THE COSMIC MeV GAMMA-RAY BACKGROUND AND HARD X-RAY SPECTRA OF ACTIVE GALACTIC NUCLEI: IMPLICATIONS FOR THE ORIGIN OF HOT AGN CORONAE

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ABSTRACT

The origin of the extragalactic gamma-ray background radiation at 1–10 MeV is still unknown. Although the cosmic X-ray background up to a few hundred keV can be accounted for by the sum of active galactic nuclei (AGNs), current models of AGN spectra cannot explain the background spectrum beyond ~1 MeV, because of the thermal exponential cutoff of the electron energy distribution assumed in the models. Here we construct a new spectral model by calculating the Comptonization process, including nonthermal electrons, which are expected to exist in an AGN’s hot corona if it is heated by magnetic reconnections. We show that the MeV background spectrum can be explained nicely by our model, when coronal electrons have a nonthermal power-law component whose total energy is a few percent of the thermal component and whose spectral index is $d \ln N / d \ln E_\gamma \approx -4$. Although in nearby AGN spectra the MeV gamma-ray flux from such a component is below the detection limit of past observations, it might be detected by MeV detectors that are planned for future use. We point out that the nonthermal component’s total energy and electron index are similar to those found for electrons accelerated by magnetic reconnections in solar flares and in the Earth’s magnetosphere, which supports the reconnection hypothesis, which in turn explains the origin of an AGN’s hot corona.

Subject headings: diffuse radiation — galaxies: active — gamma rays: theory

1. INTRODUCTION

It is well known that normal active galactic nuclei (AGNs) can account for the cosmic X-ray background (CXB) below several hundred keV (for reviews, see Boldt 1987; Fabian & Barcons 1992; Ueda et al. 2003, hereafter U03; and Gilli et al. 2007). It is also well known that rare blazar-type AGNs contribute considerably to the cosmic gamma-ray background in the energy range from 100 MeV to 100 GeV; this cosmic gamma-ray background has a hard power-law spectrum (almost flat in the $nF_n^2$ plot), although blazars cannot explain all of the background flux, which leaves some room for possible contributions from completely different sources (Narumoto & Totani 2006 and references therein).

The origin of the gamma-ray background at the gap between these two energy regions (i.e., ~1–10 MeV) has also been an intriguing mystery. The AGN spectra adopted in population synthesis models of the CXB cannot explain this component because of the assumed exponential cutoff at a few hundred keV. The background spectrum in the 1–10 MeV band is much softer (photon index $\alpha \sim 2.8$) than the GeV component, indicating a different origin from that above 100 MeV (e.g., Sreekumar et al. 1998).

A few candidates have been proposed to explain the 1–10 MeV background. One is the nuclear-decay gamma rays from Type Ia supernovae (SNe Ia; Clayton & Ward 1975; Zdziarski 1996; Watanabe et al. 1999). However, on the basis of the latest measurements of the cosmic SN Ia rates, recent studies show that the background flux expected from SNe Ia is about an order of magnitude lower than observed (Ahn et al. 2005; Strigari et al. 2005). There is a class of blazars, called “MeV blazars,” whose spectra peak at MeV energies (Blom et al. 1995; Sambruna et al. 2006), and these MeV blazars could potentially contribute to the MeV background. However, a quantitative estimate of the contribution is difficult because of the still small sample available at present. Annihilation of the dark matter particles has also been discussed (Ahn & Komatsu 2005a, 2005b; Rasera et al. 2006; Lawson & Zhitnitsky 2007), but there is no natural particle-physics candidate for such a dark matter particle with a mass scale of MeV energies. The idea of MeV dark matter annihilation has been inspired by the 511 keV line emission from the galactic center, but a few astrophysical explanations are possible for this line emission (Totani 2006 and references therein).

An important feature of the MeV background spectrum is that its power-law spectrum is smoothly connected to the peak of the CXB spectrum. If the origin of the MeV background is completely different from that of the CXB, such a smooth connection would be surprising. Rather, it seems more plausible that the MeV background flux is composed of the same populations that make up the CXB, and, quite simply, the current AGN spectral models are not sufficient to describe the MeV spectra. The X-ray AGN spectra are well described by the Comptonization of seed UV photons by the hot coronal electrons (Zdziarski et al. 1994, 1995), and the cutoff at ~100 keV reflects the thermal energy distribution of the hot electrons. Although the AGN spectra indeed show evidence for such a cutoff (Zdziarski et al. 1995; Zdziarski et al. 2000), a small amount of additional nonthermal electrons, with a soft spectrum, is sufficient to explain the MeV background. Due to the limited sensitivity of current MeV gamma-ray observations, the presence of such nonthermal components is not strongly constrained, even in the spectra of the brightest nearby AGNs. Furthermore, it is believed that coronae around accretion disks share some common features with the solar corona (e.g., Galeev et al. 1979), and magnetic reconnection in AGN coronae is a good candidate for explaining the origin of hot electrons (Liu et al. 2002). It is well known that particles are accelerated to nonthermal energies by reconnections in solar flares (Shibata et al. 1995).

Here we construct a new model of the X-ray/gamma-ray spectra of AGNs, by calculating the Comptonization process by hot electrons having both thermal and nonthermal components. On the basis of our model, we also calculate the CXB spectrum with the latest knowledge of the cosmological evolution of the AGN luminosity function, and we determine the
amount and spectrum of the nonthermal electrons in AGN coronae in order to explain the MeV background. We discuss the implied nature of nonthermal electrons in the context of the reconnection-heating scenario of the AGN coronae, comparing our results with those found in the reconnections occurring in the solar flares and in the Earth’s magnetosphere.

Rogers & Field (1991) and Field & Rogers (1993) presented an AGN spectral model that can explain the MeV background spectrum by nonthermal relativistic electrons. However, their model only considers the nonthermal component, not the thermal component, and it requires a lower cutoff of \( \gamma_r \approx 30 \) in the nonthermal component, which, as they mention in their paper, is difficult to interpret. Our model considers both the thermal and nonthermal coronal electrons whose spectra are smoothly connected to each other and is a natural extension of the popular AGN spectral models in the recent literature. Stecker et al. (1999) also discussed the possibility that the MeV background can be explained by nonthermal tails in AGN spectra, quoting the spectrum of the galactic stellar-mass black hole candidate Cyg X-1. However, a physical model explaining the nonthermal tail in an AGN spectrum was not presented.

Throughout this Letter, we adopt the cosmological parameters of \( h_0, \Omega_m, \Omega_X \) = (0.7, 0.3, 0.7).

## 2. MODEL DESCRIPTION

### 2.1. The AGN Spectra with Nonthermal Coronal Electrons

The main shape of X-ray AGN spectra is determined by the Comptonization of UV photons emitted from optically thick accretion disks by hot electrons in coronae. As in many previous studies, we consider a simple spherical and uniform distribution of the coronal electrons. The seed UV photons are injected at the center and then become X-ray photons when they escape the coronal region after Comptonization. In addition to the hot thermal electrons assumed in the conventional X-ray spectral models of AGNs, we introduce higher energy nonthermal electrons in AGN coronae, whose energy distribution is a power law \( (dN_e/dE_e \propto E_e^{-\gamma_t}) \). We introduce the transition electron Lorentz factor \( \gamma_t \), which corresponds to the transition electron energy \( E_e = m_e \gamma_t c^2 \), where the electron spectrum \( dN_e/dE_e \) has the same value for the thermal and nonthermal components. This \( \gamma_t \) is the lower limit of the Lorentz factor distribution of the nonthermal component, and hence there are no nonthermal electrons at \( E_e < m_e \gamma_t c^2 \). We also set an upper bound as \( \gamma_t = 10^3 \), although this hardly affects our results if the maximum photon energy extends well beyond 10 MeV.

We then trace the Comptonization process using a Monte Carlo method. The calculation method used here is mainly based on that found in Pozdnyakov et al. (1977) and Gorecki & Wilczewski (1984), but their original formalism in the laboratory frame is not optimized for the ultrarelativistic region. To calculate the scattering by high-energy nonthermal electrons more efficiently, we added a new formulation in the rest frame of relativistic electrons that is based on the formulation found in Corman (1970).

The reflection of X-ray photons by cool, optically thick material is also an important feature of AGN X-ray spectra. We calculate this by using the PEXRAV model (Magdziarz & Zdziarski 1995) in the XSPEC package, as was done in U03. Because of the limitation for the acceptable input spectrum in PEXRAV, we use a power-law spectrum \( (\alpha_X = 1.9) \) plus an exponential cutoff at \( E = 500 \) keV, which is a good approximation of the Comptonized spectrum with only the thermal electrons. The newly added nonthermal electrons would change the spectrum significantly at only \( E \approx 1 \) MeV, and hence this treatment is appropriate for the reflection component, which is important at only \( \sim 1-100 \) keV.

### 2.2. Calculation of the Cosmic Background Radiation

We calculate the CXB spectrum by integrating our AGN spectral model in the redshift and luminosity space, using the X-ray AGN luminosity function of U03. Following the same formulation given in U03, we take into account the absorption column density distribution \( (N_H \) function) and the contribution from Compton-thick AGNs. We confirm that our main conclusion hardly changes if instead we use the more recent population synthesis model by Gilli et al. (2007), as described below.

## 3. RESULTS

Figure 1 shows the models of AGN spectra calculated according to the procedures in the previous section. Here, in order to show the pure spectrum of the Comptonization, we do not take into account the reflection component or the absorption effect. We set \( \Gamma = 3.8 \) and \( \gamma_t = 4.4 \) as our standard model \( (\text{solid line}) \), because we find that these values give the best-fit MeV background spectrum to the data. In this standard model, 3.5% of the total electron energy is carried by the nonthermal electrons. To illustrate the effects of changing parameters, we
also show the spectra with the parameters slightly changed from those for the best-fit model. The conventional case with only the thermal electrons is also shown, where an exponential cutoff above \( \sim 100 \) keV is seen as expected.

Figure 2 shows the cosmic background radiation integrated with the luminosity function of U03 using our AGN spectral model. We know that the predicted CXB spectrum below 100 keV shown by the U03 model is 10\%-20\% higher than that shown in the HEAO-1 data. The origins of this discrepancy are still controversial. The intensity and shape of the CXB in the 10 keV–1 MeV band could be uncertain at the \( \sim 20\% \) level.

The population synthesis models also have uncertainties, such as the intensity of the reflection component assumed in the AGN spectra, the (unknown) number density of Compton-thick AGNs, and the parameters of the luminosity function itself that could be subject to cosmic variance in deep surveys. However, here we emphasize that the uncertainty hardly affects our conclusions. To confirm this, we also calculate the MeV gamma-ray background flux with the U03 luminosity function by artificially lowering its normalization by 20\% to match the HEAO-1 data. We find that the best-fit value of \( \gamma_{\text{p}} \) is slightly changed, by 0.4, whereas the change of \( \Gamma \) is negligible.

As mentioned above, we find here that the cosmic background spectrum from X-ray to the 10 MeV band can be explained nicely by our model with \( \Gamma = 3.8 \) and \( \gamma_{\text{p}} = 4.4 \). The next question is then how natural are these parameters in the context of the theoretical picture of hot electrons in AGN coronae. We will discuss this issue in the next section.

4. DISCUSSIONS

4.1. Reconnection and Nonthermal Electrons

As discussed in \S 1, magnetic reconnection is the primary candidate for the origin of the nonthermal electrons in AGN coronae, and we can compare the inferred amount of nonthermal electrons and the spectrum of electrons with those observed in reconnections in other objects. In solar flares, the electron spectrum accelerated by reconnection and injected into the solar surface (footpoints) can be estimated by thick-target bremsstrahlung (Brown 1971; Piana 1994), and a value of \( \Gamma \sim 4 \) is inferred for giant solar flares (Holman et al. 2003; Lin 2006). In the reconnection diffusion region of the Earth’s magnetotail, \( \Gamma = 3.8 \) has been measured by the Wind spacecraft (Oieroset et al. 2002). Interestingly, these values are very similar to what we found to explain the MeV background spectrum by AGNs.

The relative amounts of the thermal and nonthermal electrons are difficult to predict, but it should be determined by the balance between the cooling of the thermal electrons, the thermalization of nonthermal electrons, and the energy input rate by reconnections. In solar flares, the total energy of accumulated nonthermal electrons is comparable to, or even larger than, that of the thermal electrons (Holman et al. 2003). In the directly observed electron spectrum in the Earth’s magnetotail, the nonthermal component is smoothly connected to the thermal component at the energy where the thermal electron spectrum declines by the exponential cutoff, which is reminiscent of the cosmic background spectrum from X-ray to the MeV band. Therefore, the inferred amount of nonthermal electrons in AGN coronae seems quite reasonable.

In this Letter, we have shown that MeV gamma-ray background can be explained by the same population of AGNs that makes up the CXB, by considering Comptonization by nonthermal electrons in AGN coronae that are theoretically ex-

\[ 1 \text{ In Fig. 2, a discontinuity is seen between the HEAO-1 A-4 MED data above 100 keV and the HEAO-1 A-4 LED data below 100 keV (Gruber et al. 1999; see also Revnivtsev et al. 2005, Churazov et al. 2007, and Frontera et al. 2007). If we use the model by Gilli et al. (2007), the discrepancy is reduced below 100 keV but is enhanced above 100 keV.} \]
pected to exist. The best fit to the MeV gamma-ray background is obtained when the nonthermal component has $\sim 3.5\%$ of the total electron energy, with a spectrum $dN/dE \propto E^{-3.8}$. This power-law index is close to that of electrons accelerated by magnetic reconnections in solar flares or in the Earth’s magnetosphere (Holman et al. 2003; Lin 2006; Øieroset et al. 2002). This gives support to the idea of the reconnection-heated AGN corona (Liu et al. 2002). There is a chance that future MeV detectors, with improved sensitivity, will detect directly the nonthermal component predicted by our model, from nearby bright AGNs.

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