On the origin of the diffuse gamma-ray background radiation

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(Dated: July 21, 2006)

The spectrum and intensity of the diffuse gamma-ray background radiation in directions away from the Galactic disk and centre were measured by EGRET. We show that the observations are well explained by inverse Compton scattering of cosmic-microwave-background and starlight photons by the cosmic-ray electrons produced in our Galaxy, in external galaxies and by active galactic nuclei.

PACS numbers: 98.70.Sa, 98.70.Rz, 98.70.Vc

I. INTRODUCTION

The existence of a diffuse gamma background radiation (GBR) was first suggested by data from the SAS 2 satellite [1]. Data from the EGRET instrument of the Compton Gamma Ray Observatory supported this finding [2]. We call "the GBR" the residual of measurements made by EGRET by subtracting point sources, masking the Galactic disk at latitudes $|b| \leq 10^o$, and the Galactic centre at $|b| \leq 30^o$ for longitudes $|l| \leq 40^o$, and by extrapolating the data outside this mask to zero column density, which should eliminate the Galactic contributions of bremsstrahlung from cosmic-ray electrons (CREs), and π^0 production by CR nuclei. Outside the mask, the GBR flux in the observed range of 30 MeV to 120 GeV, shown in Fig. 1, is well described by a power law:

$$\frac{dF_\gamma}{dE} \simeq 2.74 \times 10^{-3} \left[\frac{E}{\text{MeV}}\right]^{-2.10} \frac{1}{\text{cm}^2\ \text{s sr MeV}} \,. \quad (1)$$

The spectral index of the GBR is the same, 2.1 ± 0.03, in all sky directions [2]. The normalization of the GBR flux was found to be normally distributed around the central value given by Eq. (1). These two results were used to argue for a *cosmological* (extragalactic) origin of the GBR [2]. A large number of putative sources have been proposed. Perhaps the most conservative hypothesis for the origin of an isotropic GBR is that it originates from unresolved active galactic nuclei (AGNs) [3]. The fact that blazars have a γ-ray spectrum with an average index 2.15 ± 0.04, compatible with that of the GBR, supports this hypothesis [4], but later studies have shown that $\leq 25\%$ of the GBR can result from unresolved AGNs [5]. Geminga-type pulsars, expelled into the Galactic halo by asymmetric supernova explosions, could also be abundant enough to explain the GBR [6]. Other suggestions include cosmic-ray interactions in galaxy clusters and groups [7], and fossil radiation from shock-accelerated CRs during structure formation [8]. More exotic hypotheses are a baryon-symmetric Universe [9], now excluded [10], primordial black-hole evaporation [11], supermassive black holes at very high redshift [12], and the annihilation of dark-matter particles [13].

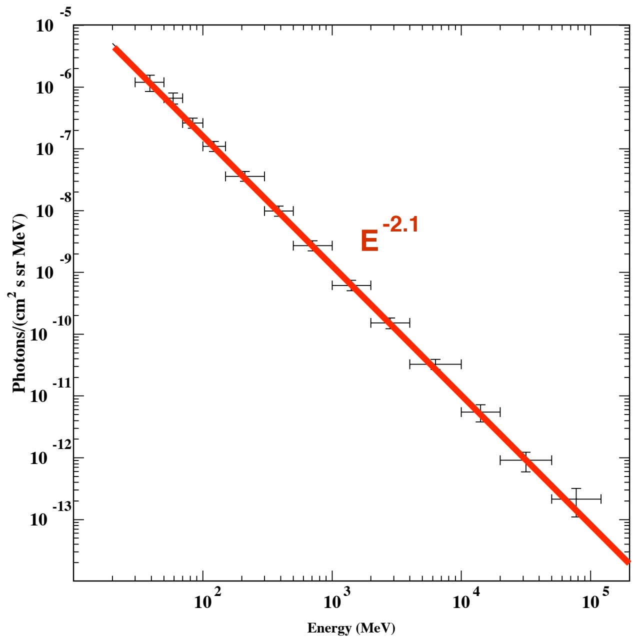

FIG. 1: The GBR spectrum, inferred by EGRET [2]. The line is their best power-law fit.

The EGRET GBR data in directions away from the Galactic disk and centre show a significant deviation from isotropy, clearly correlated with the structure of the Galaxy and our position relative to its centre [14]. This advocates a large Galactic contribution to the GBR. Indications of such a contribution were found by means of a wavelet-based "non-parametric" approach that makes no reference to a particular model [6]. Other authors [15] also found that the contribution of inverse Compton scattering (ICS) of starlight (SL) and microwave background radiation (MBR) photons by Galactic CREs is presumably much larger than expected. Earlier evidence that ICS of SL and of the MBR by CREs in the Galactic halo contributes significantly to the GBR at large Galactic latitudes was reported in [16]: $\sim 30\%$ of the intensity of the GBR at large latitudes is correlated to the Galactic radio emission at 408 MHz, which is dominated by synchrotron radiation from the same CREs as produce ~ 100 MeV γ-rays by ICS from the Galactic SL.

In [14] we went a step further, showing that the GBR could be dominated by ICS of MBR and SL by Galactic CREs, provided that the Galactic CR halo is large enough. A later analysis [17] led to the same conclusion. Here we reinforce this conclusion by showing how the intensity and directionality of the GBR can be predicted from our detailed understanding [18] of the distribution and spectra of CR electrons and nuclei in the Galaxy.

A large Galactic contribution to the GBR —correlated with the structure of the galaxy's halo and our position relative to its centre— and the uniformity of its spectral index over the whole sky suggest similar origins for the Galactic and extragalactic contributions. We shall argue that ICS of radiation by CREs in our Galaxy, in external galaxies and in the intergalactic space, is that origin. The extragalactic component is calculated directly from the CR luminosity of the main cosmic accelerators: supernova explosions and the massive black holes of AGNs. We show that the observed spectrum, intensity and angular dependence of the GBR are correctly predicted.

The energy spectrum of CREs near Earth [19], with energy $E_e > 5$ GeV, is well described by:

$$\frac{dF_e}{dE_e} = A\left[\frac{E_e}{\mathrm{MeV}}\right]^{-3.2\pm0.10} \frac{1}{\mathrm{cm^2\,s\,sr\,MeV}}\,. \qquad (2)$$

This spectrum is predicted by the Cannonball (CB) model, wherein CRs are particles of the interstellar medium accelerated by relativistic "cannonballs" —emitted in core-collapse SN explosions— to a "source" spectrum with a power-law index, $\beta_s = 13/6 \approx 2.17$ [18]. Energy loss by synchrotron emission in magnetic fields and ICS of radiation change β_s for CREs to $\beta_e = \beta_s + 1 \approx 3.17$. Radio observations of synchrotron radiation emitted by CREs in the Galaxy, external galaxies, galaxy clusters and active galactic nuclei (AGNs) support this predicted universal spectrum of high-energy CREs.

The temperature and mean energy of the MBR are $T_0 = 2.725$ K and $\epsilon_0 \approx 2.7\,k\,T_0 \approx 6.36\,\mathrm{meV}$ [20]. Starlight has an average energy $\epsilon_1 \sim 1$ eV. Consider the ICS of these radiations by CREs. The mean energy $\bar{E}_\gamma$ of the Compton upscattered photons is:

$$\bar{E}_\gamma(\epsilon_i) \approx \frac{4}{3}\left(\frac{E_e}{m_e\,c^2}\right)^2 \epsilon_i. \qquad (3)$$

The ICS of the MBR and SL photons by CREs produces a GBR with a spectrum which is a convolution [25] of the CRE spectrum with the thermal spectrum of the MBR and of SL. The result can be well approximated by:

$$\frac{dF_\gamma}{dE} \propto \frac{dE_e}{dE}\,\left[\frac{dF_e}{dE_e}\right]_{E_e^i}\,,\; E_e^i \equiv m_e c^2\sqrt{\frac{3\,\bar{E}_\gamma}{4\,\epsilon_i}}\,, \qquad (4)$$

with E_e^i obtained from Eq. (3) by inverting $\bar{E}_\gamma$. Introducing the electron flux of Eq. (2) into Eq. (4), we obtain:

$$\frac{dF_\gamma}{dE} \propto E^{-(\beta_e+1)/2} \simeq E^{-2.083}. \qquad (5)$$

The predicted photon spectral index coincides with the measured one, 2.10 ± 0.03 [2]. Next, we calculate the intensity of the extragalactic GBR produced by ICS of MBR and SL photons by CREs in external galaxies and the intergalactic medium (IGM).

Adopt a standard cosmology with a Hubble constant $H \approx 70$ km s^{-1} Mpc^{-1} and $(\Omega, \Omega_M, \Omega_\Lambda) = (1, 0.27, 0.73)$, for which the age of the Universe is approximately the Hubble time $H^{-1} \simeq 14$ Gy. Let $\sigma_{\rm T} \approx 0.65\times10^{-24}\,\mathrm{cm^{-2}}$ be the Thomson cross-section. Let U_γ be the energy density of the radiation field (MBR+SL), and $U_B = B^2/(8\pi)$ the energy density of a magnetic field B. Given Eq. (3), CREs with energy ≥ 3 GeV are needed to produce the GBR above 30 MeV by ICS of the MBR. Even for $B = 0$, the radiative lifetime of these electrons:

$$\tau_{\rm rad} = \frac{3\,m_e^2\,c^3}{4\,\sigma_{\rm T}\,E_e\,(U_\gamma + U_B)} \qquad (6)$$

is much shorter than the Hubble time. In the CR halo of galaxies and in galaxy clusters $B < 3\,\mu$G, and in the IGM, where $B \sim 50\,$nG [26], ICS of the MBR dominates over synchrotron losses on the magnetic field. Therefore, we shall calculate the intensity of the extragalactic GBR from the conclusion that practically all the kinetic energy of CREs in the Universe has been converted by ICS to γ-rays of the GBR, with the predicted spectrum of Eq. (5).

The main accelerators of high-energy CREs are supernovae (SNe) and AGNs [18]. Consider SNe first. The SN rate is proportional to the star-formation rate $R_{\rm SN}(z) \propto R_{\rm SF}(z)$, with $R_{\rm SN}(0) \approx 10^{-4}\,\mathrm{Mpc^{-3}\,yr^{-1}}$ [21]. The observed rate is well represented by $R_{\rm SF}(z)/R_{\rm SF}(0) \approx (1+z)^4$ for $z < 1.2$ and $R_{\rm SF}(z) = R_{\rm SF}(1.2)$ for $z \geq 1.2$ [22]. Let $E_k \approx 2\times10^{51}$ erg be the mean energy release in CRs per SN [18] and let f_e be the fraction of the luminosity in CREs out of the total luminosity $L_{\rm CR}$ in CRs. The CB model does not predict f_e, we shall assume that it is equal to the ratio of the Milky Way's luminosity in CREs to its total luminosity in CRs:

$$f_e \approx \int \frac{dF_e[\mathrm{MW}]}{dE}\,\frac{E\,dE}{\tau_{\rm rad}} \Big/ \int \frac{dF_{\rm CR}[\mathrm{MW}]}{dE}\,\frac{E\,dE}{\tau_{\rm dif}} \approx \frac{1}{40} \qquad (7)$$

where $\tau_{\rm dif} \approx 2\times10^8\;(E/\mathrm{GeV})^{-0.6}$ yr is the mean escape time of CR protons and electrons from the Galaxy by diffusion in its magnetic field [18].

Given our inferred 100% ICS conversion of CRE energy to photon energy, the GBR spectrum satisfies:

$$\int \frac{dF_\gamma}{dE}\,E\,dE \approx \frac{c\,L_e}{4\pi\,H\,R_{\rm SF}(0)} \int \frac{dz\,(1+z)^{-\beta_s}\,R_{\rm SF}(z)}{\sqrt{\Omega_M\,(1+z)^3 + \Omega_\Lambda}}, \qquad (8)$$

where $L_e = f_e L_{\rm CR} \approx f_e R_{\rm SN} E_k$ is the mean luminosity density of CREs in the Universe. Inserting L_e into Eq. (8)

yields the contribution to the GBR from extragalactic SNe:

$$\frac{dF_\gamma}{dE} \simeq 0.97 \times 10^{-3} \left[\frac{E}{\text{MeV}}\right]^{-2.08} \frac{1}{\text{cm}^2\ \text{s sr MeV}} \,. \tag{9}$$

Powered by mass accretion onto massive black holes, AGNs eject powerful relativistic jets whose kinetic energy is transferred mainly to CRs. The kinetic power of these jets has been estimated from their radio lobes, assuming equipartition between CR- and magnetic field energies and an energy ratio f_e similar to that observed in our Galaxy. It was estimated [23] that AGNs with a central black hole of $M \simeq 10^8\, M_\odot$ inject $\approx 10^{61-62}$ erg into the intergalactic space, mostly during their $\sim 10^8$ y bright phase around redshift $z = 2.5$. In search for an upper bound, we assume that the kinetic energy release in relativistic jets is the maximal energy release from mass accretion onto a Kerr black hole ($\approx 42\%$ of its mass), and that this energy is equipartitioned between magnetic fields and cosmic rays [18] with a fraction f_e of the CR energy carried by electrons. These CREs also cool rapidly by ICS of the MBR and SL. The energy of CREs with $\gamma_e \gtrsim 185$, whose cooling time is shorter than the look-back time to $z = 2.5$, is converted to γ-rays whose energy is redshifted by $1+z$ by the cosmic expansion. We assume the Galactic ratio of the mass of the central black hole, $3.5 \times 10^6\, M_\odot$, to the luminosity, $L_*[\text{MW}] \approx 2.3 \times 10^{10} L_\odot$, to be universal. The Universal luminosity density, $\rho_{_L} = 1.2 \times 10^8\, L_\odot\, \text{Mpc}^{-3}$, then implies that $\rho_{\text{BH}}(z=0) \sim 1.82 \times 10^4\, M_\odot\, \text{Mpc}^{-3}$ in the current Universe (see however [24]) and that AGNs have contributed an extragalactic GBR flux:

$$\frac{dF_\gamma}{dE} \simeq \frac{1.75 \times 10^{-2}\, c\, f_e\, \rho_{\text{BH}}\, c^2}{4\,\pi\,(1+z)\,\text{MeV}} \left[\frac{E}{\text{MeV}}\right]^{-2.08} \,. \tag{10}$$

With the above priors this contribution is:

$$\frac{dF_\gamma}{dE} \simeq 2.1 \times 10^{-4} \left[\frac{E}{\text{MeV}}\right]^{-2.08} \frac{1}{\text{cm}^2\ \text{s sr MeV}} \,. \tag{11}$$

Because of Feynman scaling, the GBR from π^0 production and decay in hadronic CR collisions in the ISM and IGM has the same power-law index as that of CRs [7], i.e. -2.77 in the ISM of galaxies and -2.17 in the IGM inside and outside galaxy clusters [18]. This contribution to the extragalactic GBR is much smaller than that of CREs and need not be discussed here.

The GBR contains a considerable Galactic foreground due to ICS of MBR, SL and sunlight photons by Galactic CREs [18]. The convolution of a CRE power-law spectrum with a photon thermal distribution [25] can be approximated very simply [14]. Using the index i to label the CMB, SL and sunlight fluxes, we have:

$$\frac{dF_\gamma}{dE_\gamma} \simeq N_i(b,l)\ \sigma_{\text{T}}\ \frac{dE_e^i}{dE_\gamma}\ \left[\frac{dF_e}{dE_e}\right]_{E_e=E_e^i} , \tag{12}$$

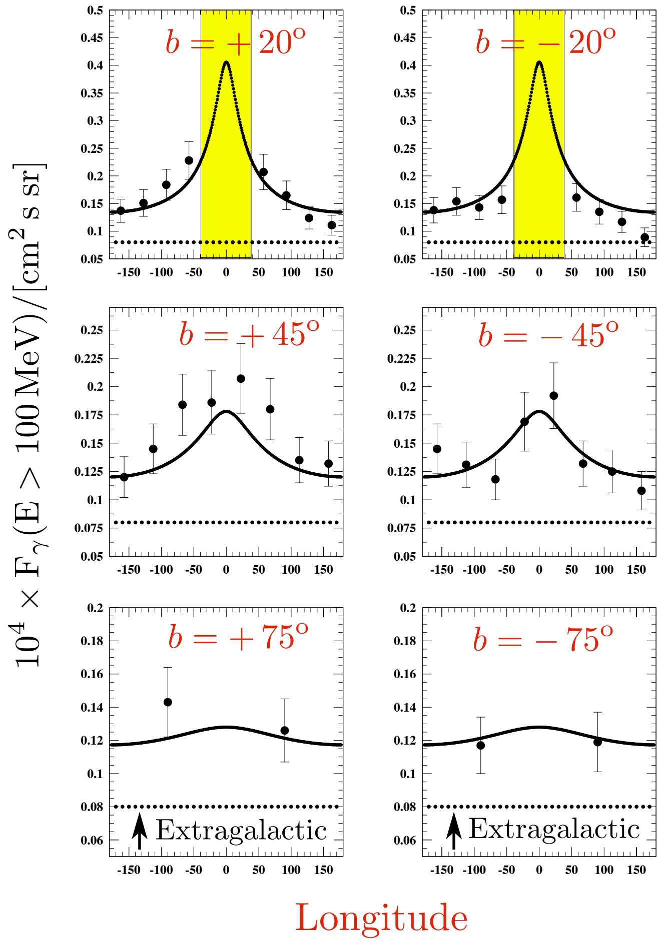

FIG. 2: The flux of GBR photons above 100 MeV: comparison between EGRET data and our model for $h_e = 8$ kpc, $\rho_e = 35$ kpc, as functions of longitude l at various fixed latitudes b. The shaded domain is EGRET's mask. The AGN contribution is subdominant: compare Eqs. (9) and (11).

where $N_i(b,l)$ is the column density of the radiation field weighted by the distribution of CREs in the direction $(b,\, l)$, and E_e^i is given in Eq. (4). The distribution of the (non-solar) SL is approximated as $\propto 1/r^2$, with r the distance to the Galactic centre, and the CREs are assumed to be distributed as a Gaussian "CR halo" [14]. Naturally, the results depend crucially on the size and shape of this halo. In this note we use our updated estimate of the halo properties [18]: a Gaussian distribution with a scale length of $\rho_e = 35$ kpc in the Galactic disk, as we used in [14], but a scale height of $h_e = 8$ kpc perpendicular to the disk [18] instead of the $h_e = 20$ kpc used before [14]. The justification for this change is as follows:

The radio emission of "edge-on" galaxies –interpreted as synchrotron radiation by electrons on their magnetic fields– offers direct observational evidence for CREs well above galactic disks (e.g. [27]). For the particularly well observed case of NGC 5755, the exponential scale height of the synchrotron radiation is $\mathcal{O}(4)$ kpc. If the CRs and the magnetic field energy are in equipartition, they should have similar distributions, and the Gaussian scale height h_e of the electrons ought to be roughly twice that of the synchrotron intensity, which reflects the convolution of the electron- and magnetic-field distributions. The inferred value is $h_e \sim 8$ kpc. The corresponding volume of the Galactic CR halo is $V_{\rm CR} = (\pi)^{3/2}\,\rho_e^2\,h_e = 1.6\times10^{69}\,{\rm cm}^3$. The SN rate in the Galaxy is $R_{\rm SN}[{\rm MW}]\sim 2$ per century, and its predicted total luminosity in CRs is $L_{\rm CR} \approx E_k\,R_{\rm SN}[{\rm MW}] \approx 4\times10^{49}\,{\rm erg\,y^{-1}}$. The CR confinement volume must obey the constraint:

$$L_{\rm CR} \sim V_{\rm CR} \times \frac{4\pi}{c}\int \frac{dE}{\tau_{\rm dif}}\,E\,\frac{dF_p}{dE}\,. \qquad (13)$$

Our estimated $\tau_{\rm dif}$ and the observed (or fitted) spectrum of CRs [19, 29] yield the expected $V_{\rm CR}\approx 1.6\times10^{69}$ cm^3. The volume inferred from a leaky-box model fit to the Galactic GBR [28] is smaller by a factor ≈ 2.5 than our estimate, reflecting the shorter confinement time of CRs estimated in leaky-box models from the abundance of unstable CRs [30], and the higher contribution assumed in [28] for the extragalactic GBR.

In Fig. 2 we compare the observed GBR with our predictions, as functions of Galactic coordinates. The prediction is a sum of a (b, l)-dependent Galactic foreground produced by ICS of the MBR, SL and sunlight, and a uniform extragalactic GBR. The result has $\chi^2/{\rm dof} = 0.85$, a vast improvement over the constant GBR fit by EGRET, for which $\chi^2/{\rm dof} = 2.6$. We conclude that the GBR can be explained by standard physics, namely, ICS of MBR and SL by CREs from the two main CR sources in the universe: SNe and AGNs. At $E_\gamma > 100$ GeV, most of the extragalactic GBR photons are absorbed by pair production on the cosmic infrared background radiation [31] and the diffuse GBR reduces to the Galactic foreground. This suppression should be observable by GLAST.

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