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Contribution from normal and starburst galaxies to the extragalactic gamma-ray background (EGRB)

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Abstract The extragalactic diffuse emission at γ-ray energies has interesting cosmological implications since these photons suffer little or no attenuation during their propagation from the site of origin. The emission could originate from either truly diffuse processes or from unresolved point sources such as AGNs, normal galaxies and starburst galaxies. Here, we examine the unresolved point source origin of the extragalactic γ-ray background emission from normal galaxies and starburst galaxies. γ-ray emission from normal galaxies is primarily coming from cosmic-ray interactions with interstellar matter and radiation ($\sim$90%) along with a small contribution from discrete point sources ($\sim$10%). Starburst galaxies are expected to have enhanced supernovae activity which leads to higher cosmic-ray densities, making starburst galaxies sufficiently luminous at γ-ray energies to be detected by the current γ-ray mission (Fermi Gamma-ray Space Telescope).

Key words: galaxy: general — galaxies: luminosity function — galaxies: starburst — gamma-rays: observations

1 INTRODUCTION

Observations have indicated the presence of diffuse emission presumably of extragalactic origin at nearly all wavelengths ranging from radio to γ-rays. The Compton Gamma-Ray Observatory (CGRO), launched in 1991 (Kanbach et al. 1988), produced the first all sky survey and revealed the presence of a nearly isotropic emission beyond 1 MeV which is generally assumed to have an extragalactic origin (Sreekumar, Stecker & Kappadath 1997). The newly launched γ-ray observatories, AGILE and Fermi Gama-ray Space Telescope (FGST), are expected to greatly enhance the depth of sky coverage and provide more frequent revisits during the next few years.

The measurement of an extragalactic diffuse emission is particularly difficult due to a strong component of diffuse emission arising from our own galaxy (Hunter et al. 1997). The measurement of an extragalactic component at low energies (0.5–10 MeV) is further constrained by the presence of significant instrumental background and nuclear line contribution. The poor angular resolution at these energies ($\sim$ degrees) further limits the ability to resolve the contribution from point sources. Above 10 MeV, where no significant line contributions are expected and pair-production is used as the primary photon detection process, the instrumental background is considerably reduced and angular resolution is significantly improved to resolve point sources. Consequently, in this paper, we focus on understanding the extragalactic γ-ray background above 100 MeV where observational results are better understood and uncertainties are less.

The first evidence for γ-ray emission from our Galaxy came from OSO-3 satellite observations (Kraushaar et al. 1972). This was supported by the SAS-2 and COS-B satellite observations (Fichtel et al. 1975) which showed a good correlation between the observed γ-ray emission and that expected from cosmic-ray interaction with interstellar matter and radiation. The presence of a residual, isotropic emission in excess of the diffuse emission from our Galaxy has been reported for the first time by SAS-2 (Fichtel et al. 1977; Fichtel, Simpson & Thompson 1978). This emission, largely believed to be of extragalactic origin, had an integrated intensity above 100 MeV (from SAS-2 data) of $(1.3 \pm 0.5) \times 10^{-5}$ photon cm^{-2}s^{-1}sr^{-1}, and the spectrum, characterized as a single power-law, had a slope of $-2.35^{+0.4}_{-0.3}$ (Thompson & Fichtel 1982).

With significantly improved sensitivity over previous experiments and a low instrumental background, EGRET (on board CGRO) provided a new platform to study the spectrum and distribution of the extragalactic emission in greater detail than was possible in the past. The derived Extragalactic Gamma-Ray Background (EGRB) spectrum could, in general, be influenced by the assumed contribution of high-latitude emission associated with the Galaxy itself. Though the processes that lead to the production of the bulk of the galactic diffuse emission is fairly well understood, the extrapolation of such models to high-latitude emission is less certain and hence can contribute towards additional uncertainties in the estimation of EGRB.

All-sky observational data from EGRET spanning more than four years have been used to derive the EGRB intensity and spectrum (Sreekumar et al. 1998; Strong, Moskalenko & Reimer 2004a,b). Sreekumar et al. (1998) derived the extragalactic emission as a constant component of the total observed emission that is uncorrelated with the line-of-sight column density of matter for thirty-six independent regions of the sky. The average spectrum is well fit with a single power-law characterized by a spectral index of (-2.10 ± 0.03) and the integrated flux above 100 MeV is derived as $(1.45 \pm 0.05) \times 10^{-5}$ photon cm^{-2} s^{-1} sr^{-1}. Strong, Moskalenko & Reimer (2004a,b) used a more extensive cosmic-ray model incorporated in the GALPROP code, inferred a new model for Galactic diffuse continuum γ-rays, and found the EGRB integrated flux above 100 MeV to be $(1.11 \pm 0.01) \times 10^{-5}$ photon cm^{-2} s^{-1} sr^{-1}, slightly lower than that obtained by Sreekumar et al. (1998). Their EGRB spectrum, if fitted with a single power law, yields an index of -2.17 ± 0.04, slightly steeper than that found by Sreekumar et al. (1998). Their data suggest a possible spectral break around 1.5 GeV. In a recent paper, Stecker, Hunter & Kniffen (2008) showed that there are additional instrumental effects that contribute in the GeV range. These effects lead to underestimation of EGRB by the approach of Strong, Moskalenko & Reimer (2004a,b), but have no impact on the approach adopted in Sreekumar et al. (1998).

The origin of the extragalactic emission has been a long standing problem. As in the case of diffuse emission at most wavelength bands, it can be interpreted either as truly diffuse in nature with a cosmological origin or arising as an artifact of limited instrument capability to individually resolve weak point sources. Truly diffuse emission can arise from numerous processes such as black hole evaporation, particle acceleration by intergalactic shocks produced during large scale structure formation (Loeb & Waxman 2000; Gabici & Blasi 2003), etc. To address the unresolved point source contribution, we start with the final EGRET γ-ray source catalog (Hartman et al. 1999) containing 271 sources (> 100 MeV), which includes five pulsars, one probable radio galaxy (Cen A), 66 high confidence identifications of a sub-class of active galactic nuclei called blazars and a single external normal galaxy, the Large Magellanic Cloud (LMC). 27 low confidence potential blazar identifications are also listed. We discuss blazar contribution to the EGRB in a separate paper. In this paper, we examine the contributions from normal and starburst galaxies to the EGRB on the basis of observational data from CGRO and by using suitable scaling relationships from observational and modeling results at other frequency bands.

Our galaxy exhibits strong diffuse emission as observed from the CGRO sky survey (Hunter et al.1997). As stated before, the origin of this emission is fairly well understood. Further, the nearest small galaxy, the LMC has also been detected in γ-rays (Sreekumar et al. 1992). Thus, normal galaxies may also contribute to the unresolved point source component of EGRB. Considering the large population of normal galaxies, its contribution towards EGRB may not be negligible.

To date, no starburst galaxy has been detected in γ-ray energies. In starburst galaxies, the star formation rate (SFR) is higher in comparison to normal galaxies. Considering that SFR is proportional to supernova rate (SNR), one can expect higher cosmic-ray densities in such galaxies. Since γ-ray luminosity of a galaxy is largely determined by its mean cosmic-ray density, starburst galaxies are expected to be potential γ-ray sources in future more sensitive sky surveys such as those from FGST. The γ-ray production mechanism in starburst galaxies is expected to be similar to that of normal galaxies, suitably enhanced by increased mean cosmic-ray densities. Hence, starburst galaxies, which are currently unresolved, also become potential sources of diffuse γ-ray emission. Current observational limits prevent clear detection of the nearest starburst galaxies M82 and NGC 253 (Sreekumar et al. 1994; Paglione et al. 1996; Blom, Paglione & Carramiñana 1999), but are expected to fall well within the sensitivity limits of FGST.

2 APPROACH TOWARD ESTIMATING SOURCE CONTRIBUTIONS

The nominal approach used to estimate the contribution to the EGRB from different source classes involves the use of source luminosity functions. The luminosity function provides the number of sources per unit co-moving volume, per luminosity interval of the universe. If $dN(L,z)$ is the number of sources having luminosities between L and $L+dL$, within a co-moving volume dV at a redshift z, then luminosity function $\phi(L,z)$ can be expressed as

$$\phi(L,z) = \frac{dN(L,z)}{dLdV}. \tag{1}$$

Integrating over luminosity and then over redshift, one can find the total energy flux per solid angle

$$S_\gamma(>100\,\mathrm{MeV}) \;=\; \frac{1}{4\pi}\int_0^z \frac{dV}{dz}dz \times \int_{L_{\min}}^{L_{\max}} \phi(L,z) \times \frac{L(1+z)^{1-\alpha}}{4\pi D_{\mathrm{L}}^2}dL, \tag{2}$$

where D_{L} is the luminosity distance of the source and α is the energy spectral index.

Among normal galaxies, only the Milky Way & LMC have been detected in γ-rays. The differential photon spectrum of diffuse γ-ray emission from our galaxy can be approximated by a power law of index –2.2. In the absence of spectral data from many sources, we assume that all normal galaxies and starburst galaxies produce γ-rays with an $E^{-2.2}$ differential number flux at the source. So, the energy spectral index (α) becomes 1.2. Given the limited number of detections, the γ-ray luminosity function of normal galaxies cannot be determined directly from available γ-ray observations. If γ-ray luminosity can be related to luminosity at some other wavelength, then the γ-ray luminosity function can be similarly related to the luminosity function at the same wavelength. Here, we make use of the linear relationship between γ-ray luminosity and infrared luminosity to derive the γ-ray luminosity function from the infrared luminosity function.

3 γ-RAY PRODUCTION PROCESSES

The main processes that are responsible for γ-ray production in our galaxy are (Bertsch et al. 1993 and references therein):

a) pion production through the interaction of cosmic-ray nuclei with interstellar matter, which decay rapidly to produce γ-rays,
b) bremsstrahlung emission from cosmic-ray electrons and
c) upscattering of soft photons through inverse Compton interaction with cosmic-ray electrons.

4 NORMAL GALAXIES

4.1 γ-ray Luminosity of Our Galaxy

Considering the source functions of different γ-ray production mechanisms as formulated by Bertsch et al. (1993), the γ-ray luminosity of our galaxy can be written as

$$\begin{aligned} L_\gamma(E) \; = \; & [c_n \, q_{\rm PP}(E) + c_e \, q_{\rm EB}(E)] \times n_{\rm ISM} \times V_{\rm eff_1} \\ & + c_e \, q_{\rm IC}(E) \, u_{\rm ph} \, V_{\rm eff_2}, \end{aligned} \tag{3}$$

where c_n and c_e are the cosmic-ray proton and electron densities respectively, relative to the values in the local solar neighborhood. $q_{\rm PP}(E)$, $q_{\rm EB}(E)$ and $q_{\rm IC}(E)$ are the source functions corresponding to pion production through nucleon-nucleon interaction, electron bremsstrahlung and inverse Compton processes, as defined in Bertsch et al. (1993). $n_{\rm ISM}$ is the mean interstellar matter density and $u_{\rm ph}$ is the interstellar photon density.

We assume that $c_n = c_e = c$ and

$$c = \frac{n_{\rm CR}}{n_{\rm local}}. \tag{4}$$

The $V_{\rm eff_1}$ and $V_{\rm eff_2}$ are the effective volumes for the pion production / electron bremsstrahlung and inverse Compton processes respectively. Since pion production and bremsstrahlung processes involve interaction between cosmic rays and the ISM, the effective γ-ray volumes ($V_{\rm eff1}$) of these two processes are assumed to be same. The inverse Compton process involves interaction between cosmic rays and interstellar radiation fields, so the effective γ-ray volume of this process ($V_{\rm eff2}$) is assumed to be different from the other two processes.

Multiplying Equation (3) with energy (E) and then integrating over energy (which gives γ-ray luminosity in erg s^{-1}), we have

$$L_\gamma = c\,[\{Q_{\rm PP} + Q_{\rm EB}\} n_{\rm ISM}] \times V_{\rm eff1} + c \times Q_{\rm IC} \times u_{\rm ph} V_{\rm eff2}, \tag{5}$$

where $Q_{\rm PP}$, $Q_{\rm EB}$ & $Q_{\rm IC}$ are the source functions corresponding to the three processes in erg s^{-1} cm^{-3}. They are calculated by multiplying the γ-ray source functions (Bertsch et al. 1993) by energy (E) and then integrating them over energy,

$$L_\gamma = L_{\gamma_{\rm PP}} + L_{\gamma_{\rm EB}} + L_{\gamma_{\rm IC}}, \tag{6}$$

where

$$L_{\gamma_{\rm PP}} \; = \; c \times Q_{\rm PP} \times n_{\rm ISM} \times V_{\rm eff1}, \tag{7}$$
$$L_{\gamma_{\rm EB}} \; = \; c \times Q_{\rm EB} \times n_{\rm ISM} \times V_{\rm eff1}, \tag{8}$$
$$L_{\gamma_{\rm IC}} \; = \; c \times Q_{\rm IC} \times u_{\rm ph} \times V_{\rm eff2}. \tag{9}$$

4.2 Cosmic Ray Density in Normal Galaxies

It is reasonable to assume that cosmic rays are produced at a rate proportional to the supernova rate which, is related to the current star formation rate ($\dot{N}_{\rm cr} \propto$ SFR).

The average cosmic-ray density can then be estimated as (Suchkov, Allen & Heckman 1993),

$$n_{\rm cr} = \frac{\dot{N}_{\rm cr}}{V_{\rm eff}} \times t, \tag{10}$$

where $V_{\rm eff}$ = effective γ-ray volume of the galaxy and t = characteristic diffusion time of cosmic rays from star-forming molecular gas clouds.

The cosmic ray proton density, relative to the local solar region is,

$$
\begin{aligned}
c_n &= \frac{n^n_{\rm cr}}{n^n_{\rm local}} = \frac{\dot{N}^n_{\rm cr} \times t}{n^n_{\rm local} V_{\rm eff}} \\
&= \frac{K^n_2 ({\rm SFR})\, t}{n^n_{\rm local} V_{\rm eff}} \quad [\,\text{assuming } \dot{N}^n_{\rm cr} \propto \ {\rm SFR}\,]\,,
\end{aligned} \tag{11}
$$

where K^n_2 is the proportionality constant between the cosmic-ray proton production rate and SFR, and $n^n_{\rm cr}$ is the cosmic-ray nucleon density.

Similarly for relative cosmic-ray electron density,

$$
\begin{aligned}
c_e &= \frac{n^e_{\rm cr}}{n^e_{\rm local}} = \frac{\dot{N}^e_{\rm cr} \times t}{n^e_{\rm local} V_{\rm eff}} \\
&= \frac{K^e_2 ({\rm SFR})\, t}{n^e_{\rm local} V_{\rm eff}} \quad [\,\text{assuming } \dot{N}^e_{\rm cr} \propto \ {\rm SFR}\,],
\end{aligned} \tag{12}
$$

where K^e_2 is the proportionality constant between the cosmic-ray electron production rate and SFR, and $n^e_{\rm cr}$ is the cosmic-ray electron density.

The constants K^n_2 and K^e_2 can be found from our galaxy data. From Equations (11) and (12)

$$
K^n_2 = \frac{c_n \times n^n_{\rm local} \times V_{\rm eff}}{{\rm SFR} \times t}, \tag{13}
$$

and

$$
K^e_2 = \frac{c_e \times n^e_{\rm local} \times V_{\rm eff}}{{\rm SFR} \times t}. \tag{14}
$$

$L_{\gamma_{\rm PP}}$, $L_{\gamma_{\rm EB}}$ and $L_{\gamma_{\rm IC}}$ have been derived for our galaxy (Hunter et al. 1997; Strong & Worrall 1976). Hence, $V_{\rm eff}$ can be found from the value of $L_{\gamma_{\rm PP}}$ and $L_{\gamma_{\rm EB}}$ using Equations (7) and (8). The average value of c (=1.2) (averaged over our galaxy) has been calculated from Hunter et al. (1997). The average ISM density is taken as 0.6 atom cm^{-2}. So, an average $V_{\rm eff}$ has been calculated which comes out to be 6×10^{66} cm^3.

The star formation rate (SFR) of our galaxy has been calculated from the infrared luminosity of the galaxy. SFR is derived from the total (8–1000 μm) IR luminosity (Kewley et al. 2002).

$$
\begin{aligned}
{\rm SFR}(M_\odot {\rm yr}^{-1}) &= 4.5 \times 10^{-44} L_{\rm TIR} && (15)\\
&\simeq 7.9 \times 10^{-44} L_{\rm FIR}, && (16)
\end{aligned}
$$

where $L_{\rm TIR}$ and $L_{\rm FIR}$ are the total infrared luminosity and far-infrared luminosity (in units of erg s^{-1}) of the galaxy respectively.

The SFR of our galaxy is found to be 1.9 $M_\odot$ yr^{-1} from the 60 μ and 100 μ flux (Kewley et al. 2002; Saunders et al. 2000). We can write,

$$
{\rm SFR} = K_3 L_{\rm TIR}, \tag{17}
$$

where K_3 = 4.5 $\times10^{-44}$ in units of $M_\odot$ yr^{-1} erg^{-1} s.

So, the proportionality constants between cosmic production rate (both for electron and proton) and star formation rate have been calculated using SFR and $V_{\rm eff}$ derived for our galaxy,

$$
\begin{aligned}
K^n_2 &= (1.9 \times 10^{33}) \times \frac{n^n_{\rm local}}{t}, && (18)\\
K^e_2 &= (1.9 \times 10^{33}) \times \frac{n^e_{\rm local}}{t}. && (19)
\end{aligned}
$$

Here, K^n_2 and K^e_2 are in units of gm^{-1} cm^3 yr$\times\frac{n^e_{\rm local}}{t}$.

4.3 Contribution to the EGRB

We derive the contribution of normal galaxies to EGRB by first deriving a relationship between γ-ray luminosity and infrared luminosity. Towards this, we examine the relative contributions from different processes responsible for γ-ray production in our galaxy.

$$\begin{aligned}\frac{L_{\gamma_{\rm PP}}+L_{\gamma_{\rm EB}}}{L_{\gamma_{IC}}} &= \frac{c\,[Q_{\rm PP}+Q_{\rm EB}]\times n_{\rm ISM}\times V_{\rm eff1}}{c\,Q_{\rm IC}\,u_{\rm ph}V_{\rm eff2}}\\ &= \frac{[Q_{\rm PP}+Q_{\rm EB}]\,n_{\rm ISM}V_{\rm eff1}}{Q_{\rm IC}\,u_{\rm ph}V_{\rm eff2}}\\ &= \frac{1}{K_1}.\end{aligned}$$

Hence,

$$L_\gamma = (1+K_1)[L_{\gamma_{\rm PP}}+L_{\gamma_{\rm EB}}], \tag{20}$$

where K_1 is the ratio between $L_{\gamma_{IC}}$ and ($L_{\gamma_{PP}}$ + $L_{\gamma_{EB}}$).

It is reasonable to assume that γ-ray production mechanisms in all normal galaxies are similar. It is also assumed that the ratio of luminosity contributions from different processes (K_1) remains constant for all normal galaxies. The value of K_1= 0.07 has been found from our galaxy data. Further, it is assumed that the constants K_2^n and K_2^e, (proportionality constants between cosmic ray production rate and star formation rate) which are given by Equations (18) and (19), remain the same for all normal galaxies. So, the luminosity of any normal galaxy becomes [from Equations (7), (8), (11), (12) and (20)],

$$\begin{aligned}L_\gamma &= (1+K_1)\times t\left[\frac{K_2^n}{n^n_{\rm local}}Q_{\rm PP}+\frac{K_2^e}{n^e_{\rm local}}Q_{\rm EB}\right]\times\left[\frac{\rm SFR}{V_{\rm eff}}\right]n_{\rm ISM}\times V_{\rm eff},\\ L_\gamma &= (1+K_1)\times t\left[\frac{K_2^n}{n^n_{\rm local}}Q_{\rm PP}+\frac{K_2^e}{n^e_{\rm local}}Q_{\rm EB}\right]\times n_{\rm ISM}\,{\rm SFR},\\ L_\gamma &= (1+K_1)\times(1.9\times10^{33})\times[Q_{\rm PP}+Q_{\rm EB}]\times n_{\rm ISM}\,{\rm SFR}.\end{aligned} \tag{21}$$

In the above equation, SFR is in units of gm yr^{-1}. Now, replacing SFR in the last equation from Equation (17)

$$L_\gamma = K_4 L_{\rm TIR}, \tag{22}$$

where, $K_4 = (1+K_1)\times t\times\left[\frac{K_2^n}{n^n_{\rm local}}Q_{\rm PP}+\frac{K_2^e}{n^e_{\rm local}}Q_{\rm EB}\right]\times n_{\rm ISM}\times K_3\times M_\odot$. The solar mass $M_\odot$ is in units of gm.

Thus, we have derived a relationship between γ-ray luminosity and infrared luminosity of normal galaxies. If $\phi_\gamma(L,z)$ and $\phi_{\rm TIR}(L,z)$ are the γ-ray luminosity function and the total infrared luminosity functions respectively, then

$$\phi_\gamma(L,z)\,dL_\gamma = \phi_{\rm TIR}(L,z)\,dL_{\rm TIR}. \tag{23}$$

From Equations (22) and (23) one can write,

$$L_\gamma\,\phi_\gamma(L,z)\,dL_\gamma = K_4\times L_{\rm TIR}\,\phi_{\rm TIR}(L,z)\,dL_{\rm TIR}. \tag{24}$$

The contribution to the γ-ray flux from the normal galaxy population now becomes

$$\begin{aligned}S_\gamma(>100{\rm MeV}) &= \frac{1}{4\pi}\int_0^z\frac{dV}{dz}dz\int_{L_{\rm min}}^{L_{\rm max}}\phi_\gamma(L,z)\times\frac{L_\gamma(1+z)^{1-\alpha}}{4\pi D_{\rm L}^2}dL_\gamma\\ &= \frac{1}{4\pi}\int_0^{z_{\rm max}}\frac{dV}{dz}\frac{(1+z)^{1-\alpha}}{4\pi D_{\rm L}^2}\,dz\\ &\quad\times\int_{L_{\rm min}}^{L_{\rm max}}\phi_\gamma(L,z)L_\gamma\,dL_\gamma.\end{aligned} \tag{25}$$

From Equations (24) and (25), one can now find S_γ (>100 MeV) by integrating over the infrared luminosity function. We used the luminosity function and comoving luminosity density from Lagache, Dole & Puget (2003). They parametrized the local luminosity function ($z = 0$) by an exponential cut-off in luminosity ($L_{\rm cut-off}$)

$$\phi_{\rm normal}(L, z = 0) = \phi_{\rm bol}(L, z = 0) \exp\left(\frac{-L}{L_{\rm cut-off}}\right), \tag{26}$$

$\phi_{\rm bol}(L, z = 0)$ was calculated from Saunders et al. (1990). They also considered a weak number evolution

$$\phi_{\rm normal}(L, z) = \phi_{\rm normal}(L, z = 0) \times (1 + z). \tag{27}$$

From figure 8 of their paper, one can find the comoving luminosity density at $z = 0$ and, using Equations (27), (24) and (25), one can find the contribution from the normal galaxies to the EGRB. The contribution from normal galaxies to EGRB comes out to be $\sim 2\times 10^{-7}$ photon cm^{-2} s^{-1} sr^{-1}.

5 STARBURST GALAXIES

5.1 Determination of γ-ray Luminosity Function

No starburst galaxy is detected so far in the 100 MeV – 10 GeV energy range. Only upper limits have been obtained on nearby starburst galaxies M82 and NGC 253. As in the case of normal galaxies, the γ-ray luminosity function of starburst galaxies cannot be constructed directly from γ-ray data.

The main processes that are responsible for γ-ray production in starburst galaxies are similar to those of normal galaxies. It is assumed that the constant $K_1 (= \frac{L_{\gamma_{\rm IC}}}{L_{\gamma_{\rm PP}} + L_{\gamma_{\rm EB}}})$ is the same as that for normal galaxies. The constants $K_2^{n^{\rm S}}$ and $K_2^{e^{\rm S}}$ (proportionality constants between cosmic ray production rate and star formation rate for starburst galaxies) are calculated by comparing SFR and cosmic-ray density of M82 and our galaxy. The average ISM density of starburst galaxies is assumed to be the same as that of normal galaxies,

$$K_2^{n^S} = \beta K_2^n ,$$
$$K_2^{e^S} = \beta K_2^e ,$$

and,

$$\beta = \frac{c^{\rm M82}}{c^{\rm MW}} \times \frac{\rm SFR_{MW}}{\rm SFR_{M82}} . \tag{28}$$

[It is assumed $c_n^{\rm M82} = c_e^{\rm M82} = c^{\rm M82}$.]

The γ-ray luminosity of a typical starburst galaxy can be expressed as

$$\begin{aligned} L_\gamma &= (1 + K_1) \times t \left[\frac{K_2^{n^{\rm S}}}{n_{\rm local}^n} Q_{\rm PP} + \frac{K_2^{e^{\rm S}}}{n_{\rm local}^e} Q_{\rm EB}\right] \times \left[\frac{\rm SFR}{V_{\rm eff}}\right] n_{\rm ISM} \times V_{\rm eff}, \\ L_\gamma &= (1 + K_1) \times t \left[\frac{K_2^{n^{\rm S}}}{n_{\rm local}^n} Q_{\rm PP} + \frac{K_2^{e^{\rm S}}}{n_{\rm local}^e} Q_{\rm EB}\right] \times n_{\rm ISM} {\rm SFR}, \\ L_\gamma &= (1 + K_1) \times \beta \times (1.9 \times 10^{33}) \\ &\quad \times [Q_{\rm PP} + Q_{\rm EB}] \times n_{\rm ISM}\, {\rm SFR}. \end{aligned} \tag{29}$$

Now, from Equations (15) and (29), one can write

$$L_\gamma(L, z) = \eta L_{\rm TIR}. \tag{30}$$

Therefore, the γ-ray luminosity function $[\phi_\gamma(L, z)]$ and total infrared luminosity function $[\phi_{\rm TIR}(L, z)]$ of starburst galaxies will be related as

$$\phi_\gamma(L, z)\, dL_\gamma = \phi_{\rm TIR}(L, z)\, dL_{\rm TIR}. \tag{31}$$

5.2 Contribution to the EGRB

Since total infrared luminosity and γ-ray luminosity are linearly related, it is possible to calculate the starburst galaxy contribution to the EGRB. From Equations (30) and (31), one can write,

$$L_{\gamma}\phi_{\gamma}(L,z)dL_{\gamma} = \eta \times L_{\rm TIR} \times \phi_{\rm TIR}(L,z)dL_{\rm TIR}. \tag{32}$$

So, the contribution to the EGRB can be found from Equations (25) and (32). The contribution to the EGRB from the redshift interval 0 to 2.6 has been calculated considering the total infrared luminosity density values (for different redshift bins) for both luminosity and density evolution given in Pérez-González et al. (2005). To calculate the contribution from redshift 2.6 to 5, we use the total infrared luminosity density profile given in Lagache et al. (2004). The infrared luminosity densities at various redshifts are found from figure 1 of their paper. Once we have the infrared luminosity densities at various redshifts, then using Equations (32) and (25), one can find their contribution to the EGRB. Since these luminosity functions and hence comoving luminosity densities are calculated for all star-forming galaxies, in order to get the comoving luminosity densities for only starburst galaxies, we subtracted the contribution from normal galaxies. The integrated photon flux from the starburst galaxy population comes out to be $\sim 7\times 10^{-7}$ photon cm^{-2} s^{-1} sr^{-1} (for β = 1.33). Considering the uncertainties of infrared luminosity densities as estimated by Pérez-González et al. (2005), the maximum starburst galaxy contribution becomes $\sim 6\%$ of the EGRB (Sreekumar et al. 1998).

6 DISCUSSION

Even though the new γ-ray missions AGILE & FGST are expected to significantly contribute to the field, EGRET, on board the CGRO satellite, has provided the best data set at present to characterize the diffuse extragalactic γ-ray background. The EGRET exposure across the full sky is non-uniform since the sky survey was largely derived from many individual viewings driven by observations of specific sources. Further, there have been systematic changes in the spark-chamber response due to reduction in detection efficiency arising from changes in the gas properties with use. The loss in detection efficiency has been recovered five times during the mission using gas refills on board. Esposito et al. (1999) discuss the approach taken to correct data for these time-dependent changes in the system response. Despite the best efforts in understanding the system response, these realities introduce uncertainties in the determination of the extragalactic diffuse background. The choice of model used to account for the Galactic diffuse emission also plays an important role in defining the final spectral and spatial uniformity of EGRB.

As stated earlier, the extragalactic γ-ray background can arise from truly diffuse processes or from cumulative contributions from many groups of γ-ray emitting sources which are, at present, spatially unresolved. Truly diffuse processes can include contributions from evaporation of primordial black holes, shocks in the intergalactic medium which up-scatter soft photons to γ-ray energies, decay of topological defects, etc. Hawking (1974) showed that black holes can evaporate. Small primordial black holes, which were formed by fluctuations in the early Universe, would radiate high energy photons which can contribute to a cosmic background. MacGibbon & Carr (1991) and Page & Hawking (1976) have calculated the integrated γ-ray emission from primordial black holes in the Universe. The predicted γ-ray spectrum from primordial black holes is $\sim 10^{-7}$ photon cm^{-2} s^{-1} sr^{-1} MeV^{-1} at 100 MeV and has a predicted spectrum characterized by a power law of index –3 above 120 MeV (Page & Hawking 1976). They predict γ-rays from primordial black hole emission could significantly contribute to EGRB between 50 and 600 MeV (see figure 5 in their paper).

During the merger of clusters of galaxies (large scale structure formation), the baryonic components are forced to move supersonically under the gravitational potential created mainly due to dark matter in the clusters. This process produces intergalactic shock waves which accelerate the electrons and hadrons. These highly relativistic electrons scatter a small fraction of the cosmic microwave background photons in the local universe up to γ-ray energies (Loeb & Waxman 2000; Gabici & Blasi 2003). The calculated

γ-ray spectrum from structure formation has a spectral index between –2 and –2.1 and the integrated flux above 100 MeV is 1%–10% of the observed background.

Bhattacharjee, Shafi & Stecker (1998) discussed production of Higgs bosons from cosmic topological defects. Decay of the Higgs and gauge bosons give rise to γ-rays. However, they concluded that this is expected to contribute significantly only above 1 GeV (see figure 1 in their paper).

Alternatively, as in the case of diffuse backgrounds at other frequencies, the γ-ray background can also be largely explained as arising from unresolved point sources. The natural choice of candidate sources will be those listed in the final γ-ray source catalog (Hartman et al. 1999). A sub-class of active galaxies viz., blazars, forms the largest class of identified extra-galactic γ-ray sources and hence substantial attention has gone towards predicting AGN contribution to EGRB (Stecker, Salamon & Malkan 1993; Chiang et al. 1995; Stecker & Salamon 1996; Chiang & Mukherjee 1998; Mücke & Pohl 2000; Narumoto & Totani 2006). The predictions vary from nearly 25% to 100%, indicating the degree of uncertainty in these calculations. In order to calculate the contribution from blazars to the EGRB, one needs to construct the luminosity function from a complete sample of blazars. Bhattacharya, Sreekumar & Mukherjee (2009) studied the γ-ray luminosity function and evolution of Flat Spectrum Radio Quasars (FSRQs) and BL Lacs separately. Carrying out standard $\langle \frac{V}{V_{\max}} \rangle$ tests, they found that BL Lacs do not show any evolution while FSRQs do exhibit evolution. Early results from FGST also support this conclusion (Abdo et al. 2009), though the luminosity function of BL Lacs determined from FGST data is found to be harder than that calculated for EGRET. These differences can arise from many factors. Being strongly time-variable sources, one needs to derive time-averaged source characteristics to address contributions of source classes to the background; the next two years of data from FGST should provide this. This consideration was incorporated into the characterization of EGRET-detected sources by taking averages across multiple observations spread across the full mission by Bhattacharya, Sreekumar & Mukherjee (2009). However, the limited number of EGRET detected sources prevented serious examination of both density and luminosity evolution of FSRQs. Within the next few years, FGST observation will provide a much more enhanced source list and hence a better determination of blazar luminosity function. AGN contribution to EGRB is discussed in detail in a companion paper. Here, we focus on the estimated contributions from normal and starburst galaxies.

Contributions of normal galaxies to EGRB have been addressed in the past by various authors (Strong, Wolfendale & Worrall 1976; Lichti, Bignami & Paul 1978; Pavlidou & Fields 2002). Strong, Wolfendale & Worrall (1976) considered no evolution of normal galaxies and found the contribution is a few percent ($<$5%) of the total EGRB. Lichti, Bignami & Paul (1978) included galactic evolution and found a much larger contribution. Pavlidou & Fields (2002) used the observational estimates of the cosmic star formation rate to model the evolution of normal galaxies in γ-rays. Kneiske (2008), using the model of Pavlidou & Fields (2002), reports that the γ-ray flux from normal galaxies are $\sim 6 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} and $\sim 2 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} for a star formation rate with and without dust correction, respectively.

The normal galaxy contribution discussed in our paper uses the detailed measurements of our galaxy (Hunter et al. 1997) to derive suitable scaling relations to extend the analysis beyond the Milky Way. The differential γ-ray photon spectrum of our galaxy can be approximated by a power law, $E^{-2.2}$. In this paper, it is assumed that this is representative of all normal and starburst galaxies.

For starburst galaxies, the contribution depends on the relative ratio (β) of cosmic ray enhancement per SFR w.r.t the Milky Way. To find the proportionality constants between cosmic ray production rate and SFR of starburst galaxies, M82 is taken as a standard. The proportionality constant is scaled to that of normal galaxies by comparing the average cosmic-ray density and SFR of our galaxy and M82. The SFR of M82 is calculated using Equation (16) which is 6 $M_{\odot}$ yr^{-1}. The cosmic-ray density of M82 is taken from Akyüz, Brouillet & Özel (1991). According to that paper, if scaling for dilution is to be made through the ratio of the total volume to the active volume of M82, then the ratio of mean cosmic-ray densities of M82 and our galaxy (relative to solar neighborhood value, i.e. $\frac{c^{\rm M82}}{c^{\rm MW}}$) becomes 4.17.

We applied the relationships derived in this paper to determine the γ-ray intensity (> 100 MeV) from nearby galaxies. The γ-ray luminosity value of LMC is estimated using Equations (16) and (21) as 2.6×10^{-7} photon $cm^{-2}s^{-1}$. This can be compared with the observed value (Sreekumar et al. 1992) of $1.9 \pm 0.4 \times 10^{-7}$ photon $cm^{-2}s^{-1}$. Since LMC is an irregular galaxy and we have calculated the expected γ-ray flux from the LMC by assuming that it is a normal galaxy like the Milky Way, small differences in the observed and calculated fluxes are expected.

The expected γ-ray emission for M31, M82 and NGC 253 are derived using Equations (16), (21) and (29). The FIR flux of M31 is taken from Saunders et al. (2000) and Rice et al. (1988). The FIR luminosity and, hence, the SFR of M82 and NGC 253 are calculated from Rice et al. (1988) which also matches previous estimates (Radovich, Kahanpää & Lemke 2001).

The expected γ-ray emission from these galaxies are compared with the derived γ-ray upper limits (Sreekumar et al. 1994; Paglione et al. 1996; Blom, Paglione & Carrami$\tilde{n}$ana 1999) as shown in Table 1. FGST, with a sensitivity limit of $\sim 1.5 \times 10^{-9}$ photon cm^{-2} s^{-1} (> 100 MeV) (Chen, Reyes & Ritz 2004; Michelson 2003), is expected to detect at least these nearby galaxies.

Table 1 Total Integrated Photon Flux (>100 MeV) for Nearby Galaxies

Galaxy	Predicted flux ($\frac{\rm photon}{\rm cm^2\ s}$)	EGRET upper limit
M31	2.7×10^{-9}	0.8×10^{-7}
M82	3.9×10^{-9} (for β= 1.33)	0.5×10^{-7}
NGC 253	3.8×10^{-9} (for β= 1.33)	1.0×10^{-7}

Thompson, Quataert & Waxman (2007) also estimated the contribution from starburst galaxies to the EGRB at 1GeV. They considered that γ-rays are only produced from neutral pion decay. They assumed that electrons lose energy mainly via synchrotron emission while evoking inverse Compton and bremsstrahlung losses to flatten the electron spectrum and ensure consistency with the measured radio synchrotron spectral index. However, EGRET observations (Hunter et al. 1997) show significant contribution from inverse Compton and bremsstrahlung processes in the energy range of 30 MeV–10 GeV. Thompson, Quataert & Waxman (2007) considered $\eta = 0.05$ (fraction of the supernova energy supplied to protons) i.e., 5% of the supernova energy is supplied to protons. The value of η has been discussed by various authors with values as high as 0.5 (Ellison & Eichler 1984; Ellison, Decourchelle & Ballet 2004). An η value > 0.05 may be necessary if the inverse Compton process and bremsstrahlung process contribute significantly to the electron energy loss. In another paper, Stecker (2007) estimated starburst galaxy contribution to EGRB which is a factor of 5 smaller than that estimated by Thompson, Quataert & Waxman (2007). In both papers (Stecker 2007; Thompson, Quataert & Waxman 2007), starburst galaxy contribution to EGRB is calculated as a fraction of the total infrared background that comes from starburst galaxies. Since this fraction is not well constrained, they obtained different results. In this paper, a more direct approach is adopted. Here, the luminosity function of star-forming galaxies is taken from Pérez-González et al. (2005), from which the starburst galaxy contribution is calculated.

The contribution from the normal and starburst galaxy populations to the extragalactic γ-ray background ($\sim$1 $\%$ and $\sim$6$\%$) is small but cannot be neglected. In particular, the enhanced cosmic-ray activity in starburst galaxies suggests significant production of γ-rays and, hence, is an important contributor to EGRB. Since the detected members of these two classes are either few or nil, the constants K_1, K_2^n and K_2^e are not well constrained at present. FGST will be able to detect additional normal and starburst galaxies. This will provide a direct measure of the β-factor necessary to derive improved estimates of starburst galaxy contribution to EGRB.

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