Origin of the High Energy Extragalactic Diffuse Gamma Ray Background

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(Received 26 January 1995)

Recent x-ray observations have discovered that groups and clusters of galaxies contain many more baryons in intergalactic gas than in stars. If high-energy cosmic rays are present there with an average intensity comparable to that observed in our Galaxy, they could produce the extragalactic diffuse gamma radiation.

PACS numbers: 98.70.Rz, 98.62.Ra, 98.70.Vc

Observations with the gamma ray satellite SAS-II have shown [1] that in addition to the galactic diffuse gamma radiation, which varies strongly with direction and can be explained by cosmic ray interactions in the galactic interstellar medium, there appears to be an unaccounted diffuse component which is isotropic at least on a coarse scale and fits well at low photon energies to the extragalactic hard x-ray background radiation. These two features suggest an extragalactic origin of this isotropic component [1]. Its spectrum in the energy range 35–300 MeV was fitted [2] by a power law with a spectral index $-2.35^{+0.4}_{-0.3}$ and an intensity $I_\gamma(>100\ \mathrm{MeV}) = (0.7-2.3)\times 10^{-5}\ \gamma\,\mathrm{cm^{-2}\,s^{-1}sr^{-1}}$ at energies greater than 100 MeV. Recent analyses [3–5] of observations with the Energetic Gamma Ray Experiment Telescope (EGRET) on board the Compton Gamma Ray Observatory (CGRO) have yielded similar results. For instance, a detailed analysis [3] of the high-quality data from "phase 1" of the EGRET observations obtained the result that the differential intensity of the GBR in the energy range 50–10 GeV is well represented by

$$\frac{dI_\gamma}{dE} = 9.6\times 10^{-7}E^{-\alpha}\ \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}\,GeV^{-1}}, \qquad (1)$$

with $\alpha = 2.11 \pm 0.05$. Equation (1) yields an intensity $I_\gamma(E > 100\ \mathrm{MeV}) = (1.1 \pm 0.05)\times 10^{-5}\ \gamma\ \mathrm{cm^{-2}} \times \mathrm{s^{-1}\,sr^{-1}}$ at energies greater than 100 MeV.

Since cosmic ray interactions in the interstellar gas of our Milky Way (MW) galaxy explain [6,7] most of the gamma ray emission of the MW, it was suggested [8] that cosmic ray interactions in external galaxies may explain the extragalactic diffuse gamma background radiation (GBR). However, it was found that the summed emission from cosmic ray interactions in external galaxies falls short by a large factor (>20) in explaining the observed intensity of the GBR [9]. This can be seen easily: The total emissivity of the MW in high energy gamma rays ($E > 100$ MeV) was estimated [6] to be $L_\gamma(>100\ \mathrm{MeV}) \approx 1.3\times 10^{42}\ \gamma\,\mathrm{s^{-1}}$, while its optical luminosity was estimated [10] to be $L_{\mathrm{MW}} = (2.3 \pm 0.6)\times 10^{10}L_\odot$. The average luminosity density of the Universe was measured [11] to be $\rho_L \approx (1.83 \pm 0.35)\times 10^8\ hL_\odot\mathrm{Mpc^{-3}}$, where $H_0 = 100h\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ is the Hubble constant. If the gamma ray and optical emissivities of galaxies are approximately proportional to the galactic mass, then their ratio is approximately universal and equal to that of the MW. The intensity of the extragalactic GBR is then given by

$$I_\gamma(>E) \approx \frac{c}{4\pi H_0}\frac{\rho_L L_\gamma(>E)}{L_{\mathrm{MW}}}. \qquad (2)$$

It yields $I_\gamma(>100\ \mathrm{MeV}) \approx (2.6 \pm 0.8)\times 10^{-7}\ \gamma \times \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$, independent of the value of h. This intensity is smaller by a factor 30–80 than the observed intensity of the GBR [12].

Whereas the ratio of gas mass to stellar light for the MW is $M_{\mathrm{gas}}/L_{\mathrm{MW}} \approx 4.8\times 10^9\ M_\odot/2.3\times 10^{10}\ L_\odot \approx 0.21 M_\odot/L_\odot$, recent x-ray observations show that this ratio for clusters and groups of galaxies is larger by almost two orders of magnitude [13]. For instance, analyses of recent observations with the ROSAT x-ray telescope coupled with precise photometric measurements yielded $M_{\mathrm{gas}}/L_B \approx 4.4\times 10^{11}M_\odot h^{-5/2}/2.4\times 10^{10}h^{-2}L_\odot \approx 19h^{-1/2}M_\odot/L_\odot$ within a distance of $0.24h^{-1}$ Mpc from the center of HCG62 [14], and M_{gas} within a distance of $1.5h^{-1}$ Mpc from the center of the Coma cluster [15]. These ratios are larger by about two orders of magnitude than the MW ratio, which was used in Eq. (2). They suggest that perhaps cosmic ray interactions with intergalactic gas within groups and clusters of galaxies [16] have produced the GBR.

In this Letter we show that if high energy cosmic rays are present in intergalactic space within groups and clusters with an *average* intensity comparable to that observed in the MW [17], they could produce the observed GBR. We also produce some observational tests of the cosmic ray origin of the extragalactic GBR.

For the sake of simplicity, let us first ignore cosmic evolution effects (e.g., Hubble expansion, energy redshift, gas consumption by stellar formation, evolution of the cosmic ray flux). Bremsstrhalung and inverse Compton scattering from cosmic ray electrons dominate gamma ray production at low energies while π^0 production by cosmic ray nuclei dominate gamma ray production at high energies [9]. Thus, for a universal cosmic ray flux (same average intensity and composition) in the intergalactic space within groups and clusters, the emission is proportional to the mass of the gas. Detailed averaging of the gas

0031-9007/95/75(17)/3052(4)$06.00

to light ratio over field galaxies, groups, and clusters, using fitted Schechter luminosity functions for galaxies [11], and for groups and clusters [18] and gas to light ratios obtained from EINOBS and ROSAT observations, yields [19] a mean gas to light ratio of $\langle M_{\rm gas}/L_B \rangle = \beta M_{\rm gas}/L_{\rm MW} \approx (13 \pm 6)h^{-1/2} M_\odot/L_\odot$. Consequently, if cosmic rays are present in the intergalactic space within groups and clusters with an intensity comparable to that observed in the MW, then they produce there an extragalactic diffuse GBR whose energy spectrum is similar to that of the galactic diffuse gamma radiation, and its intensity is larger by a factor $\beta \approx (62 \pm 31)h^{-1/2}$ than that predicted by Eq. (2). Namely, $I_\gamma(>100~{\rm MeV}) \approx (2.0 \pm 1.2) \times 10^{-5}~\gamma~{\rm cm^{-2}~s^{-1}sr^{-1}}$, where we used the value $h = 0.65 \pm 0.15$, the weighted average of the most recent measurements of the Hubble constant [20]). This intensity agrees well within the experimental uncertainties with the observed intensity of the extragalactic diffuse GBR.

The large formal uncertainty in the above estimate is due to the uncertain values of the total gamma ray and optical luminosities of the MW, of the Hubble constant, and of the ratio of gas to light averaged over field galaxies, groups, and clusters. They can be avoided, however, by using an alternative estimate: The x-ray observations combined with the mean baryon density deduced from big-bang nucleosynthesis [21] indicate that a large fraction, $f = M_{\rm gas}/M_b > 0.8$, of the baryons in the present Universe are in intergalactic gas within groups and clusters. At higher redshifts, $f \longrightarrow 1$ because cosmic evolution transforms gas into stars. Thus, if n_b is the average density of baryons in the Universe, then a fraction fn_b is in the form of intergalactic gas within groups and clusters which is exposed to a MW-like cosmic ray flux. This exposure generates a high energy extragalactic GBR with an intensity

$$I_\gamma(>E) \approx cH_0^{-1} f n_b j_H(>E), \tag{3}$$

where $j_H(>E)$ is the total emissivity in high energy gamma rays per baryon due to cosmic ray interactions. From cosmic ray interactions in the MW it was found that [22] $j_H(E > 100~{\rm MeV}) = (1.8 \pm 0.2) \times 10^{-26} \gamma~{\rm s^{-1}sr^{-1}}$. Standard big bang nucleosynthesis (SBBN) theory and the observed abundances of the light elements, H, D, ^{4}He, and ^{7}Li extrapolated to zero age imply that the ratio of the mean densities of baryons and photons in the Universe is [21] $\eta = n_b/n_\gamma = (1.6 \pm 0.1) \times 10^{-10}$. The mean density of background photons measured [23] with the Cosmic Background Explorer (COBE) satellite is $n_\gamma = 411 \pm 8~{\rm cm^{-3}}$. Consequently, SBBN yields $n_b = (6.6 \pm 0.4) \times 10^{-8}~{\rm cm^{-3}}$, and from Eq. (3) it follows that for $f = 0.8$

$$I_\gamma(>100~{\rm MeV}) \approx (1.35 \pm 0.40) \times 10^{-5} \gamma~{\rm cm^{-2}~s^{-1}sr^{-1}}, \tag{4}$$

This intensity is in good agreement with the measured intensity of the GBR at energies greater than 100 MeV.

Note that we used a mean baryon density which is implied [21] by the recent measurements of the abundance of deuterium in a high-redshift low-metallicity cloud [24] [$(1.9-2.5) \times 10^{-4}$ by number] and also by the current best determinations [25] of the primordial abundance of ^{4}He($22.9 \pm 0.5\%$ by mass). However, if the primordial abundance of deuterium is that observed in the local interstellar medium [26] [$(1.65^{+0.07}_{-0.18}) \times 10^{-5}$] or that deduced from the solar system abundances [27], then n_b and consequently $I_\gamma(>E)$ are larger by approximately a factor of two.

We will now consider cosmic evolution effects in a Friedman-Robertson-Walker universe with a zero cosmological constant and a scaled density $\Omega = \rho/\rho_c$, where $\rho_c = 3H_0^2/8\pi G$ with G being Newton's constant of gravity. In this universe, a population of gamma ray sources s with differential luminosities $L_s(E) \propto E^{-\alpha}$, a number density at the present epoch n_s, and evolution functions $f_s(z)$ (which describe how the intrinsic luminosities of sources s change with redshift z) generate a diffuse extragalactic GBR at the present cosmic epoch, $z = 0$, whose intensity is given by

$$\frac{dI_\gamma}{dE} = \sum\nolimits_s \frac{L_s n_s}{4\pi} \frac{c}{H_0} \int_0^\infty \frac{f_s(z)dz}{(\Omega z + 1)^{1/2}(1 + z)^{1+\alpha}} . \tag{5}$$

In Eqs. (2)–(5) we have neglected gamma ray absorption in the intergalactic space which becomes important only for $E_\gamma > 500$ GeV due to e^+e^- pair production in collision with the intergalactic IR, visible, and UV background radiations [28]. The most uncertain factor in Eq. (5) is the evolution of the intracluster cosmic ray flux. We have investigated various plausible cosmic ray evolutions and found out that they can change the predicted intensity of the GBR as given by Eq. (4) by less than a factor 2. For instance, if the intensity of intracluster cosmic rays is time independent, then the redshift of the gamma ray energies due to the cosmic expansion decreases the predicted GBR by a factor $K \approx (1/(\alpha + \Omega/2 - 1) \approx 0.9 - 0.6$ for $\alpha = 2.11 \pm 0.05$ and $0.10 \le \Omega \le 1$. Thus for $h = 0.65 \pm 0.15$ and $\Omega = 0.15 \pm 0.05$ (the current best observational estimates of these parameters) we predict that

$$I_\gamma(>100~{\rm MeV}) \approx (1.2 \pm 0.4) \times 10^{-5} \gamma~{\rm cm^{-2}~s^{-1}sr^{-1}}, \tag{6}$$

The above prediction is in good agreement with the observed intensity of the extragalactic GBR. This is also demonstrated in Fig. 1 which presents a comparison between the observed and predicted differential intensities of the extragalactic GBR. For energies greater than 100 MeV, the extragalactic GBR produced by cosmic rays is expected to have the same spectrum as that of gamma rays emitted by the MW with an integral intensity given by Eq. (6) [29]. Figure 1 clearly demonstrates that cosmic rays with an average intensity in the intergalactic space of groups and clusters comparable to that observed in the Milky Way could produce the observed extragalactic GBR at energies greater than 100 MeV.

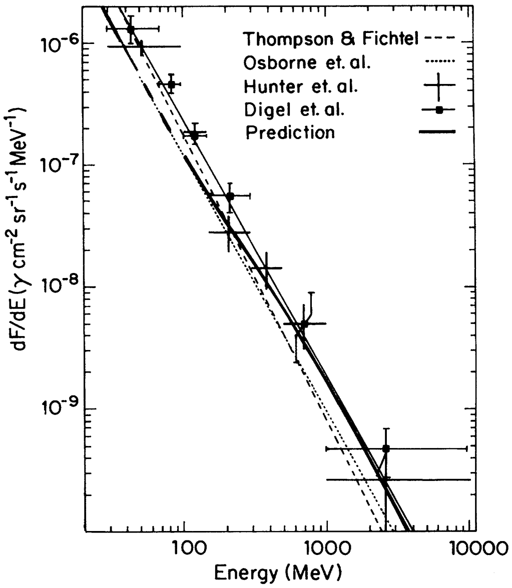

FIG. 1. Comparison between the predicted (thick line) extragalactic GBR produced by a universal MW-like cosmic ray flux in groups and clusters [Eq. (6)] and the observed high-energy GBR. The dashed, dotted, and full lines are the spectrum of the extragalactic GBR derived by Fichtel, Simpson, and Thompson [1] from SAS-2 observations, by Osborne *et al.* [3] from phase I of EGRET observations on CGRO, and by Digel *et al.* [5] from EGRET/CGRO observations of the Orion region, respectively. The actual data points of the measured GBR by Hunter *et al.* [4] and by Digel *et al.* [5] from EGRET/CGRO observations of the Ophiuchus and Orion regions, respectively, are also displayed.

The cosmic ray origin of the GBR can be further tested in future observations.

(1) Nearby gas-rich clusters which were observed with the ROSAT x-ray telescope, such as the Coma cluster [15] ($D \approx 70h^{-1}$ Mpc), the Perseus cluster [30] ($D \approx 55h^{-1}$ Mpc), and the Virgo cluster [31] ($D \approx 14h^{-1}$ Mpc), may be detected by EGRET in high energy gamma rays. The expected gamma ray flux from these clusters at a luminosity distance D is given by

$$F_\gamma(>E) \approx \frac{M_{\rm gas} j_H[>(1+z)E]}{m_p D^2}\,. \tag{7}$$

For the Coma cluster, $M_{\rm gas} = (9.0 \pm 2.6) \times 10^{13} h^{-5/2} M_\odot$ within a radius of 100 arcmin from its center [15]. Consequently, its expected gamma ray flux at Earth is $F_\gamma(>100\ {\rm MeV}) \approx 0.5 \times 10^{-7} \gamma\,{\rm cm}^{-2}\,{\rm s}^{-1}$.

For the Perseus cluster, $M_{\rm gas} = (1.2 \pm 0.3) \times 10^{14} h^{-5/2} M_\odot$ within a radius of 100 arcmin from its center [32]. Consequently, its expected gamma ray flux at Earth is $F_\gamma(>100\ {\rm MeV}) \approx 1.0 \times 10^{-7} \gamma\,{\rm cm}^{-2}\,{\rm s}^{-1}$. For the core region of Virgo around the elliptical galaxy M87, $M_{\rm gas} \approx (2.0 \pm 0.3) \times 10^{13} h^{-5/2} M_\odot$ within a radius of 2.5° [31], and its expected gamma ray flux at earth is $F_\gamma(>100\ {\rm MeV}) = (2.2 \pm 0.3) \times 10^{-7} \gamma\,{\rm cm}^{-2}\,{\rm s}^{-1}$. Such fluxed are marginally detectable by EGRET. However, a positive detection by EGRET of such time independent gamma ray fluxes from the directions of the Coma and Perseus clusters and from the core region of Virgo around M87 will provide supportive evidence for the universality of cosmic rays in galaxies, groups, and clusters and for the cosmic ray origin of the extragalactic GBR. Conversely, a failure to detect gamma rays from the Coma, Perseus, and Virgo (the halo around M87) clusters by EGRET can be used to set a limit on the cosmic ray intensity in these clusters, on the validity of the universality of cosmic rays in clusters and groups, and on the validity of the cosmic ray origin of the extragalactic GBR.

(2) The extragalactic GBR and the Galactic GBR produced by cosmic rays must exhibit the same power-law spectrum as that of the high energy cosmic ray flux. Namely, their power index increases gradually from $\alpha \sim 2.1 \pm 0.1$ around 1 GeV to $\alpha \sim 2.67$ around 100 GeV. Beyond 500 GeV the power index of the Galactic GBR remains that of the MW cosmic rays ($\sim$2.7) while that of the extragalactic GBR increases due to e^+e^- pair production off extragalactic UV, V, and IR background photons [28].

(3) Cosmic ray interactions in extragalactic gas also produce a high energy extragalactic neutrino background radiation (NBR), with intensity proportional to the cosmic ray intensity [33]:

$$\frac{dI_{\nu_\mu}}{dE} \approx 1.5 \times 10^{-6} \frac{dI_{CR}}{dE}\,. \tag{8}$$

Such NBR may dominate the atmospheric neutrino background at energies beyond 2×10^3 TeV and may be detected by the new generation of neutrino telescopes under construction [33].

Other explanations of the origin of the GBR have been proposed [9]. They include the summed emission from discrete sources such as active galactic nuclei (AGN), radio galaxies, Seyfert galaxies, and BL Lac objects, and more speculative diffuse sources such as matter-antimatter annihilation, cosmic strings, annihilation of dark matter particles, and decay of particles relics from the Big-Bang. However, most of these explanations have been later questioned by observations [9].

Perhaps the most promising of these explanations has been that the GBR is the sum of gamma ray emission from unresolved AGN [34]. When this explanation was suggested, only the relatively nearby quasar 3C 273 had been seen in high energy ($E > 100$ MeV) gamma rays [35]. Since the launch of the CGRO in 1991, the EGRET instrument has detected additional 32 AGN in high energy gamma rays [36], all of which seem to belong to the "blazar" class. Although it is difficult to see how the observed isotropic GBR can be produced by the highly beamed emission from blazars, many of which have a much harder spectrum than that of the GBR, apparently, with additional *ad hoc* assumptions (which may be true) the observed GBR can be explained as the summed emission from blazars [37]. Such a GBR produced by blazars is expected to exhibit significant angular and time variability, while a GBR produced by cosmic ray interactions in groups and clusters is expected to be highly isotropic and time independent. Moreover, the power index of a high energy GBR produced by blazars is -2.06 ± 0.05 up to 500 GeV. (This is the power index of Mk 421, the only blazar that has been detected in both GeV and TeV gamma rays, by EGRET and by the Whipple Observatory, [38] respectively. It was assumed to represent well the power index of the high energy gamma ray emission by blazars.) These features may also help distinguish between the proposed cosmic ray and blazar origins of the extragalactic GBR.

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