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THE CONTRIBUTION TO THE EXTRAGALACTIC γ-RAY BACKGROUND BY HADRONIC INTERACTIONS OF COSMIC RAYS PRODUCING EUV EMISSION IN CLUSTERS OF GALAXIES

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ABSTRACT

A substantial number of processes have been suggested as possible contributors to the extragalactic γ-ray background (EGRB). Yet another contribution to this background will be emission produced in hadronic interactions of cosmic-ray protons with the cluster thermal gas; this class of cosmic rays (CRs) has been shown to be responsible for the EUV emission in the Coma Cluster of galaxies. In this paper we assume the CRs in the Coma Cluster is prototypic of all clusters and derive the contribution to the EGRB from all clusters over time. We examine two different possibilities for the scaling of the CR flux with cluster size: the number density of the CRs scale with the number density of the thermal plasma, and alternatively, the energy density of the CRs scale with the energy density of the plasma. We find that in all scenarios the EGRB produced by this process is sufficiently low that it will not be observable in comparison with other mechanisms that are likely to produce an EGRB.

Key words : cosmology – clusters of galaxies – gamma rays: observations and theory – radiation mechanisms: non-thermal

I. INTRODUCTION

A diffuse γ-ray background (DGRB) was first detected by Kraushaar et al. (1972), based on OSO-3 satellite data. This was further studied by the SAS-2 satellite (Thompson & Fichtel 1982) and EGRET (Sreekumar et al. 1998, and references therein). Analyzing the EGRET data, Sreekumar et al. claimed the DGRB could be described by a power-law spectrum $\propto E_\gamma^{-2.1}$ with an integrated photon flux above 100 MeV of $1.45 \pm 0.05 \times 10^{-5}$ photons cm^{-2} s^{-1} sr^{-1} at the Galactic poles. This flux has almost universally been described as an extragalactic γ-ray background (EGRB) and for convenience we will use this terminology. However, Strong et al. (2004) carried out a new analysis of the relevant data and concluded the EGRB was lower than the commonly referenced values derived by Sreekumar et al. by a factor of 2, depending upon the energy, and had a somewhat different spectral shape. Further, Keshet et al. (2004) in an extensive analysis of the flux near the Galactic poles concluded that it was possible that all of the flux measured could be Galactic foreground emission.

A true EGRB will be present at some level. It is useful to consider what processes will contribute to this background and to what extent these processes may actually be observable. From a new analysis of data from the *Extreme Ultraviolet Explorer* (*EUVE*) on the Coma Cluster, Bowyer et al. (2004) demonstrated that the only source mechanism that could produce the EUV-excess emission in this cluster is secondary electrons generated in collisions between CR protons and thermal ions in the intracluster medium (ICM). This population of CRs will also produce γ-ray emission through inelastic collisions with the thermal ions in the cluster. These authors showed that the γ-ray emission produced in the Coma Cluster did not exceed the observational upper limits for the cluster.

In this paper we derive a more definitive value for the γ-ray emission from the Coma Cluster. We then estimate the contribution to the EGRB from all clusters of galaxies assuming the Coma Cluster is prototypic for CRs in clusters of galaxies.

II. THE γ-RAY EMISSION PRODUCED BY HADRONIC INTERACTIONS OF COSMIC RAYS

The spectrum of CR protons is assumed to be a power law in momentum

$$f_p(r,p)dp = n_p(r)\left(\frac{p}{\mathrm{GeV/c}}\right)^{-\alpha_p}\left(\frac{dp}{\mathrm{GeV/c}}\right). \qquad (1)$$

The γ-ray source function due to the decay of neutral pions produced from the collisions between CR protons and thermal ions in an ICM is (Pfrommer & Ensslin 2004)

$$q_\gamma(r,E_\gamma)dE_\gamma \simeq \sigma_{pp} c n_{tp}(r) n_p(r) \xi^{2-\alpha_\gamma} \times \frac{4}{3\alpha_\gamma} \times$$

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$$\left[\left(\frac{2E_\gamma}{m_{\pi^0}c^2}\right)^{\delta_\gamma} + \left(\frac{2E_\gamma}{m_{\pi^0}c^2}\right)^{-\delta_\gamma}\right]^{-\alpha_\gamma/\delta_\gamma} \times$$
$$\left(\frac{m_{\pi^0}c^2}{\mathrm{GeV}}\right)^{-\alpha_\gamma}\left(\frac{dE_\gamma}{\mathrm{GeV}}\right), \qquad (2)$$

where $\xi = 2$, $\alpha_\gamma = \alpha_p$, $\delta_\gamma = 0.14\alpha_\gamma^{-1.6} + 0.44$, and $\sigma_{pp} = 32 \times [0.96 + \exp(4.4 - 2.4\alpha_\gamma)]$ mbarn. This formulization employs Dermer's model (Dermer 1986a,b) for the hadronic interaction.

The inverse Compton scattering (ICS) of cosmic microwave background (CMB) photons by secondary electrons also produces γ-rays. Only electrons with energies $\gtrsim 1$ GeV will contribute to the γ-ray flux. The spectrum of this electron population can be described by a power law (Pfrommer & Ensslin 2004)

$$f_{se}(r, E_e)dE_e = n_{se}(r)\left(\frac{E_e}{\mathrm{GeV}}\right)^{-\alpha_e}\left(\frac{dE_e}{\mathrm{GeV}}\right), \qquad (3)$$

$$n_{se}(r) = n_{tp}(r)n_p(r)\frac{2^7\pi 16^{-(\alpha_e-1)}}{\alpha_e - 2}\left(\frac{\sigma_{pp}}{\sigma_T}\right) \times$$
$$\left(\frac{m_e c^2}{\mathrm{GeV}}\right)\left(\frac{m_e c^2}{B^2 + B^2_{\mathrm{cmb}}}\right). \qquad (4)$$

The parameter $(B^2 + B^2_{\mathrm{cmb}})/8\pi$ is the energy density of the cluster magnetic field and the CMB equivalent field, σ_T is the Thomson cross section, and $\alpha_e = \alpha_p + 1$. In this study, we neglect the contribution by bremsstrahlung of secondary electrons; this emission is considerably less than the emission from neutral pion decay and from ICS of CMB photons by secondary electrons (Berrington & Dermer 2003).

III. THE γ-RAY EMISSION PRODUCED IN THE COMA CLUSTER

The thermal gas distribution in the Coma Cluster is modeled by a beta-model and is expressed as

$$n_{tp}(r) = n_{tp0}\left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta/2}, \qquad (5)$$

where $n_{tp0} = 4.09 \times 10^{-3}h^{1/2}$ cm^{-3}, $r_c = 10\farcm5 = 0.21h^{-1}$ Mpc, and $\beta = 0.75$ (Briel et al. 1992). The Hubble constant is defined as $\mathrm{H}_0 = 100h$ km s^{-1} Mpc^{-1}. A virial radius R_{v} of $1.64h^{-1}$ Mpc, and a virial mass M_{v} of $4.97 \times 10^{14}h^{-1}$ $M_\odot$ (Girardi et al. 1998) are adopted for the Coma Cluster. Based on the EUV flux, Bowyer et al. (2004) found the ratio between the number of CR protons and the number of thermal protons in the cluster is $f_p = n_p/n_{tp} \sim 1.4 \times 10^{-7}$ for a power-law index $\alpha_p = 2.5$. Following Bowyer et al., we choose 2.5 for the power-law index α_p, and we also examined a flatter power law of index 2.1. For different α_p, we employ equation (4) of Bowyer et al. (2004) to derive the ratio required to produce the observed EUV flux. For $\alpha_p = 2.1$, we find $f_p \sim 2.7 \times 10^{-8}$. In these calculations, we adopt 1 μG as the magnetic-field strength in the Coma Cluster.

The γ-ray flux $F_\gamma(E_\gamma > 100\mathrm{MeV})$ for the case of $\alpha_p = 2.5$ is $\approx 1.7 \times 10^{-9}$ photons cm^{-2} s^{-1}. This is similar to the results obtained by Bowyer et al. (2004), 1.4×10^{-9} photons cm^{-2} s^{-1}, who used simpler approximations to derive this flux. The γ-ray flux $F_\gamma(E_\gamma > 100\mathrm{MeV})$ for the case of $\alpha_p = 2.1$ is $\approx 0.9 \times 10^{-9}$ photons cm^{-2} s^{-1}. These fluxes are substantially less than the most stringent observational upper limits to the γ-ray flux from the Coma Cluster of 3.81×10^{-8} photons cm^{-2} s^{-1} (Reimer et al. 2003). The γ-ray luminosity of the Coma Cluster as a function of energy for both cases are shown in Figures 1 and 2.

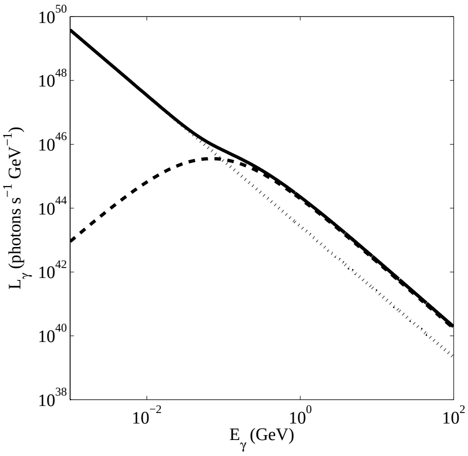

Fig. 1.— The γ-ray luminosity of the Coma Cluster: $\alpha_p = 2.1$. The total luminosity is shown as a *solid curve*, the luminosity from neutral pion decay is shown as a *dashed curve*, and the luminosity from ICS of CMB photons by secondary electrons is shown as a *dotted line.*

IV. THE EGRB PRODUCED BY ALL CLUSTERS OF GALAXIES

In order to estimate the contribution to the EGRB produced by populations of CRs of this class from all clusters of galaxies, we assume the Coma Cluster is prototypic for this class of CRs, and derive the resultant γ-ray emission. Bowyer et al. (2004) found the γ-ray luminosity of the Coma Cluster $L_\gamma \propto q_\gamma V \propto n_p n_{tp} V \propto f_p n_{tp}^2 V \propto f_p M_{gas}^2/V$, where M_{gas} and V are the gas mass and cluster volume, respectively. Arnaud & Evrard (1999) found that the gas fraction $f_{gas} = M_{gas}/M$ where M is the cluster mass including dark matter in clusters is fairly constant. Consequently, we assume the gas fraction is constant for all clusters of galaxies. Assuming the ratio f_p is universal in clusters of galaxies, then the γ-ray luminosity of a cluster $L_\gamma(M) \propto M\rho$, where ρ is the cluster mass density. According to the spherical collapse model, ρ is the

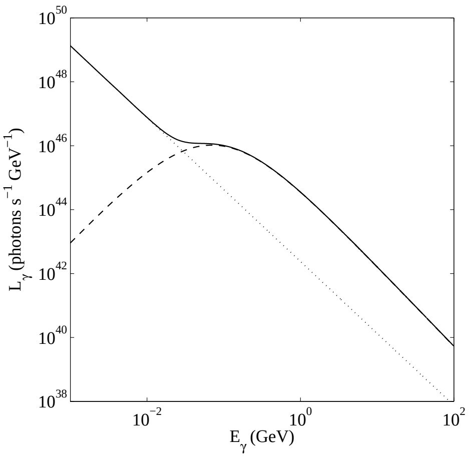

Fig. 2.— The γ-ray luminosity of the Coma Cluster: $\alpha_p = 2.5$. The total luminosity is shown as a *solid curve*, the luminosity from neutral pion decay is shown as a *dashed curve*, and the luminosity from ICS of CMB photons by secondary electrons is shown as a *dotted line.*

virial density $\rho_{\rm vir} = \Delta_c \rho_c$, $\Delta_c = 18\pi^2 + 82x - 39x^2$ and $x = [\Omega_M(1+z)^3/(\Omega_M(1+z)^3 + \Omega_\Lambda)] - 1$. The parameter $\Omega_M \equiv \rho_0/\rho_c(z=0)$ is the ratio of the present mean density to the critical density $\rho_c = 3H(z)^2/(8\pi G)$ at present, Ω_Λ is defined as $\Lambda/(3H_0^2)$, and Λ is the cosmological constant. Normalized to the luminosity of the Coma Cluster, the γ-ray luminosity of a cluster with mass M at redshift z is then given by

$$L_\gamma(E_\gamma, z, M) = \frac{M}{M_{\rm Coma}} \frac{\rho_{\rm vir}(z)}{\rho_{\rm vir}(z_{\rm Coma})} L_\gamma^{\rm Coma}(E_\gamma). \quad (6)$$

We convolve this result with the number density and evolution of clusters of galaxies as a function of time. The Press-Schechter mass function (Press & Schechter 1974) is used to model the cluster number density and its evolution. The comoving number density of clusters in the mass range $M \sim M + dM$ at time t is given by

$$\begin{aligned} n_{ps}(M,t)dM &= \sqrt{\frac{2}{\pi}} \frac{\rho_0}{M} \frac{\delta_c(t)}{\sigma^2(M)} \left| \frac{d\sigma(M)}{dM} \right| \times \\ & \exp\left[-\frac{\delta_c^2(\mathrm{t})}{2\sigma^2(\mathrm{M})} \right] \mathrm{dM}, \quad (7) \end{aligned}$$

where $\delta_c(t)$ is the critical density threshold for a spherical perturbation to collapse by the time t, and $\sigma(M)$ is the present rms density fluctuation smoothed over a region of mass M. For $\sigma(M)$, we use an approximate formula proposed by Kitayama & Suto (1996) for the cold dark matter fluctuation spectrum and choose the value of 0.84 derived from the combination of WMAP data with other finer scale CMB experiments (ACBAR and CBI), 2dFGRS measurements, and Lyα forest data for σ_8 (Spergel et al. 2003). A low-density flat model (ΛCDM), $\Omega_M = 0.27, \Omega_\Lambda = 0.73, h = 0.71, \Gamma = 0.2$ (Spergel et al. 2003), is assumed for these calculations where Γ is the shape parameter defined by Sugiyama (1995). The spectrum of EGRB is then

$$\begin{aligned} J(E_\gamma) = \frac{1}{4\pi} \times \quad (8) \\ \int\int \frac{L_\gamma(E_\gamma(1+z), z, M) n_{ps}(M,z)}{(1+z)^3} \frac{dl}{dz} dz dM, \end{aligned}$$

where

$$\frac{dl}{dz} = \frac{c}{H_0}(1+z)^{-1}[\Omega_M(1+z)^3 + \Omega_\Lambda]^{-1/2}. \quad (9)$$

Several groups have argued that the energy density of cluster CRs will scale as the energy density of the thermal gas (e.g., Pfrommer & Ensslin 2004), and we explored the consequences of this possibility. For simplicity, we assume the ratio between the energy density of CR protons and the energy density of thermal gas is universal in clusters of galaxies. In this case, $L_\gamma \propto M_{gas}^2 T/V$, where T is the gas temperature. According to the mass-temperature relationship proposed by Bryan & Norman (1998), T is proportional to $M^{2/3}\rho^{1/3}$. Thus the γ-ray luminosity of a cluster with mass M at redshift z is given by

$$\begin{aligned} L_\gamma(E_\gamma, z, M) = \quad (10) \\ \left(\frac{M}{M_{\rm Coma}}\right)^{5/3} \left[\frac{\rho_{\rm vir}(z)}{\rho_{\rm vir}(z_{\rm Coma})}\right]^{4/3} L_\gamma^{\rm Coma}(E_\gamma). \end{aligned}$$

We convolve this result with the number density and evolution of clusters of galaxies as a function of time as before.

The spectrum of the EGRB produced by hadronic interactions of CRs with the cluster thermal gas is shown in Figure 3. The flux produced if the CRs scale with the energy density is substantially less than that if the CRs scale with the gas density. In all scenarios studied here, the resultant EGRB will be substantially less than the observed diffuse γ-ray flux.

V. SUMMARY

The contribution to the EGRB by hadronic interactions of CRs with the thermal cluster gas is relatively small. This is superficially surprising, given the large γ-ray flux produced by this mechanism in the Coma Cluster. However, the background depends upon both the overall number density of large clusters like the Coma Cluster, and the fall-off with mass (and hence the γ-ray emissivity) of smaller clusters. Clusters like the Coma Cluster are quite rare. The number density of smaller clusters is much larger, but their masses fall rapidly with size, so these clusters will contribute far fewer γ-rays to the overall background.

An EGRB certainly exists at some level. If it is eventually possible to measure this flux, or if it has already been measured albeit with some uncertainty in intensity and spectral shape, it will still be difficult to

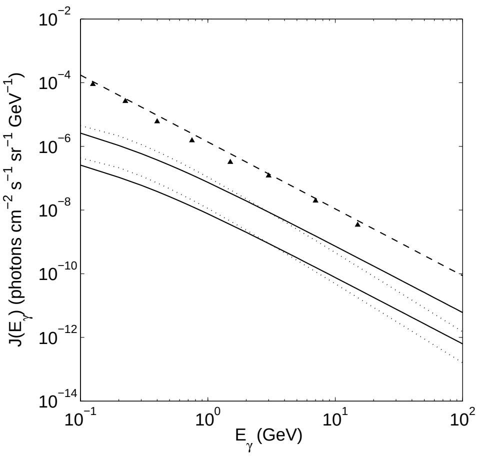

Fig. 3.— The EGRB produced by hadronic interactions of CR protons with the cluster thermal gas. The heavy dashed line is the observational result of Sreekumar et al. (1998); the triangles are the more stringent results of Strong et al. (2004). The upper dotted and solid lines show the flux produced if the CRs in clusters scale with the gas density: $\alpha_p = 2.1$ (*solid line*) and $\alpha_p = 2.5$ (*dotted line*). The lower dotted and solid lines show the flux produced if the CRs scale with the energy density: $\alpha_p = 2.1$ (*solid line*) and $\alpha_p = 2.5$ (*dotted line*).

identify the separate processes that are contributing to this background. Emission produced by hadronic interactions of CR protons with the thermal gas in clusters will be one of the components of the EGRB, but we have shown that if the Coma Cluster is prototypic for these CRs, this process will produce an integrated flux which is far lower than the γ-ray flux produced by other suggested mechanisms. Nevertheless, future missions with high spatial resolution may well be able to identify the signature of this process in at least a few large clusters of galaxies.

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