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Gamma-Ray Background: A Review

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Abstract The gamma-ray background is still a subject under great debate. All phenomena in the universe emitting gamma-rays can contribute directly as diffuse emission or as an isotropic component from unresolved point sources. The question of the origin of the extragalactic component cannot be answered without determining the galactic emission. To discuss in detail all models resulting in gamma-ray background contributions is far beyond the scope of this paper. Therefore the focus will be on recent publications on the extragalactic high energy (>100 MeV) part of the gamma-ray background.

Key words: gamma-rays: diffuse emission – observations theory – galaxies: starburst – active – luminosity function

1 INTRODUCTION

The first gamma photon ever detected by astronomers was a background photon possibly of galactic origin. Since then observations have improved and a lot of ideas have been introduced to explain the data. It is still under debate what causes diffuse emission. Is it isotropic radiation due to particle processes in our Galaxy or in the universe or just a faint residue by gamma-ray sources which are too dim to be detected by recent telescopes and observatories. The gamma-ray background signal is so important because it is a strict upper limit for theoretical models of possible contribution. For example, models including number density of the extragalactic contribution by unresolved point sources has to predict a gamma-ray flux which is below the observed signal. If gamma rays and neutrinos are produced in the same process, one can also derive an upper limit for the neutrino background using the extragalactic component of the diffuse gamma-ray observation. The paper will focus on energies above 100 MeV and is organized as follows. A brief summary of observations will be followed by the question how to determine the galactic flux. The next section will focus on different contributions by unresolved point sources after showing a general method for the calculation, including cascade emission which is initiated by the annihilation of gamma-ray and low energy background photons. In the last chapter other possible contribution will be discussed.

2 OBSERVATIONS

In 1965 Kraushaar published the first detection of a gamma-ray photon above 100 MeV. The total flux was $F = 3 \times 10^{-4}$ cm^{-2} s^{-1} sr^{-1} (Kraushaar et al. 1965) which is still a factor of 20 higher than the number of recent observations. A few years later the same authors published results of the OSO-3 satellite which not only showed an isotropic component but also could distinguish between a strong galactic and a fainter extragalactic component (Kraushaar et al. 1972). The first spectrum above 35 MeV could be derived with data from SAS-2 with a spectral index of –2.35 (Thomson & Fichtel 1982). This number is very close to the –2.1 which can be fitted to the extragalactic data taken with EGRET (Sreekumar 1998). GLAST which to be launched by the end of this or the beginning of next year will be able to improve the observation due to its much better resolution and sensitivity. After detecting the total signal the problem of distinguishing of galactic and extragalactic components occurs.

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3 GALACTIC EMISSION

The determination of galactic emission which is more than one order of magnitude higher is crucial. The sky map has to be divided into several regions to get different flux levels. The extragalactic component is assumed to be isotropic, which leads to the same flux and the same spectrum for each region. A theoretical model has to be developed for the galactic component (GB). A subtraction for each region with this model should lead to the same residue, which is the extragalactic component. The uncertainties can be reduced by fitting only the shape of the galactic flux but not the absolute value. By introducing a normalization factor (c_1) for each sky region the dependence on fluctuations in gas densities, in the interstellar radiation field and in the cosmic ray densities can be reduced. In our Galaxy the interactions of cosmic-ray protons with the interstellar gas and electrons interacting with stellar photons are believed to be the main mechanisms of gamma-ray emission. At MeV energies inverse Compton scattering and bremsstrahlung are dominating the flux, while the GeV photons are produced in neutral pion decay (Stecker 1977). A first analysis of Sreekumar et al. (1998) led to a spectrum which could be fitted by the power law with the spectral index of $\alpha = -2.1$. Using an updated galactic model, Strong, Moskalenko & Reimer (2004) recalculated the EGRET data and found a smaller flux with an excess above 1 GeV.

The idea that another galactic contribution could come from dark matter (DM) annihilation was presented by De Boer et al. (2005). The excess in the EGRET data above 1 GeV is then explained by a dark matter annihilation signal from Weakly Interacting Massive Particles (WIMPS) in a mass range from ≈ 50 to 100 GeV. The resulting extragalactic gamma-ray background was published by De Boer et al. (2007) and is closer to the results of Strong, Moskalenko & Reimer (2004).

This would lead to a formalism where for every given direction Ξ in the sky the flux can be written as

$$F_{\mathrm{obs}}(\Xi) = c_1 \cdot F_{\mathrm{GB}} + F_{\mathrm{EGB}} + c_2 \cdot F_{\mathrm{DM}} \,, \tag{1}$$

while the dark matter contribution is still under discussion. For example in a recent study Stecker, Hunter & Kniffen (2007) were re-examining in detail the so called GeV “anomaly”. They found that instead of an astrophysical phenomenon it could be explained by correcting the flux sensitivity of EGRET above 1 GeV. Their analysis confirmed the results by Sreekumar et al. (1998).

Another very detailed analysis of the background determination is published by Keshet, Waxman & Loeb (2004). They show that methods previously used to identify the Galactic emission depend on the Galactic tracers used and on the part of the sky examined. In comparison to the other results they found a quite low flux at 1 GeV in their analysis.

Keeping the problems of data analysis and galactic emission in mind we will proceed with possible interpretations of the extragalactic component.

4 FAINT COSMIC SOURCES

4.1 Method

To calculate the total flux contribution to the extragalactic background by a population of unresolved sources, the following equation is used

$$\frac{dN}{dE_\gamma \, d\Omega} = \frac{1}{4\pi} \int_0^{z_m} \frac{dV_c}{dz} \int_{L_{\mathrm{m}}}^{\infty} \frac{dN}{dV \, dL} \frac{dN^i}{dE_\gamma}(z) \, \mathrm{dL} \, \mathrm{dz}, \tag{2}$$

with $dN^i/dE_\gamma(z)$ as the intrinsic gamma-ray flux. dV_c/dz as the cosmological volume element, L_m as the total luminosity of the weakest source and the luminosity function $dN/(dV \; dL)$.

A template spectrum dN/dE_γ can be derived by averaging observed gamma-ray spectra for a certain source population. If no observations are available, a theoretical model has to be developed based on average parameters derived from observations in other wavelengths. Crucial for the calculation is the gamma-ray luminosity function $dN/(dLdV)$. If a statistical relevant number of sources have been detected in gamma rays a local luminosity function can be derived including a term for density and/or luminosity evolution. Without gamma-ray observations the luminosity function has to be calculated using observations in a different energy range and a correlation function.

4.2 Absorption and Cascade Emission

Is the gamma-ray spectrum of an extragalactic source extending to energies above ≈ 20 GeV, extragalactic absorption due to photon-photon pair production with low energy background photons has to be taken into account. The produced electron-positron pair is initiating an inverse Compton - pair cascade which leads to a gamma-ray flux by secondary photon production. For a simple analytical description equation 2 can be modified by taking absorption and the first generation of secondary gamma-ray photons from cascade emission into account

$$\begin{aligned}\frac{dN}{dE_\gamma\, d\Omega} &= \frac{1}{4\pi}\int_0^{z_m}\frac{dV_c}{dz}\int_{L_\mathrm{m}}^{\infty}\frac{dN}{dV\,dL}x \\ &x\ \left[\frac{dN^i}{dE_\gamma}(z)+\frac{dN^c}{dE_\gamma}(z)\right]\ e^{-\tau_{\gamma\gamma}(z)}\ \mathrm{dL\ dz_s},\end{aligned} \qquad (3)$$

with the cascade emission $dN^c/dE_\gamma(z, L)$ and pair creation optical depths $\tau_{\gamma\gamma} \gg 1$.

For a detailed calculation a monte carlo cascade code has to be used. The absorption is due to a photon background at ultraviolet, optical and infrared energies which is produced by stars in galaxies. The measurements of the so called extragalactic background light are leaving room for uncertainties within one order of magnitude. For other redshifts no direct observations can be obtained. Models for the extragalactic background light (EBL) have been developed by several authors (see the review by Hauser & Dwek 2001). To calculate the absorption and cascade emission for a population of sources at low and high redshift the redshift evolution of the EBL has to be taken into account (e.g. Salamon & Stecker 1998, Kneiske et al. 2002, 2004). The models include optically selected galaxies and infrared galaxies by spectral synthesis models, a cosmic star formation rate and the physics of the interstellar medium. The result is the optical to infrared flux as a function of redshift, where the optical part is due to direct starlight while the infrared emission is re-radiated starlight by interstellar dust. A model based on Kneiske et al. (2004) is shown for four selected redshifts in Fig. 1. The EBL model takes new observations into account by choosing values for model parameters as stated in figure 1.

The electrons and positrons interact via inverse Compton scattering with cosmic microwave photons. The interaction takes place at a distance of a few hundred Mpc to a few Gpc depending on the energy of the primary photon (Protheroe & Stanev 1993). This is outside of the large scale cosmic structure where the magnetic field is assumed to be very small. Depending on the actual strength of the magnetic field the secondary gamma-rays are beamed into the same direction as the primaries and would simply add to the primary flux. In case of a high magnetic field, they are distributed isotropically in a halo around the gamma-ray source.

4.3 Star Forming Galaxies

Based on the fact that high energy gamma-ray emission has been observed in our own Galaxy a so called guaranteed flux from other galaxies can be calculated. Pavlidou & Fields (2002) used a power law fit of the Galactic spectrum with a spectral break at 850 MeV, a total gas mass of $10^{10}\ M_\odot$, a gas density of 1 cm^{-3} and a star formation of 3.2 $M_\odot$ yr^{-1} to get luminosity at gamma-ray energies for a Milky-Way-like galaxy. Integrating the luminosity with the cosmic star formation rate up to a redshift of 5, they got a flux of 2 and 6×10^{-7} GeV cm^{-2} s^{-1} sr^{-1} for a star formation without and with dust correction respectively. Most of the flux is emitted by galaxies with redshifts smaller than $z = 1$.

The same authors have calculated contribution by unidentified EGRET sources (Pavlidou et al. 2007). The idea is, if these sources are of extragalactic origin they contribute as a distinct extragalactic population. If these sources are located within the Galaxy, their counterparts in external galaxies could contribute to the unresolved emission from theses systems. For this calculation two assumptions had to be made. The first is that all unidentified EGRET sources without counterpart are in fact one class of objects, so that a flux distribution can be obtained. The second assumption is that the flux distribution can be extrapolated to the faint end. The result is in agreement within the confident limits of the EGRET background data by Strong et al. (2004). This is quite interesting although it is questionable that unidentified EGRET sources can be taken as distinct class of objects.

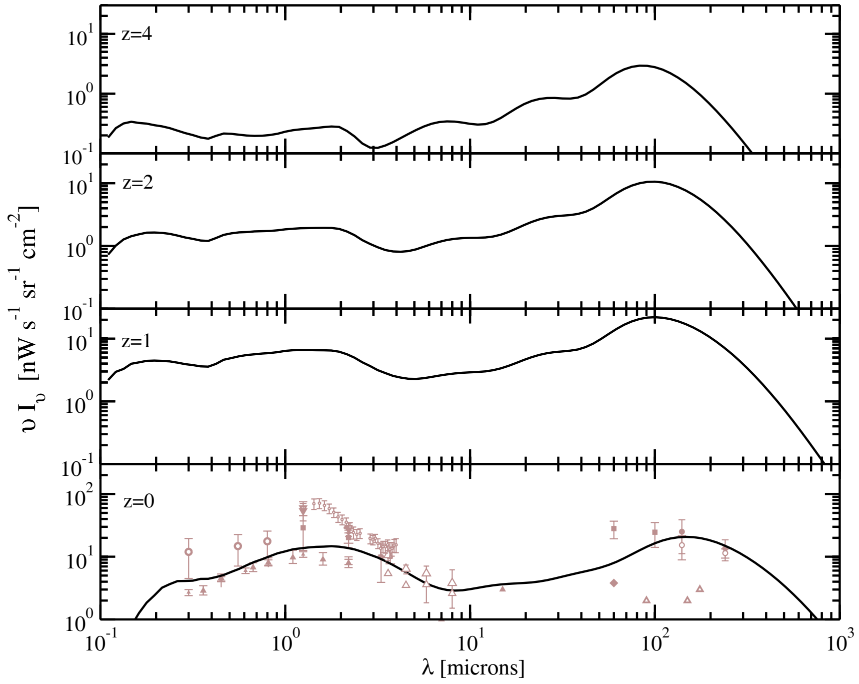

Fig. 1 The metagalactic radiation field for four selected redshifts. For data point references, a detailed model description and parameter definition see Kneiske et al. (2004, 2007). The values for the shown EBL model are: $\mathrm{SFR}_{\mathrm{opt}}$=(3.5, −1.2, 1.2, 0.1), $\mathrm{SFR}_{\mathrm{LIG}}$=(4.5, 0, 1.0, 0.1), f_{esc}=0; $c_2 = \mathrm{pow}(10, -23.4)$. They are chosen to account for recent observations by the infrared satellite SPITZER.

A more extreme class of star forming galaxies are the starburst and luminous infrared galaxies (LIG). They have high infrared luminosities, high gas densities and star formation rates which are a factor of ten higher than in the Milky Way. Therefore they are very good candidates for high energy gamma-ray emission although it has not been detected yet. Based on the assumption that relativistic protons lose nearly all their energy due to pion production within a luminous infrared galaxy and that the observed radio synchrotron flux is only emitted by secondary electrons Thompson, Quataert & Waxman (2006) came to a 10% contribution of the extragalactic gamma-ray background. In their calculation some of the favorable LIGs and starbursts (M82, NGC253, and IC342) should be observable with the next gamma-ray satellite GLAST. This result was questioned by Stecker (2006). He argued that even if the assumptions were correct, another problem occurred. The gamma-ray background calculation is normalized to the total local infrared luminosity density from the IRAS2Jy sample (Yun et al. 2001). From the radio-FIR relation, which seems to be also valid for starburst regions, a radio luminosity function at 1.4 GHz is calculated. And because of the assumption that the radio and the gamma-ray flux are both produced in pion decay, it is straightforward to derive a gamma-ray luminosity function. Stecker pointed out that not 100% of the local infrared luminosity density is due to emission from starbursts but rather 10%. Including the emission from starburst at higher redshift the percentage comes to about 23%. Therefore the contribution of starburst galaxies is a factor of five smaller.

4.4 Active Galactic Nuclei

Back in 1996 Stecker & Salamon calculated a contribution of blazars using a radio luminosity function and a linear correlation between radio and gamma-ray luminosity. They also included a flaring component of blazars taking the steepening of the spectrum into account. The result was that blazars could account for 100% of the observed flux. They added the effect of extragalactic absorption in Salamon & Stecker (1998). Chiang & Mukherjee (1998) showed that Stecker & Salamon had failed to reproduce the observed number

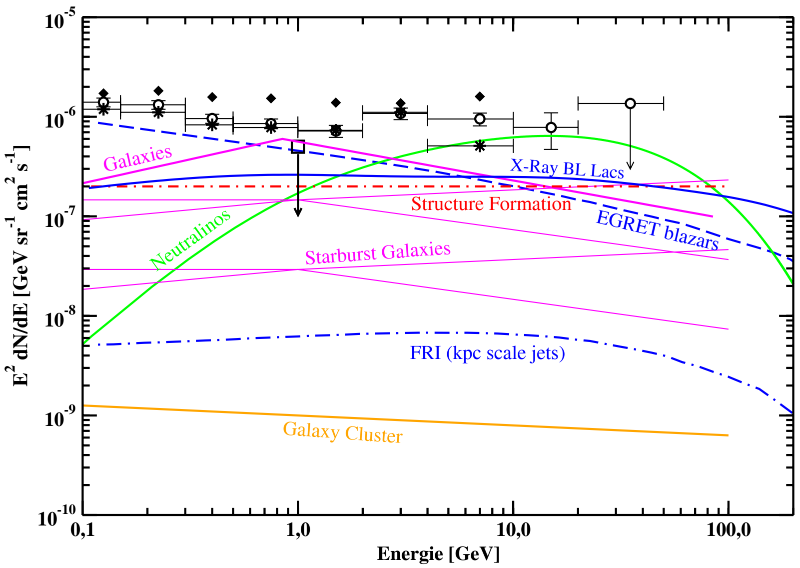

Fig. 2 Gamma-ray background contributions. Shown are contribution by normal galaxies (thick pink line; Pavlidou & Fields 2002); starburst galaxies (thin pink line; Thompson, Quataert & Waxman 2007); EGRET blazars (blue dashed line; Kneiske & Mannheim 2008); X-Ray BL Lacs (blue solid line; Kneiske & Mannehim 2008); Neutralinos (green solid line; Elsaesser & Mannheim 2005); FRI (kpc scale jets (blue dot-dashed line; Stawarz, Kneiske & Kataoka 2006); Galaxy Clusters solid orange line; Colafrancesco & Blasi 1998); Structure Formation (red dot-dashed line; Miniati 2002).

of sources detected by EGRET by overproducing the number at low redshift. Stecker (2001) argued that his assumption of a correlated radio and gamma-ray emission in blazars is contrary to the statistical independent analysis in CM98 which introduces a bias. Thus, the calculation in Chiang & Mukherjee (1998) using the EGRET luminosity function and a radio luminosity function for completeness came only to 25%–50% of the observed background flux. A simple correlation between luminosities is always a source of uncertainty so other models started with multiwavelength spectra. Giommi et al. (2005) modeled a synchrotron self Compton spectrum for blazars. The spectrum was normalized to radio and X-ray data. Using a radio luminosity function they could reproduce the X-ray background very well but had problems at higher energies. Other models by Muecke & Pohl (2000) included a contribution of BL Lacs and Flat Spectrum Radio Quasars separately. From this calculation 40%–80% of the background are due to unresolved AGN. This work was updated recently by Dermer (2007) where he used a physical model to fit the redshift and size distribution of EGRET blazars.

A contribution of secondary gamma-rays from BL Lacs has been calculated by Kneiske & Mannheim (2008). Direct emission of X-ray BL Lac (XBL) can only make a minor contribution, since the maximum of high energy emission is at TeV energies. But the secondary gamma-rays have energies about two orders of magnitude below the primary photons. An X-ray luminosity function showing almost no evolution has been used. The result was a contribution of about 10% to the observed GeV background which is almost all due to secondary flux.

A similar calculation has been done by Stawarz, Kneiske & Kataoka (2006) for the extended jet emission from Faranoff-Riley (FR) galaxies. Assuming that the observed X-ray emission in the bright knots of the kiloparsec scale jets are due to synchrotron emission, a gamma-ray flux can be calculated. Including the secondary gamma-ray photons we found that only 1% of the gamma-ray background could be explained by the extended luminosity of FRI galaxies.

4.5 Gamma-Ray Bursts

In the analysis by Casanova, Dingus & Zhang (2007) the contribution of gamma-ray bursts have been calculated. A power-law for the synchrotron and inverse Compton component has been used where the inverse Compton flux is higher by a factor of ten. Extragalactic absorption has been taken into account too. The result is a 10% contribution at GeV energies.

4.6 Galaxy clusters

Galaxy clusters have not been detected by EGRET, but an analysis by Scharf & Mukherjee (2002) has shown that a possible correlation exists between high Galactic latitude EGRET data and Abell clusters ($\geq 3\ \sigma$). They have shown that 447 of the richest clusters with a bolometric luminosity of $L \approx 10^{44}$ erg s^{-1} and no evolution could explain about 1% to 10% of the gamma-ray background.

A more theoretical calculation by Colafrancesco & Blasi (1998) is based on a self-consistent picture of cluster formation and evolution. The model starts from a primordial density perturbation spectrum, and a realistic modeling for the distribution of the intergalactic medium. They found that an evolving population of clusters can only produce up to 2% of the observed flux.

5 OTHER CONTRIBUTIONS

Other ideas have been published on the origin of the extragalactic gamma-ray background, like matter-antimatter annihilation (e.g. Stecker, Morgan & Bredekamp 1971, Cohen, Rujula & Glashow 1998) or the decaying of primordial black holes (MacGibbon & Carr 1991). Purely diffuse orgins were discussed in Stecker 1973. The resulting spectra are quite different from what has been observed with EGRET, so it is very unlikely to have a significant contribution from this processes. Some of the more recent results are the following.

Elsaesser & Mannheim (2005) used high resolution simulations of structure formation to calculate contribution with a maximum around 10 GeV from neutralino annihilation in cold dark matter halos. They found a neutralino mass of 515 GeV for their best-fit model.

Gravitational induced shock waves produced during cluster mergers and large-scale structure formation give rise to highly relativistic electrons that are responsible for inverse Compton scattering of the cosmic microwave background photons to GeV energies. A contribution to the gamma-ray background is produced in filaments, sheets, and extended gamma-ray halos associated with massive cluster (Loeb & Waxman 2000). Similar to this Miniati (2002) found that cosmic rays of cosmological origin can account for about 20% of the gamma-ray background. In his calculation 30% of the computed flux is emitted by the decay of neutral pions generated in p-p collisions of the ionic cosmic-ray component with the thermal gas.

In Dado, Dar & Rujula (2007) the authors explain the extragalactic gamma-ray background by inverse Compton scattering of the cosmic microwave background and stellar photons by cosmic-ray electrons in the interstellar and intergalactic space. In their work they get a much higher galactic contribution from cosmic-ray electrons in the Galactic halo. The extragalactic emission is calculated from electrons ejected by supernova explosions and AGN.

A fluctuation analysis could give a better understanding which of the many possible origins are dominating. The angular power spectrum of intensity fluctuations of the extragalactic gamma-ray background measured in the future by GLAST could probe its origin (Miniati et al. 2007).

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