The Guaranteed Gamma-ray Background

Vasiliki Pavlidou and Brian D. Fields
Center of Theoretical Astrophysics, Department of Astronomy,
University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

Abstract

The diffuse extragalactic gamma-ray background (EGRB) above 100 MeV encodes unique information about high-energy processes in the universe. The systems certain to make *some* contribution to the EGRB are blazars and normal galaxies. We evaluate their combined contribution to the background using the Stecker-Salamon model for the blazar component and a new calculation for the normal galaxy component. Assuming that most of the gamma-ray emission from normal galaxies is due to cosmic-ray interactions with diffuse gas, we use cosmic star formation rate observations to follow the evolution of the cosmic ray flux and the gas content of normal galaxies. We find that normal galaxies are responsible for a significant portion ($\sim 1/3$) of the EGRB near 1 GeV, but make a smaller contribution at other energies. The combined spectrum of this 2-component model is an excellent fit to the EGRET observations of the EGRB spectrum. Finally, we discuss a series of observational tests for the two-component model which can be performed by future gamma-ray observatories such as GLAST.

1. Introduction

All-sky γ-ray observations by SAS 2 (Fichtel et al. 1977; Fichtel, Simpson & Thompson 1978) and most recently by EGRET (Sreekumar et al. 1998) have revealed the existence of an isotropic diffuse $\gamma-$ray emission, presumably of extragalactic origin. A variety of possible contributions to the EGRB have been proposed. There are, however, two classes of $\gamma-$ray sources whose existence has been observationally established and thus guarantees that these make *some* contribution to the EGRB: blazars and normal galaxies.

Blazars comprise the vast majority of the identified $\gamma-$ray point sources detected by EGRET (Hartman et al. 1999). It is therefore only logical to argue that a population of unresolved blazars has to be the origin of a significant portion of the EGRB. Given the EGRET results on blazars, Salamon & Stecker (1994) and Stecker & Salamon (1996, hereafter SS96) made a detailed calculation of the

pp. 1–7

blazar contribution to the EGRB and indeed found it to be dominant, although the shape of the predicted blazar emission energy spectrum does not match the flatter spectrum of the latest EGRET EGRB determination (Sreekumar et al. 1998).

While the EGRET catalog of point sources is dominated by blazars, the EGRET diffuse flux is dominated by emission from the Galactic plane. The latter is, for the most part, the result of the decay of neutral pions produced when cosmic rays interact with the interstellar medium. The superposition of this diffuse $\gamma-$ray emission from all unresolved normal galaxies is the second guaranteed source of extragalactic background $\gamma-$ray intensity.

We define the sum of the $\gamma-$ray emission from all unresolved blazars and from all unresolved normal galaxies to be the guaranteed EGRB. If the intensity level of the guaranteed EGRB can be confidently estimated, then by comparison to the observed EGRB one can constrain the observationally allowed contributions from any other hypothesized sources.

Here, we summarize a new calculation (Pavlidou & Fields 2002) of the contribution of normal galaxies to the EGRB. We use observational estimates of the cosmic star formation rate (CSFR) to model the evolution of normal galaxy $\gamma-$ray emission. To the latter, we then add the blazar component of the spectrum as given by SS96. Our results are computed for the currently favored $\Omega_\Lambda = 0.7$, $\Omega_{\rm m} = 0.3$ cosmology. The resulting minimal two-component model proves to be an excellent fit to the observed EGRET EGRB spectrum for energies up to 15 GeV, where $\gamma-$ray extinction is not important. For further discussion, see Pavlidou & Fields (2002).

2. Formalism

The observable quantity which describes the EGRB is the differential intensity $dI_E/d\Omega$. In a flat universe with matter density parameter $\Omega_{\rm m}$ and vacuum energy density parameter $\Omega_\Lambda = 1 - \Omega_{\rm m}$, the differential intensity detected at t_0 due to a population of $\gamma-$ray sources with collective comoving differential $\gamma-$ray emissivity density $\dot{n}_{\gamma,{\rm com}}$ will be

$$\frac{dI_E}{d\Omega} = \frac{c}{4\pi H_0} \int \frac{\dot{n}_{\gamma,{\rm com}}[z,(1+z)E]}{\sqrt{\Omega_\Lambda + \Omega_{\rm m}(1+z)^3}} dz \ . \quad (1)$$

In the case of blazars, SS96 have calculated $\dot{n}_{\gamma,{\rm com}}$ considering blazars to be in either one of two states, flaring and quiescent, and for an $\Omega_{\rm m} = 1$ cosmology. We have adapted their model to our preferred cosmology, keeping all other parameters the same.

In the case of normal galaxies, $\dot{n}_{\gamma,\rm com}$ can be expressed in terms of the CSFR function $\dot{\rho}_\star(z)$ (mass being converted to stars per unit time per unit comoving volume). We assume that: (1) the high mass end of the initial mass function (IMF) is universal, and thus the star formation rate ψ (mass being converted to stars per unit time) is always proportional to the supernova explosion rate in the same galaxy; (2) the cosmic ray flux in a galaxy is proportional to ψ and the cosmic ray spectral shape is universal (see Fields et al. 2001); and (3) at any cosmic epoch the cosmic ray escape properties are the same as in the present Milky Way, and any γ-rays produced after escape are negligible. The emissivity density will then be

$$\dot{n}_{\gamma,\rm com}(z,E) = L_{\gamma,\rm MW}(E)\frac{\dot{\rho}_\star(z)}{\psi_{\rm MW}}\frac{\mu(z)}{\mu(0)}\ , \tag{2}$$

Note that, due to our assumptions, the conversion of a certain amount of gas into stars will result to the production of the same amount of γ rays from CR-ISM interactions *regardless of the way the star formation is distributed among galaxies*. The factor $\mu(z)/\mu(0)$ (ratio of gas mass fractions between epoch z and the present) has been introduced to account for the increase of target atoms at earlier cosmic epochs and assumes a "closed box" galaxy.

3. Inputs

In computing the normal galaxy contribution to the EGRB we use the analytic fit of the CSFR evolution given by Cole et al. (2001). We will refer to their fit of data points (not) corrected for dust extinction as the ("uncorrected") "dust-corrected" CSFR.

The shape of the differential diffuse $\gamma-$ray (number) luminosity of the Milky Way, $L_{\gamma,\rm MW}$ is deduced using EGRET observations of the $\gamma-$ray *flux* from the Galactic plane. The EGRET flux spectrum can be well fitted by a double power law, of spectral indices -1.52 for energies below $850\,\rm MeV$ and -2.39 for higher energies. The normalization of the (number) luminosity spectrum can be determined from the requirement that $\int_{100\,\rm MeV}^{\infty} L_{\gamma,\rm MW}(E)dE = q_\gamma(>100\,\rm MeV)\mathcal{N}_{\rm H,MW}$ where $q_\gamma(>100\,\rm MeV)$ is the total $\gamma-$ray emissivity per hydrogen atom and $\mathcal{N}_{\rm H,MW}$ is the number of H atoms in the MW (detailed fit appears in Pavlidou & Fields 2002).

For the MW star formation rate we use $\psi_{\rm MW} = 3.2\,\rm M_\odot\,yr^{-1}$ (McKee 1989) which lies in the upper end of the available estimates and therefore leads to a conservative estimate of the normal galaxy EGRB component. For the MW gas mass fraction today we adopt $\mu_{0,\rm MW} = 0.14$. Finally, we use $z_\star = 5$ for the redshift for which star formation begins.

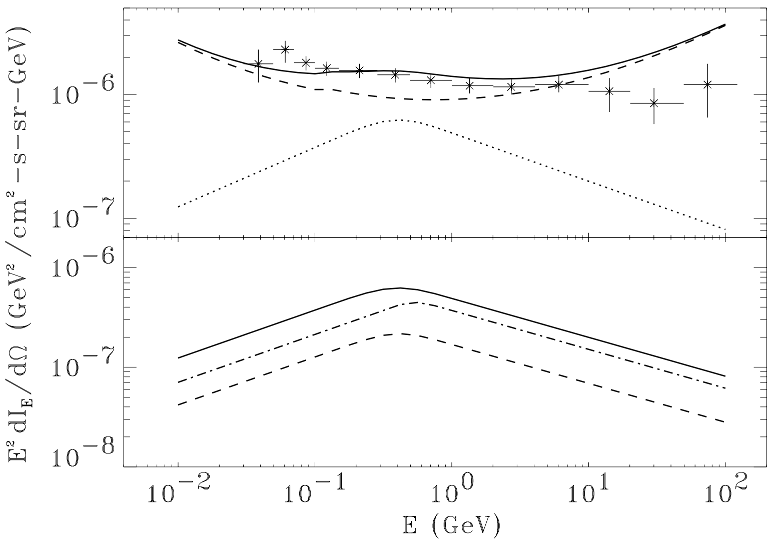

Fig. 1. Upper panel: Blazar (dashed line) and normal galaxy (dotted line) contributions to the EGRB, overplotted with the summed spectrum (solid line) and the EGRET data points from Sreekumar et al. (1998). Lower panel: Normal galaxy spectrum for a dust-corrected CSFR (solid line), uncorrected CSFR (dashed line) and dust-corrected CSFR with the integration only extending up to $z_\star = 1$ (dot-dashed line).

4. Results

The spectrum of the normal galaxy contribution to the EGRB, for a dust-corrected CSFR, is plotted in the upper panel of Fig. 1. In the same plot, we have overplotted the blazar contribution as calculated from the SS96 model and for our preferred cosmology, as well as the "minimal" two-component model of the guaranteed EGRB. This summed spectrum has a flatter shape than either of its constituent spectra due to the fact that the maximum of the convex normal galaxy curve happens to lie in the same energy regime with the minimum of the concave blazar spectrum.

The "minimal model" is in excellent agreement with the observational data points from EGRET (Sreekumar et al. 1998), both in amplitude and in spectral shape, for energies up to 15 GeV. For higher energies, absorption effects due to pair production, which have not been treated here, become important, and the reader should be aware that our spectra should be reduced by about a factor ~ 2; The effect of pair producion absorption on blazar spectra has been studied by Salamon & Stecker (1998).

Uncertainties in our normal galaxy spectrum calculation are introduced due to uncertainties in the determination of $\dot{\rho}_\star(z)$, $M_{\rm gas,MW}$, $\mu_{0,\rm MW}$ and $q_{\gamma,\rm MW}$. Of our input parameters, $\psi_{\rm MW}$ and $q_{\gamma,\rm MW}$ enter our calculation as multiplicative factors and therefore uncertainties in their values do not affect the shape of the spectrum, but only the overall normalization (introducing an overall uncertainty of a factor ~ 4). Our results are relatively insensitive to the value of $M_{\rm gas,MW}$ since a change in its value affects the calculation through $L_{\gamma,\rm MW}$ and $\mu_{0,\rm MW}$ in opposite directions. In addition, our calculation shows that most of the background intensity in the normal galaxy component originates from $z < 1$. Therefore, our results are not affected significantly by the CSFR evolution at $z > 1$ where the CSFR uncertainties can reach an order of magnitude. This fact is demonstrated in the lower panel of Fig. 1., where we have plotted the normal galaxy spectrum for both the dust-corrected CSFR and the uncorrected CSFR, together with the spectrum derived for a dust-corrected CSFR in the extreme case where *no* star formation is assumed to have taken place at $z > 1$. The difference from the full integration up to $z = 5$ is less than a factor of 2. We note that in the latter case, the peak of the spectrum is displaced towards higher energies. On the other hand, if the CSFR was much higher at high redshifts, as suggested recently by Lanzetta et al. (2002), this would displace the peak of the spectrum towards lower energies.

5. Discussion

The minimal 2-component model of the EGRB can be tested and improved in various ways when observations from future γ - ray telescopes such as GLAST become available.

On the one hand, the improved point source sensitivity of GLAST will allow it to resolve more blazars (~ 100 more than EGRET, Stecker & Salamon 1999), and therefore the blazar contribution to the EGRB will be reduced by about a factor of 2. If unresolved blazars are the only constituent of the EGRB, the *fractional change* of the EGRB will be the same as the fractional change of the background blazar emission. If, however, there is a second component in the EGRB (in our case, that of normal galaxies), the fractional change of the EGRB should be smaller.

On the other hand, with the blazar component reduced by a factor of 2, our calculated normal galaxy contribution will become comparable to that of blazars for energies ~ 1GeV. Therefore, if the relative contributions of blazars and normal galaxies to the minimal model are comparable to our estimates, the shape of the EGRB spectrum should start to exhibit a (detectable in principle) deviation from its single power-law form at ~ 1 GeV, corresponding to the normal galaxy spectrum peak. Were this peak detected, the relative contribution of normal galaxies to the EGRB could be determined observationally.

In addition, the observations of GLAST can be used to improve the minimal model and its predictions, by allowing a better determination of the observational inputs for the SS96 blazar model, as pointed out by Stecker & Salamon (1999), and by testing our assumption of the universality of the galactic diffuse gamma-ray emission spectrum, as GLAST is expected to detect several Local Group galaxies (the SMC, LMC, M31 and maybe M33; Pavlidou & Fields 2001).

Finally, with both guaranteed EGRB components well-understood, one can better identify or constrain any other components and any new physics which might generate them.

V.P. acknowleges an Amelia Earhart Fellowship, and a student grant from the conference; she thanks the organizers for their hospitality and an enlightening and stimulating conference. This work was supported in part by the National Science Foundation under Grant No. AST-0092939.

6. List of Symbols

$a = (1+z)^{-1}$

$dI_E/d\Omega = dN_\gamma/(dtdAdEd\Omega)$

$\dot{\rho}_\star(z)$=CSFR

t_0=present cosmic epoch

H_0 = Hubble parameter at t_0

$\dot{n}_{\gamma,\rm com}(z,E) = dN_\gamma/(dtdV_{\rm com}dE)$

ψ = SFR of a galaxy

μ = gas mass fraction of a galaxy

7. References

1. Cole, S. et al. 2001, MNRAS, 326, 255
2. Fichtel, C. E., et al. 1977, ApJ, 217, L9
3. Fichtel, C. E., Simpson, G. A., & Thompson, D. J. 1978, ApJ, 222, 833
4. Fields, B. D., Olive, K. A., Cassé, M., & Vangioni-Flam, E. 2001, A&A, 370, 623
5. Hartman, R. C. et al. 1999, ApJS, 123, 79
6. Lanzetta, K. M. et al. 2002, ApJ, 570, 492
7. McKee, C. F. 1989, ApJ, 345, 782
8. Pavlidou, V., & Fields, B.D. 2001, ApJ, 558, 63
9. Pavlidou, V. & Fields, B.D. 2002, ApJ, 575, L5
10. Salamon, M. H. & Stecker, F. W. 1994, ApJ, 430, L21
11. Salamon, M. H. & Stecker, F. W. 1998, ApJ, 493, 547
12. Sreekumar, P. et al. 1998, ApJ, 494, 523
13. Stecker, F. W. & Salamon, M. H. 1996, ApJ, 464, 600 (SS96)
14. Stecker, F. W. & Salamon, M. H. 1999, Proc. 26th ICRC, 3, 313