NONTHERMAL EMISSION FROM RELATIVISTIC ELECTRONS IN CLUSTERS OF GALAXIES:
A MERGER SHOCK ACCELERATION MODEL

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ABSTRACT

We have investigated evolution of nonthermal emission from relativistic electrons accelerated around the shock fronts during mergers of clusters of galaxies. We estimate synchrotron radio emission and inverse Compton scattering of cosmic microwave background photons from extreme ultraviolet (EUV) to hard X-ray range. The hard X-ray emission is most luminous in the later stage of a merger. Both hard X-ray and radio emissions are luminous only while signatures of merging events are clearly seen in the thermal intracluster medium (ICM). On the other hand, EUV radiation is still luminous after the system has relaxed. Propagation of shock waves and bulk-flow motion of ICM play crucial roles in extending radio halos. In the contracting phase, radio halos are located at the hot region of ICM or between two substructures. In the expanding phase, on the other hand, radio halos are located between two ICM hot regions and show rather diffuse distribution.

Subject headings: acceleration of particles — galaxies: clusters: general — hydrodynamics — intergalactic medium — radiation mechanisms: nonthermal

1. INTRODUCTION

Some clusters of galaxies have diffuse nonthermal synchrotron radio halos, which extend in a ~ megaparsec scale (e.g., Giovannini et al. 1993; Röttgering et al. 1997; Deiss et al. 1997). This indicates that there exists a relativistic electron population with energy of a few GeV (if we assume the magnetic field strength is an order of μG) in intracluster space in addition to the thermal intracluster medium (ICM). Furthermore, it is well known that such clusters of galaxies show evidence of recent major mergers in X-ray observations (e.g., Henriksen & Markovitch 1996; Honda et al. 1996; Markevitch, Sarazin, & Vikhlinin 1999; Watanabe et al. 1999). In such clusters of galaxies with radio halos, nonthermal X-ray radiation due to inverse Compton (IC) scattering of cosmic microwave background (CMB) photons by the same electron population is expected (Rephaeli 1979). Indeed, nonthermal X-ray radiation was recently detected in a few rich clusters (e.g., Fusco-Femiani et al. 1999; Rephaeli, Gruber, & Blanco 1999; Kaastra et al. 1999) and several galaxy groups (Fukazawa et al. 1999), although their origins are still controversial. In addition to such relatively high energy nonthermal emission, diffuse extreme ultraviolet (EUV) emission is detected from a number of clusters of galaxies (Lieu et al. 1996; Mitz, Lieu, & Lockman 1998; Lieu, Bonamente, & Mitz 1999). Although their origins are also unclear, one hypothesis is that EUV emission is due to IC emission of CMB. If the hypothesis is right, this indicates existence of relativistic electrons with energy of several hundred MeV in intracluster space.

The origin of such relativistic electrons is still unclear. Certainly, there are point sources like radio galaxies in clusters of galaxies, which produce such an electron population. However, the electrons can spread by diffusion in an area on the scale of only a few kiloparsecs during the IC cooling time. Clearly, this cannot explain the typical spatial size of radio halos. One possible solution of this problem is a secondary electron model, where the electrons are produced through decay of charged pions induced by the interaction between relativistic protons and thermal protons in ICM (Dennison 1980). In the secondary electron model, however, too much gamma-ray emission is produced through neutral pion decay to fit the Coma Cluster results (Blasi & Colafrancesco 1999). Moreover, the secondary electron model cannot explicitly explain the association between merger and radio halos.

From N-body + hydrodynamical simulations, it is expected that shock waves and strong bulk-flow motion exist in ICM during a merger (e.g., Schindler & Müller 1993; Ishizaka & Mineshige 1996; Takizawa 1999, 2000). This suggests that relativistic electrons are produced around the shock fronts through first-order Fermi acceleration and that propagation of the shock waves and bulk flow of ICM are responsible for extension of radio halos. Obviously, the merger shock acceleration model can explicitly explain the association between mergers and radio halos. However, such hydrodynamical effects on time evolution and spatial distribution of relativistic electrons during mergers have not been properly considered in previous studies.

In this paper, we investigate the evolution of a relativistic electron population and nonthermal emission in the framework of the merger shock acceleration model. We perform N-body + hydrodynamical simulations, explicitly considering the evolution of a relativistic electron population produced around the shock fronts.

The rest of this paper is organized as follows. In § 2 we show order estimation of about the spatial size of radio halos. In § 3 we describe the adopted numerical methods and initial conditions for our simulations. In § 4 we present
the results. In § 5 we summarize the results and discuss their implications.

2. ORDER ESTIMATION

In this section, we estimate several kinds of spatial length scales relevant to the extent of cluster radio halos.

2.1. Diffusion Length

According to Bohm diffusion approximation, a diffusion coefficient is

$$\kappa = \frac{\eta E_e c}{2eB}$$

(1)

where $\eta$ is an enhanced factor from the Bohm diffusion limit, $E_e$ is the total energy of an electron, $c$ is the velocity of light, $e$ is the electron charge, and $B$ is the magnetic field strength of intracluster space. Since IC scattering of CMB photons is the dominant cooling process for electrons with energy of $\sim$ GeV in typical intracluster conditions (Sarazin 1999), electron cooling time in this energy range is

$$t_{IC} = 1.1 \times 10^9 \text{ yr} \left(\frac{E_e}{\text{GeV}}\right)^{-1},$$

(2)

where we assume that the cluster redshift is much less than unity. Thus, the diffusion length within the cooling time is

$$L_{\text{diff}} \sim \sqrt{\kappa t_{IC}} \sim 1.1 \times 10^{-4} \text{ Mpc} \left(\frac{\eta}{10^2}\right)^{1/2} \left(\frac{B}{\mu\text{G}}\right)^{-1/2}.$$  

(3)

This is much less than the spatial size of radio halos. For this reason, electrons that are leaking from point sources such as active galactic nuclei (AGNs) cannot be responsible for the radio halos.

2.2. Shock Wave Propagation Length

From N-body + hydrodynamical simulations of cluster mergers, the propagation speed of the shock waves is an order of $\sim 1000$ km s$^{-1}$ (Takizawa 1999). Thus, the length scale where the shock front propagates during the cooling time of equation (2) is

$$L_{\text{shock,prop}} \sim 1.1 \text{ Mpc} \left(\frac{v_{\text{shock}}}{1000 \text{ km s}^{-1}}\right) \left(\frac{E_e}{\text{GeV}}\right)^{-1},$$

(4)

where $v_{\text{shock}}$ is the propagation speed of the shock front. Roughly speaking, $L_{\text{shock,prop}}$ is related to the extent of radio halos along the collision axis since the accelerated electrons can emit synchrotron radio radiation only during the cooling time behind the shock front.

2.3. Spatial Size of Shock Surfaces

In cluster mergers, the shock front spreads over a cluster scale ($\sim$ Mpc). Thus, even if the shock is nearly standing, radio halos spread in a Mpc scale. Roughly speaking, this is related to the extent of radio halos perpendicular to the collision axis.

In the merger shock acceleration model, therefore, propagation of shock fronts and the spatial size of shock surfaces play a more crucial role to the extent of radio halos than diffusion. Furthermore, the model naturally produces three-dimensionally extended radio halos in a megaparsec scale.

3. MODELS

We consider the merger of two equal mass ($0.5 \times 10^{15} M_\odot$) subclusters. In order to calculate the evolution of ICM, we use the smoothed particle hydrodynamics (SPH) method. Each subcluster is represented by 5000 N-body particles and 5000 SPH particles. The initial conditions for ICM and N-body components are the same as those of Run A in Takizawa (1999). The numerical methods and initial conditions for the N-body and hydrodynamical parts are fully described in § 3 of Takizawa (1999). Our code is fully three-dimensional.

To follow the evolution of a relativistic electron population, we should solve the diffusion-loss equation (see Longair 1994) for each SPH particle. Since the diffusion term is negligible, as mentioned in § 2, the equation is

$$\frac{dN(E, t)}{dt} = \frac{\partial}{\partial E} \left(b(E, t)N(E, t)\right) + Q(E, t),$$

(5)

where $N(E, t)$ $dE$ is the total number of relativistic electrons per SPH particle with kinetic energies in the range $E$ to $E + dE$ (hereafter, we denote kinetic energy of an electron as $E_e$). $b(E_e, t)$ is the rate of energy loss for a single electron with an energy of $E_e$, and $Q(E_e, t) dE_e$ gives the rate of production of new relativistic electrons per SPH particle.

According to the standard theory of first-order Fermi acceleration, we assume that $Q(E_e, t) \propto E_e^{-\alpha}$, where $\alpha$ is described as $(r + 2)/(r - 1)$, using the compression ratio of the shock front, $r$. For the shocks that appeared in this simulation, the ratio is roughly $\sqrt{10}$ (Takizawa 1999), which yields $\alpha = 2.4$. Since it is very difficult to monitor the compression ratio at the shock front for each SPH particle for each time step, we neglect the time dependence of $\alpha$. The influence of the changes in $\alpha$ on the results is discussed in § 5. The normalization of $Q(E_e, t)$ is proportional to the artificial viscous heating, which is nearly equal to the shock heating. We generate the relativistic electrons everywhere, even if explicit shock structures do not appear in the simulation. We assume that a subshock exists where a fluid element has enough viscous heating. Such subshocks are recognized in higher resolution simulations (e.g., Roettiger, Burns, & Stone 1999a). We assume that the total kinetic energy of accelerated electrons from $E_e = 0$ to $+ \infty$ is 5% of the viscous energy, which is consistent with the recent TeV gamma-ray observational results for the galactic supernova remnant SN 1006 (Tanimori et al. 1998; Naito et al. 1999).

Note that equation (5) for the evolution of a relativistic electron population is linear in $N(E_e, t)$. Thus, it is easy to rescale our results of $N(E_e, t)$ if we choose other parameters for the acceleration efficiency. We neglect energy loss of thermal ICM due to the acceleration.

For $b(E_e, t)$, we consider IC scattering of the CMB photons, synchrotron losses, and Coulomb losses. We neglect bremsstrahlung losses for simplicity, which is a good approximation in typical intracluster conditions (Sarazin 1999). Then, if we ignore weak energy dependence of coulomb losses, the loss function $b(E_e, t)$ becomes

$$b(E_e, t) = b_1(t) + b_2(t)E_e^2,$$

(6)

where $b_1(t) = 7.0 \times 10^{-16}[n_e(t) \text{ cm}^{-3}]$ and $b_2 = 2.7 \times 10^{-17} + 2.6 \times 10^{-18}[B(t)/\mu\text{G}]^2$ [if $b(E_e, t)$ and $E_e$ are given in units of GeV s$^{-1}$ and GeV, respectively]. In the above expressions, $n_e$ is the number density of ICM electrons and $B$ is the strength of the magnetic field.

To integrate equation (5) with the Courant and viscous time step control (see Monaghan 1992), we use the analytic solution as follows. First, we integrate equation (5) from $t$ to $t + \Delta t$, regarding the second term on the right-hand side as
negligibly small. Then,
\[
N(E_e, t + \Delta t) = \begin{cases} 
N(E_{e, 0}, t) \frac{b(E_{e, 0})}{b(E_e)} , & (E_e < E_{e, \text{max}}) , \\
0 , & (E_e > E_{e, \text{max}}) , 
\end{cases} 
\]
where
\[
E_{e, 0} = \sqrt{\frac{b_e}{b_1}} \tan \left( \arctan \sqrt{\frac{b_1}{b_e}} E_e + \sqrt{\frac{b_e}{b_1}} \Delta t \right), \tag{8}
\]
\[
E_{e, \text{max}} = \sqrt{\frac{b_e}{b_1}} \frac{1}{\tan \sqrt{\frac{b_1}{b_e}} \Delta t}. \tag{9}
\]
Next, we add the contribution from the second term to the above \(N(E_e, t + \Delta t)\), using the second-order Runge-Kutta method. In the present simulation, \(N(E_e, t)\) is calculated on 300 logarithmically equally spaced points in the range \(E_e = 0.05\) to 50 GeV for each SPH particle.

Magnetic field evolution is included by means of the following method. We assume initial magnetic pressure is 0.1% of ICM thermal pressure. This corresponds to \(B = 0.1 \mu G\) in volume-averaged magnetic field strength. For Lagrangian evolution of \(B\) due to the frozen-in assumption, we apply \(B(t)/B(t_0) = [\rho_{\text{ICM}}(t)/\rho_{\text{ICM}}(t_0)]^{2/3}\). Field changes due to the passage of the shock waves are not considered in this paper. The change may depend on field configuration at the shock front and have value of \(\sim 1-4\). However, it is difficult to examine it in the present simulation, even under high \(\beta\) conditions. We will address this problem in the future paper.

Our model implies continuous production of power-law-distributed relativistic electrons around the shock fronts. This is valid only when \(\Delta t_{\text{acc}}\) is sufficiently shorter than the dynamical timescale of the system (\(\sim 10^9\) yr), where \(\Delta t_{\text{acc}}\) denotes acceleration time in which \(Q(E_e, t)\) becomes a power-law distribution. It is presented in the framework of the standard shock acceleration theory as \(\Delta t_{\text{acc}} = 3ru^{-2}(r - 1)^{-1} (\kappa_1 + r\kappa_2)\), where \(u\) is the flow velocity of the upstream of the shock front and \(\kappa_1, \kappa_2\) are diffusion coefficients of the upstream and downstream, respectively (see e.g., Drury 1983). Assuming \(B_1 = B_2\) and the Bohm diffusion approximation of equation (1),
\[
\Delta t_{\text{acc}} = 1.9 \times 10^2 \text{ yr} \left( \frac{E_e}{\text{GeV}} \right) \left( \frac{\eta}{10^2} \right)
\times \left( \frac{u}{10^3 \text{ km s}^{-1}} \right)^2 \left( \frac{B}{\mu G} \right)^{-1}. \tag{10}
\]
This value is certainly much shorter than the dynamical timescale.

4. RESULTS

Figure 1 shows the time evolution of nonthermal emission for various energy bands: from top to bottom, IC emission of the Extreme Ultraviolet explorer (EUV) band (65–245 eV), the soft X-ray band (4–10 keV), and the hard X-ray band (10–100 keV), and synchrotron radio emission (10 MHz–10 GHz). The times are relative to the most contracting epoch. The calculation of the luminosity for each band is performed under the simplified assumption that electrons radiate at a monochromatic energy given by \(E_X = 2.5 \text{ keV} \left( E_\mu / \text{GeV} \right)^2 \) and \(v = 3.7 \text{ MHz} \left( B / \mu G \right) \left( E_\mu / \text{GeV} \right)^2\) for IC scattering and synchrotron emission, respectively. Since cooling time is roughly proportional to \(E_e^{-1}\) in these energy ranges, the higher the radiation energy of the IC emission is, the shorter the duration of the luminosity increase is. In other words, luminosity maximum comes later for lower energy bands. Hard X-ray and radio emissions come from the electrons with almost the same energy range. The luminosity maximum in the hard X-ray band, however, comes slightly after the most contracting
epoch. On the other hand, radio emission reaches maximum at the most contracting epoch since the change of magnetic field due to the compression and expression plays a more crucial role than the increase of relativistic electrons. In any case, radio halos and hard X-rays are well associated with merger phenomena. They are observable only when thermal ICM has definite signatures of mergers, such as complex temperature structures, nonspherical and elongated morphology, or substructures. Soft X-ray emission, which is observable only in clusters (or groups) with relatively low temperature ($\gtrsim 1$ keV) ICM, is still luminous $\sim 1$ Gyr after the merger. Thus, the association of mergers in this band is weaker than in the hard X-ray band. Moreover, EUV emission continues to be luminous after the signatures of the merger have disappeared in the thermal ICM.

Figure 2 shows the IC spectra at $t = 0.0$ (solid lines) and 0.25 (dotted lines). In lower energies, $L_\nu \propto \nu^{-0.7}$, which is originated from the electron source spectrum $Q(E_e) \propto E_e^{-2.4}$. On the other hand, in higher energies, the spectrums become close to steady solution, $L_\nu \propto \nu^{-1.2}$, owing to the IC and synchrotron losses (Longair 1994). The break point of the spectrum moves toward lower energies as time proceeds.

Figure 3 shows the snapshots of synchrotron radio (10 MHz–10 GHz) surface brightness distribution (solid lines) and X-ray one of thermal ICM (dashed lines) seen from the direction perpendicular to the collision axis. Lines are equally spaced on a logarithmic scale and separated by a factor of 7.4 and 20.1 for radio and X-ray maps, respectively. At $t = -0.25$, the main shocks are located between the two X-ray peaks and relativistic electrons are abundant there. Thus, the radio emission peak is located between the two X-ray peaks, although the magnetic field strength there is weaker. At $t = 0.0$, relativistic electrons are concentrated around the central region since the main shocks are nearly standing and located near $X \approx \pm 0.2$. Furthermore, gas infall compresses ICM and the magnetic field. Thus, radio distribution shows rather strong concentration. In these phases (at $t = -0.25$ and 0.0), the radio halo is located at the high-temperature region of ICM. On the other hand, at $t = 0.25$, relativistic electron distribution becomes rather diffuse since fresh relativistic electrons are producing in the outer regions as the shock waves propagate outward. At $t = 0.25$, the main shocks are located at $X \approx \pm 1$. Between the shock fronts, rather diffuse radio emission is seen. In this phase, the radio halo is located between two high-temperature regions of ICM.

As described above, the morphology of the radio halo is strongly dependent on the phase of the merger when viewed from the direction perpendicular to the collision axis. When viewed nearly along the collision axis, however, this is not the case. Figure 4 shows the same content as Figure 3, but seen from the direction tilted at an angle of 30° with respect to the collision axis. Radio and X-ray morphology are similar to each other in all phases. When the cluster is viewed along the collision axis, the distribution of rela-
tivistic electrons roughly follows that of the thermal ICM since the shock fronts face the observers and spread over the cluster. The distribution of magnetic field strength also roughly follows that of the thermal ICM. Therefore, the radio morphology follows the X-ray morphology.

Figure 5 shows the synchrotron radiation spectra at $t = 0.0$ (solid lines) and 0.25 (dotted lines). At $t = 0.0$, the synchrotron spectrum follows that of IC emission. On the other hand, at $t = 0.25$ there exists a bump at lower energies in the spectrum, which cannot be seen in the spectrum of IC emission. Emissivity of synchrotron radiation depends on not only relativistic electron density but also magnetic energy density, which is larger in the central region in this model. On the other hand, IC emissivity depends on the electron density and CMB energy density, which is homogeneous. Thus, the total synchrotron spectrum is more like that in the central region than the total IC spectrum. At $t = 0.0$, since relativistic electrons are centered, the emission from the outer region is negligible for both spectra. Thus, similar results are given. On the other hand, at $t = 0.25$, propagation of shocks makes a diffuse distribution of relativistic electrons. Therefore, the contribution from the outer region is not negligible for the total IC spectrum, while the total synchrotron spectrum is still biased toward the central region, as seen in Figure 3. In the central region, however, electrons produced by the main shocks at $t \approx 0$ with energies more than $\sim$ several GeV have already cooled down. Thus, the spectrum in the central region has a bump in lower energies, which is present in the total spectrum. The emission above $\sim 30$ MHz is mainly due to the electrons produced by the subshocks there. If such subshocks do not exist, the emission near the main shocks, where the magnetic field strength is rather weaker, can be seen in this energy range. Note that this feature of the synchrotron spectrum is sensitive to the spatial distribution of magnetic field.

5. CONCLUSIONS AND DISCUSSION

We have investigated evolution of nonthermal emission from relativistic electrons accelerated around the shock fronts during mergers of clusters of galaxies. Hard X-ray and radio radiation are luminous only while merger signatures are left in thermal ICM. Hard X-ray radiation reaches maximum in the later stage of a merger. In our simulation, radio emission is most luminous at the most contracting epoch. This is due to the magnetic field amplification by compression. According to recent magnetohydrodynamical simulations (Roettiger, Stone, & Burns 1999b), however, it is possible that the field amplification occurs as the bulk flow is replaced by turbulent motion in the later stages of the merger. If this is effective in real clusters, radio emission can increase by a factor of 2 or 3 more than our results in the later stages of the merger. EUV emission is still luminous after the merger signatures have disappeared in thermal ICM. This is consistent with the EUVE results.

The morphological relation between radio halos and ICM hot regions is described as follows. In the contracting phase, radio halos are located at the hot regions of thermal ICM or between two substructures (see the left panel of Fig. 3). This may correspond to A2256 (Röttgering et al. 1994). In the expanding phase, on the other hand, radio halos are located between the two hot regions of ICM and show rather diffuse distribution (see the right panel of Fig. 3). This may correspond to Coma (Giovannini et al. 1993; Deiss et al. 1997) and A2319 (Feretti, Giovannini, & Böhringer 1997). In the later phase, the shock fronts reach outer regions and the GeV electrons are already cooled in the central parts. Then, radio halos are located in the cluster’s outer regions near the shock fronts and we cannot detect radio emission in the central part of the cluster. However, observational correlation between ICM hot regions and radio halos is not clear since the electron temperature there is significantly lower than the plasma mean temperature because of the relatively long relaxation time between ions and electrons (Takizawa 1999, 2000). Note that until now we could find the electron temperature only through X-ray observations. This may correspond to A3667 (Röttgering et al. 1997). It is possible that such radio ”halos” located in the outer regions are classified into radio ”relics” since their radio powers and spatial scales become weaker and smaller than those of typical radio halos, respectively. When the cluster is viewed nearly along the collision axis, however, such morphological relations between radio halo and ICM are unclear and radio and X-ray distributions become similar to each other.

We neglect the changes of the spectral index in the electron source term. Since the Mach number is gradually increasing as the merger proceeds (Takizawa 1999), the spectrum of relativistic electrons becomes flatter as time proceeds. We believe that such changes in the spectral index do not influence our results seriously because most of relativistic electrons are produced in the central high-density region, where the Mach number is almost constant. In the later stage of the merger, however, the contribution of relativistic electrons produced in the outer region cannot be negligible in the higher energy range ($\sim 10$ GeV) since cooling time is relatively short. Thus, it is probable that the inverse Compton spectrum in the hard X-ray ($\sim 10$–100 keV) becomes flatter in the later stages.

The lower energy part of the electron spectrum can emit hard X-rays through bremsstrahlung. Whether IC scattering or bremsstrahlung is dominant in the hard X-ray range depends on the shape of the electron spectrum. Roughly speaking, when the spectrum of relativistic electrons is flatter than $E_e^{-2.5}$, IC scattering dominates the other and vice versa (see Appendix). Furthermore, the shape of the electron spectrum in the lower energy part is flatter than the originally injected form, since the cooling time due to the coulomb loss is proportional to $E_e$ and very short.
(Sarazin 1999). In the present simulation, therefore, it is most likely that the contribution of the bremsstrahlung components in the hard X-ray range is negligible. More detailed calculations, including nonlinear effects for the shock acceleration (Jones & Ellison 1991), by Sarazin & Kempner (2000) show that IC scattering is dominant in the hard X-ray when the accelerated electron momentum spectrum is flatter than \( p_e^{-2.7} \), which corresponds to the electron energy spectrum of \( E_e^{-2.7} \) in the fully relativistic range. Thus, the bremsstrahlung contribution in the hard X-ray should be considered in mergers with low Mach numbers.

A merger shock acceleration model also predicts some gamma-ray emission (T. Naito & M. Takizawa 2000, in preparation). Electrons that radiate EUV due to IC scattering also emit \( \sim 100 \) MeV gamma-rays through bremsstrahlung. Furthermore, it is most likely that protons as well as electrons are accelerated around the shock fronts. Such high-energy protons also produce gamma rays peaked at \( \sim 100 \) MeV through decay of neutral pions. Although the energy density ratio between electrons and protons in acceleration sites is uncertain, the contributions of protons and the bremsstrahlung to the emission become important in the higher energies. We think that it is interesting to investigate emissions from hundreds of MeV to multiple TeV, which are observable with operating instruments such as EGRET, ground-based air Cerenkov telescopes, and planned projects like GLAST satellites. However, since the diffusion length of protons within the cooling time is much longer than that of electrons, treatment of the diffusion-loss equation for protons is more complex than the model in this paper.

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APPENDIX

ESTIMATION OF THE BREMSSTRAHLUNG CONTRIBUTION IN THE HARD X-RAY RANGE

We estimate the contribution of the bremsstrahlung form the lower energy part of the electron spectrum to the hard X-ray emission in our model, which is neglected in this paper. Although the crude estimations discussed here are order of magnitudes, it is helpful to explain which mechanism, IC scattering or bremsstrahlung radiation, is dominant.

The standard theory of first-order Fermi acceleration provides a power-law spectrum in momentum distribution. We, therefore, assume that the momentum spectrum of accelerated electrons has a form of

\[
\frac{dN_e}{dP_e} = cN_0 \left( \frac{P_e}{m_e c} \right)^{-z} \quad [\text{cm}^{-3} \text{eV}^{-1} \text{c}^{-1}],
\]

where \( P_e \) is an electron momentum, \( c \) is the speed of light, and \( m_e \) is the electron rest mass. Using the relation between the momentum \( P_e \) and the kinetic energy \( E_e \), \( E_e = (P_e^2 c^4 + m_e^2 c^6)^{1/2} - m_e c^2 \), the spectrum for kinetic energy is given by

\[
\frac{dN_e}{dE_e} = N_0 \frac{E_e + m_e c^2}{m_e c^2} \left( \frac{P_e}{m_e c} \right)^{-z-1} \quad [\text{cm}^{-3} \text{eV}^{-1}].
\]

For relativistic electrons, \( E_e \gg m_e c^2 \), the spectrum becomes

\[
\frac{dN_e}{dE_e} = N_0 \left( \frac{E_e}{m_e c^2} \right)^{-z},
\]

which is consistent with an assumption of \( \Omega(E_e, t) \) in § 3. Since the hard X-ray photons are produced from the CMB photon field via IC scattering of relativistic electrons in our model, we use this form for the estimation of IC emissivity. For nonrelativistic electrons, \( E_e \ll m_e c^2 \), the spectrum becomes

\[
\frac{dN_e}{dE_e} = 2^{-\alpha - 1/2} N_0 \frac{E_e + m_e c^2}{m_e c^2} \left( \frac{E_e}{m_e c^2} \right)^{-(\alpha + 1/2)}
\]

where we use the relation \( E_e = P_e^2/(2m_e) \). Since the bremsstrahlung radiation at the hard X-ray range is emanated from electrons with almost the same energy range, we use this form for the estimation of bremsstrahlung emissivity.

For simplicity, we approximate the emissivity, \( \epsilon \), for both IC and bremsstrahlung processes to be

\[
\epsilon = \left. \frac{dN_e}{dE_e} \frac{dE_e}{dt} \right| \frac{dE_e}{d\epsilon_e} \quad \text{[ergs} \text{s}^{-1} \text{cm}^{-3} \text{eV}^{-1}].
\]

where the emission rate is assumed to be equal to the electron energy loss rate and \( \epsilon_e \) is the photon energy.

To obtain the bremsstrahlung emissivity, we assume that an electron with energy \( E_e \) loses its energy to emit photons of energy \( \epsilon_e = E_e \) after it has traversed one mean free path \( X_o \). Hence,

\[
\frac{dE_e}{d\epsilon_e} = 1,
\]

(A6)
where $v_e$ is electron velocity. From $\sigma_T n_0 X_0 \sim 1$, we approximate

$$\frac{dE_e}{dt} \sim e_\gamma v_e \frac{v_e}{X_0} \quad \text{(ergs s}^{-1})^,$$

where $\sigma_T$ denotes the cross section of Thomson scattering and $n_0$ denotes the density of ambient matter. Using equations (A4), (A5), (A6), and (A8), we estimate the bremsstrahlung emissivity in the hard X-ray energy range, $e_\gamma = e_{\text{HXR}}$, as

$$\epsilon_{\text{brem}} \sim 2^{-\alpha/2} N_0 \sigma_T c n_0 m_e c^2 \left(1 + \frac{\epsilon_{\text{HXR}}}{m_e c^2}\right) \left(\frac{\epsilon_{\text{HXR}}}{m_e c^2}\right)^{-1 - \frac{\alpha}{2}}. \quad \text{(A9)}$$

For IC scattering of CMB photons, the photon energy after the scattering by an electron with energy $E_e = m_e \gamma_e c^2$ is approximated by single energy of $e_\gamma = \gamma_e \bar{E}_{\text{CMB}}$, where $\bar{E}_{\text{CMB}}$ is the peak energy of the CMB spectrum. Thus,

$$\frac{dE_e}{d\gamma_e} = \frac{4}{3} \frac{\sigma_T}{\gamma_e^2} \bar{E}_{\text{CMB}} n_{\text{CMB}} \quad \text{(ergs s}^{-1}), \quad \text{(A11)}$$

where $n_{\text{CMB}}$ is the photon number density of CMB fields. Using equations (A3), (A5), (A10), and (A11), we estimate the IC emissivity in the hard X-ray energy range, $e_\gamma = e_{\text{HXR}}$, as

$$\epsilon_{\text{IC}} = \frac{2}{3} N_0 \sigma_T c \bar{E}_{\text{CMB}} n_{\text{CMB}} \left(\frac{\bar{E}_{\text{CMB}}}{m_e c^2}\right)^{(\alpha - 3)/2} \left(\frac{e_{\text{HXR}}}{m_e c^2}\right)^{-\frac{\alpha - 1}{2}}, \quad \text{(A12)}$$

From equations (A9) and (A12), we derive the emissivity ratio as

$$\frac{\epsilon_{\text{brem}}}{\epsilon_{\text{IC}}} = \frac{3}{2} \frac{n_0}{n_{\text{CMB}}} \left(1 + \frac{e_{\text{HXR}}}{m_e c^2}\right)^{1/2} \left(\frac{e_{\text{HXR}}}{m_e c^2}\right)^{1/2} \left(\frac{2}{m_e c^2}\right)^{-\alpha}. \quad \text{(A13)}$$

For $\epsilon_{\text{brem}} < \epsilon_{\text{IC}}$, we get the relation

$$\alpha < 2 \ln \left[\frac{3}{2} \frac{n_0}{n_{\text{CMB}}} \left(1 + \frac{e_{\text{HXR}}}{m_e c^2}\right)^{1/2} \left(\frac{e_{\text{HXR}}}{m_e c^2}\right)^{1/2} \left(\frac{2}{m_e c^2}\right)^{-\alpha}\right], \quad \text{(A14)}$$

Substituting typical values for ICM at $z \sim 0$, $n_0 = 1 \times 10^{-3} \text{ cm}^{-3}$, $n_{\text{CMB}} = 400 \text{ cm}^{-3}$, $\bar{E}_{\text{CMB}} = 6.57 \times 10^{-4} \text{ eV}$, and $e_{\text{HXR}} = 10 \text{ keV}$, we obtain $\alpha < 2.5$. At $e_{\text{HXR}} = 100 \text{ keV}$, the spectrum of equation (A9) becomes steeper as electrons enter the transrelativistic energy range. As a result, the bremsstrahlung emissivity is reduced so that the larger index of electron spectrum is accepted for $\epsilon_{\text{brem}} < \epsilon_{\text{IC}}$.

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