On the origin of the diffuse extragalactic gamma-ray background radiation

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We show that inverse Compton scattering of cosmic-microwave-background and starlight photons by cosmic-ray electrons in the interstellar and intergalactic space explains well the spectrum and intensity of the diffuse gamma-ray background radiation (GBR), which was measured by EGRET aboard the Compton Gamma Ray Observatory (CGRO) in directions away from the Galactic disk and centre. The Gamma Ray Large Area Space Telescope (GLAST) will be able to separate the Galactic foreground from the extragalactic gamma-rays, and to provide stringent tests of the theory.

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The intensity and spectrum of the diffuse $\gamma$ radiation was measured by EGRET aboard the Compton Gamma Ray Observatory (CGRO). An extragalactic gamma-ray ‘background’ radiation (GBR) was inferred \cite{1} from the extrapolation of these measurements (in directions away from the Galactic disk and center) to zero column density, which should eliminate the Galactic contributions of bremsstrahlung from cosmic-ray electrons (CREs), and $\pi^0$ production by cosmic ray (CR) nuclei. This GBR flux in the observed range of 30 MeV to 120 GeV, shown in Fig. 1, is well described by a power-law:

$$\frac{dF_\gamma}{dE} \simeq (2.7 \pm 0.1) \times 10^{-3} \left[ \frac{E}{\text{MeV}} \right]^{-2.1} \frac{1}{\text{cm}^2 \text{ s sr MeV}}.$$ \hspace{1cm} (1)

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

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 \cite{13}. This advocates a large Galactic contribution to the GBR. In \cite{13} it was shown that the EGRET GBR could be dominated by inverse Compton scattering (ICS) of the cosmic microwave background radiation (MBR) and starlight by Galactic cosmic ray electrons, provided that the Galactic cosmic-ray halo is large enough. Indications of a large Galactic contribution to the GBR were found by means of a wavelet-based “non-parametric” model-independent approach \cite{5}. Other authors \cite{14} also found that the contribution of inverse Compton scattering of starlight and microwave background radiation photons by Galactic CREs is presumably much larger than expected. Ear-
lier evidence that ICS by CREs in the Galactic halo contributes significantly to the GBR at large Galactic latitudes was reported in [13]: ∼30% of the intensity of the GBR at large latitudes is correlated to the diffuse Galactic radio emission at 408 MHz, which is dominated by synchrotron radiation from the same CREs that produce ∼100 MeV γ-rays by ICS from the Galactic star-light.

The uniformity of the GBR spectral index over the whole sky, despite a large Galactic contribution correlated with the structure of the galaxy’s halo and our position relative to its centre, suggests similar origins of the Galactic and extragalactic contributions. In this letter we argue that ICS of the cosmic microwave background radiation by extragalactic CR electrons [16], when added to the Galactic foreground, explains the EGRET GBR. The extragalactic component is calculated directly from the CR luminosity of the main putative cosmic accelerators [16]: supernova explosions and accreting massive black holes in active galactic nuclei (AGN). Unlike in previous estimates of the contribution from AGN [2,3,4], which included only the γ-ray emission from blazars (AGN with jets and γ rays beamed in our direction), we calculate the much larger contribution from CREs injected into the intergalactic medium (IGM) in arbitrary directions by all AGN jets, and subsequently isotropized by the IGM magnetic fields. The Galactic component was calculated as in [13] from our estimated Galactic CR luminosity [16] and from the locally observed flux and spectrum of CREs. We show that the observed spectrum, intensity and angular dependence of the EGRET GBR are correctly predicted.

The energy spectrum of CREs near Earth [17], with energy $E_e > 5$ GeV, is well described by:

$$\frac{dF_e}{dE_e} = (2.5 \pm 0.5) \times 10^5 \left(\frac{E_e}{\text{MeV}}\right)^{-3.2 \pm 0.1} \frac{1}{\text{cm}^2 \text{sr MeV}}. \quad (2)$$

The spectral index is predicted by the Cannonball (CB) model, wherein CRs are particles of the interstellar medium accelerated by relativistic “cannonballs” — emitted in core-collapse supernova (SN) explosions — to a “source” spectrum with a power-law index, $\beta_e = 13/6 \approx 2.17$ [16]. Energy loss by synchrotron emission in magnetic fields and ICS of radiation change $\beta_e$ for CREs to $\beta_e = \beta_e + 1 \approx 3.17$. Radio observations of synchrotron radiation emitted by CREs in the Galaxy, external galaxies, galaxy clusters and AGN, support this predicted universal spectrum of high-energy CREs.

The temperature and mean energy of the MBR are $T_0 = 2.725$ K and $\epsilon_0 \approx 2.7 k T_0 \approx 0.64$ meV [18]. Starlight has $\epsilon_1 \approx 1$ eV. Consider the ICS of these radiations by CREs. The mean energy of the upscattered photons is:

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

The ICS of the microwave background and starlight photons by CREs produces a GBR with a spectrum which is a convolution [23] of the CRE spectrum with a thermal target spectrum. The result can be approximated by:

$$\frac{dF_e}{dE_e} \propto \frac{dE_e}{dE} \left[ \frac{dF_e}{dE_e} \right] E_e^\epsilon = m_e c^2 \sqrt{\frac{3 \bar{E}_\gamma}{4 \epsilon_i}}, \quad (4)$$

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

$$\frac{dF_e}{dE} \propto E^{-(\beta_e+1)/2} \approx E^{-2.08}. \quad (5)$$

The predicted index agrees with the measured one, $2.10 \pm 0.03$ [1]. Given Eq. (3), CREs of energy $E_{\text{EBR}} > 96$ GeV produce the GBR above 30 MeV by ICS of the current ($z = 0$) MBR; CREs with energy $E_e \geq 2.4$ GeV suffice for ICS on starlight. Let $\epsilon_2 \approx 0.65 \times 10^{-24} \text{cm}^{-2}$ be the Thomson cross-section and let $U_i = m_e \epsilon_i$. In our neighbourhood, $U_* \approx U_{\text{MBR}} = 0.26$ eV cm$^{-3}$. For electrons of energy $E_e$, the radiation cooling times are $\tau_{\text{rad}}(t) = 3 m_e^2 c^3/(4 \epsilon_2 E_e U_i)$, so that locally $\tau_{\text{rad}}(\approx) \approx 6 \times 10^8$ years and globally $\tau_{\text{rad}} > 1.3 \times 10^7/(1+z)^2$ years. These numbers are much shorter than a Hubble time. ICS of CREs dominates the production of the extragalactic GBR, as we argue next.

Adopt a standard cosmology with $H \approx 70$ km s$^{-1}$ Mpc$^{-1}$ and $(\Omega, \Omega_M, \Omega_L) = (1, 0.27, 0.73)$, for which the age of the Universe is $H^{-1} \approx 14$ Gy. For a Galactic magnetic field $B \sim 3 \mu G$, $U_g \approx U_{\text{MBR}}$; synchrotron cooling and emission are locally relevant [13]. In our model, CRs transfer their kinetic energy to CRs all along their trajectories, which extend from the SN-rich inner galaxies to their halos and beyond. In galactic halos and galaxy clusters, $B < 3 \mu G$, and in the IGM, $B \sim 50 nG$ [24]. In both places starlight is irrelevant, and ICS of the MBR whose energy density increases with $z$ like $(1+z)^4$ dominates over synchrotron losses on the magnetic field. Thus, we calculate the intensity of the extragalactic GBR from the conclusion that the kinetic energy of CREs in the Universe with a lifetime shorter than the Hubble time has been converted by ICS of the MBR to γ-rays with the predicted spectrum of Eq. (5).

In the CB model, the main accelerators of high-energy CREs are the relativistic jets of supernovae (SNe) and AGNs [16]. The SN rate is proportional to the star-formation rate $R_{\text{SF}}(z) \propto 10^{-4} \text{Mpc}^{-3} \text{yr}^{-1}$ [19]. The observations are well represented by $R_{\text{SF}}(z)/R_{\text{SF}}(0) \approx (1+z)^4$ for $z < 1$ and $R_{\text{SF}}(z) = R_{\text{SF}}(1)$ for $z \geq 1.2$ [20]. Let $E_k \approx \frac{2 \times 10^{53}}{10} \text{erg}$ be the mean energy release in CRs per SN [16] and let $f_\epsilon$ be the fraction of the luminosity in CRs out of the total luminosity in CRs. The CB model does not predict $f_\epsilon$, we assume that it is equal to the ratio of the Milky Way’s luminosity in CREs to its total luminosity in CRs:

$$f_\epsilon \approx \int \frac{dF_{\text{MW}}[\text{CR}]}{dE} \frac{E dE}{\tau_{\text{rad}}} \int \frac{dF_{\text{CR}}[\text{MW}]}{dE} E dE \left(\frac{E_{\text{esc}}}{\tau_{\text{esc}}\approx 10^{40}} \right). \quad (6)$$

where $\tau_{\text{esc}} \approx 2 \times 10^8 (E/\text{GeV})^{-0.6}$ yr is the mean escape time of CR protons and electrons from the Galaxy and
its halo by diffusion in its magnetic field [16]. In the CB model the volumes occupied by electron and proton CRs are similar, because CBs generate CRs all along their trajectories, which constitute a dense mesh in the Galaxy and its halo. The integrals in Eq. (5) extend from a lower fixed Lorentz factor, which drops from the ratio $f_e$, since the integrands are source spectra, identical in the CB model for electrons and protons.

The energy of CRE made by SN jets is converted, above $E_e \sim 100$ MeV, to photon energy. Their contribution to the GBR spectrum satisfies:

$$\int \frac{dF_\gamma}{dE} dE \approx \frac{e L_e / R_{SF}(0)}{4\pi H_0} \int dz \frac{R_{SF}(z)/(1+z)^3}{\sqrt{\Omega_M (1+z)^3 + \Omega_{\Lambda}}}$$  \tag{7}

where $L_e = f_e L_{SN} \gamma_e^{-1/6} \approx f_e R_{SF} E_k \gamma_e^{-1/6}$ is the mean luminosity density of CREs with Lorentz factor above $\gamma_e = \sqrt{3 E_e/4 e_0}$. Hence, Eq. (7) yields for the contribution to the GBR from extragalactic SNe:

$$\frac{dF_\gamma}{dE} \approx 0.9 \times 10^{-3} \left[ \frac{E}{\text{MeV}} \right]^{-2.08} \frac{1}{\text{cm}^2 \text{s sr MeV}}.$$  \tag{8}

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 [21] that AGNs with a central black hole of $M \approx 10^8 M_\odot$ inject $\approx 10^{51-52}$ erg into the intergalactic space, mostly during their $\sim 10^8$ yr 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 [16] with a fraction $f_e$ of the CR energy carried by electrons. These CREs also cool rapidly by ICS of the MBR. The energy of CREs whose radiative cooling rate $\tau_{rad}(z)$ is larger than the cosmic expansion rate, $H(z)$, is converted to $\gamma$-rays. Their energy is redshifted by $1 + z$ by the cosmic expansion. Using a black hole density $\rho_{BH}(z = 0) \sim 2 \times 10^5 M_\odot \text{Mpc}^{-3}$ in the current Universe [22], and the CB-model injection spectral index [16], our estimated contribution from AGNs to the extragalactic GBR flux,

$$\frac{dF_\gamma}{dE} \approx 2.4 \times 10^{-3} \frac{c f_e \rho_{BH} \rho^2}{4 \pi (1+z) \text{MeV}^2} \left[ \frac{E}{\text{MeV}} \right]^{-2.08},$$  \tag{9}

is,

$$\frac{dF_\gamma}{dE} \approx 4.0 \times 10^{-4} \left[ \frac{E}{\text{MeV}} \right]^{-2.08} \frac{1}{\text{cm}^2 \text{s sr MeV}}.$$  \tag{10}

This upper limit is smaller than the SN result of Eq. (8).

The GBR contains a considerable Galactic foreground due to ICS of MBR, starlight and sunlight photons by Galactic CREs [16]. The convolution of a CRE power-law spectrum with a photon thermal distribution [23] can be approximated very simply [13]. Using the index $i$ to label the MBR, starlight and sunlight fluxes, we have:

$$\frac{dF_\gamma}{dE} \approx N_i(b,l) \sigma_T \frac{dE_\gamma}{dE_i} \left[ \frac{dF_\gamma}{dE_i} \right]_{E_i = E_{\gamma}}$$  \tag{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 $E_{\gamma}$ is given in Eq. (4). The distribution of the non-solar starlight 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” [13]. Naturally, the results depend crucially on the size and shape of this halo. In this note we use our updated estimate of the CR halo [16]: a Gaussian distribution with a scale length of $\rho_e = 35$ kpc in the Galactic disk, as we used in [13], but a scale height of $h_e = 8$ kpc perpendicular to the disk [16] instead of the $h_e = 20$ kpc used in

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{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 fixed latitudes $b$. The shaded domain is EGRET’s mask. Notice that the vertical scales do not start at zero.}
\end{figure}
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 CRs well above galactic disks (e.g., [24]). 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 $V_{CR} = \frac{1}{2} \rho_c h_e^2 = 1.6 \times 10^{69}$ cm$^3$. The SN rate in the Galaxy is $R_{SN}[MW] \sim 2$ per century, and its predicted total luminosity in CRs is $L_{CR} \approx E_{k} R_{SN}[MW] \approx 4 \times 10^{49}$ erg y$^{-1}$. The CR confinement volume must obey the constraint:

$$L_{CR} \sim V_{CR} \frac{4\pi}{c} \int \frac{dE}{\tau_{esc}} E \frac{dE}{dE}.$$  \hspace{1cm} (12)

Our estimated $\tau_{esc}$ and the observed (or fitted) spectrum of CRs [17, 24] yield the expected $V_{CR} \approx 1.6 \times 10^{69}$ cm$^3$. The volume inferred from a leaky-box model fit to the Galactic GBR [27] is smaller by a factor $\approx 2.5$ than our estimate, reflecting the shorter confinement time of CRs estimated in leaky-box models from the abundance of unstable CRs [28], and the higher contribution assumed in [27] 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, starlight and sunlight, and a uniform extragalactic GBR. The result has $\chi^2$/dof $= 0.85$, a vast improvement over the constant GBR fit by EGRET, for which $\chi^2$/dof $= 2.6$. The ratios of $l$-integrated extragalactic to galactic fluxes are $0.5, 0.9, 1.5$, for $|b| = 20^\circ, 45^\circ, 75^\circ$. The ‘foreground’ component of the $\gamma$ ‘background’ is $\sim 50\%$ of the total radiation.

We conclude that the GBR can be explained by standard physics, namely, ICS of MBR and starlight by CRs from the two main CR sources in the universe: SNe and AGNs. At $E_{\gamma} > 100$ GeV, most of the extragalactic GBR is absorbed by pair production on the CMB [29] and the diffuse GBR reduces to the Galactic foreground. This suppression, and a decisive determination of the angular dependence in Fig. 2, should be observable by GLAST.

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