}$. The maximum frequency of the SSC emission $\nu_{\rm ssc}$ can be evaluated with equation (13). $\nu_{\rm ssc} \sim \gamma^2\, \nu_{\rm syn} \sim 1 \times 10^6\, \gamma^4 B$ Hz can be evaluated as

$$\nu_{\rm ssc}(t) \sim 1 \times 10^{17} \gamma_4^4 B_{-5} \left(\frac{t}{10^7\ {\rm yr}}\right)^{Y}\ {\rm Hz}, \tag{15}$$

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

4 SUMMARY

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

(i) We predict, for the first time, the bremsstrahlung emission peaked in the MeV–γ band as a result of standard shock dissipation of relativistic jets in AGNs. The temperatures of the cocoon are governed only by the bulk Lorentz factor of the jet $\Gamma_{\rm j}$. The electron temperature $T_{\rm e}$ relevant to observed emissions is typically predicted in the range of MeV for $\Gamma_{\rm j} \sim 10$. Constant temperatures of plasma in the cocoon can be realized because of continuous energy injection by the jet with constant $\Gamma_{\rm j}$. It should be emphasized that the constant behaviour of AGN cocoon temperatures is different from the well-known cases of γ-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 an older cocoon is naturally expected.

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

ACKNOWLEDGMENTS

We are indebted to M. C. Begelman, A. Celotti, F. Takahara, N. Isobe and J. Kataoka for valuable comments and discussions. The anonymous referee is thanked for thoughtful comments that improved the quality of the paper. MK acknowledges the Grant-in-Aid for Scientific Research of the Japanese Ministry of Education, Culture, Sports, Science and Technology No. 14079025. HI acknowledge the Grant-in-Aid for the 21st Century COE Program (Physics of Self-Organization Systems) and a Grant for Special Research Projects at Waseda University.

REFERENCES

Begelman M. C., 1996, in Carilli C. L., Harris D. E., eds, Cygnus A – Study of a Radio Galaxy. Cambridge Univ. Press, Cambridge, p. 209
Begelman M. C., Cioffi D. F., 1989, ApJ, 345, L21 (BC89)
Begelman M. C., Blandford R. D., Rees M. J., 1984, Rev. Mod. Phys., 56, 255
Blandford R. D., 1990, in Courvoisier T. J.-L., Mayor M., eds, Active Galactic Nuclei. Springer-Verlag, New York
Blandford R. D., Rees M. J., 1974, MNRAS, 169, 395
Blanton E. L., Sarazin C. L., McNamara B. R., Wise M. W., 2001, ApJ, 558, L15
Boehringer H., Voges W., Fabian A. C., Edge A. C., Neumann D. M., 1993, MNRAS, 264, L25
Bridle A. H., Perley R. A., 1984, ARA&A, 22, 319
Celotti A., Fabian A. C., 2004, MNRAS, 353, 523
Conway J. E., 2002, New Astron. Rev., 46, 263
Croston J. H., Hardcastle M. J., Harris D. E., Belsole E., Birkinshaw M., Worrall D. M., 2005, ApJ, 626, 733
Drury L. O., 1983, Rep. Prog. Phys., 46, 973
Dunn R. J. H., Fabian A. C., 2004, MNRAS, 355, 862
Fabian A. C. et al., 2000, MNRAS, 318, L65
Feigelson E. D., Laurent-Muehleisen S. A., Kollgaard R. I., Fomalont E. B., 1995, ApJ, 449, L149
Frederiksen J. T., Hededal C. B., Haugbølle T., Nordlund Å., 2004, ApJ, 608, L13
Hasinger G. et al., 2001, A&A, 365, L45
Isobe N., Tashiro M., Makishima K., Iyomoto N., Suzuki M., Murakami M. M., Mori M., Abe K., 2002, ApJ, 580, L111
Iwamoto S., Takahara F., 2002, ApJ, 565, 163
Kawaguchi T., Shimura T., Mineshige S., 2001, ApJ, 546, 966
Kawakatu N., Kino M., 2006, MNRAS, 370, 1513
Kino M., Kawakatu N., 2005, MNRAS, 364, 659
Kino M., Takahara F., 2004, MNRAS, 349, 336
Koratkar A., Blaes O., 1999, PASP, 111, 1
Leahy J. P., Gizani N. A. B., 2001, ApJ, 555, 709
Liu R., Pooley G., Riley J. M., 1992, MNRAS, 257, 545
Martí J. M. A., Mueller E., Font J.A., Ibanez J.M.A., Marquina A., 1997, ApJ, 479, 151
Miley G., 1980, ARA&A, 18, 165
Milne P. A., Kroeger R. A., Kurfess J. D., The L.-S., 2002, New Astron. Rev., 46, 617
Nishikawa K.-I., Hardee P., Richardson G., Preece R., Sol H., Fishman G. J., 2003, ApJ, 595, 555
O'Dea C. P., Baum S. A., 1997, AJ, 113, 148
Piran T., 1999, Phys. Rep., 314, 575
Readhead A. C. S., Taylor G. B., Pearson T. J., Wilkinson P. N., 1996, ApJ, 460, 634
Reynolds C. S., Fabian A. C., Celotti A., Rees M. J., 1996, MNRAS, 283, 873
Roques J. P. et al., 2003, A&A, 411, L91
Rybicki G. B., Lightman A. P., 1979, Radiative Processes in Astrophysics. Wiley-Interscience, New York
Scheck L. et al., 2002, MNRAS, 331, 615 (S02)
Scheuer P. A. G., 1974, MNRAS, 166, 513
Scheuer P. A. G., 1995, MNRAS, 277, 331
Shimada N., Hoshino M., 2000, ApJ, 543, L67
Sikora M., Madejski G., 2000, ApJ, 534, 109
Takahashi T. et al., 2004, New Astron. Rev., 48, 269
Totani T., 1998, ApJ, 502, L13
Vink J., Snellen I., Mack K.-H., Schilizzi R., 2006, MNRAS, 367, 928
Wardle J. F. C., Homan D. C., Ojha R., Roberts D. H., 1998, Nat, 395, 457
Weaver R., McCray R., Castor J., Shapiro P., Moore R., 1977, ApJ, 218, 377

This paper has been typeset from a TEX/LATEX file prepared by the author.