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Testing the origin of the extragalactic gamma ray background by modelling its high energy spectrum

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Abstract. The origin of the Extragalactic Gamma Ray Background (EGRB) is still a matter of discussion. With the increasing number of detected gamma ray point sources, it becomes increasingly likely that the seemingly diffuse EGRB is a superposition of the radiation of still unresolved point sources. Most models describe the gamma radiation of these point sources in accordance with the Unified Scheme (US) of Active Galactic Nuclei (AGN) as generated through a process of inverse Compton scattering in relativistically beamed plasma blobs in blazars. Earlier theoretical calculations of the contribution of these point sources to the EGRB have failed to consider the anisotropic beaming characteristics of the blazars. We show that it is possible to model the EGRB on the basis of the assumption that it is generated by unresolved blazars when these anisotropic effects are properly taken into account. Furthermore we demonstrate, using the example of an idealised blazar model, that predictions of the EGRB-spectrum at high energies can be made, which can in principle be used to test whether the EGRB is generated by unresolved blazars. We argue that the principle of that test applies not only to blazars, but also to every possible point source with anisotropic beaming pattern.

Key words: galaxies: active – cosmology: diffuse radiation – gamma rays: theory

1. Introduction

Observations with the Energetic Gamma-Ray Experiment Telescope (EGRET) on the Compton Gamma Ray Observatory (CGRO), launched on April 5th 1991, enabled scientists to map the sky at very high photon energies. The measurements revealed an extended gamma radiation from the Milky Way (see e.g. Kniffen et al. 1996), several point sources including extragalactic ones, and in addition the existence of a background component – the EGRB (e.g. Sreekumar et al. 1998, Pohl et al. 1997). The origins of the latter are still in question, but with the increasing number of gamma ray point sources also detected with CGRO, a possible explanation could be, that at least part of it could be produced by unresolved sources. Possible candidate sources are blazars, which produce gamma radiation by scattering photons in relativistically beamed plasma blobs through an inverse Compton process (for review see e.g. Sikora et al. 1997, Urry & Padovani 1995, Longair 1981, Rees 1966, Dermer 1997, Dermer & Schlickeiser 1992, Montigny 1997, Ribicki & Lightman 1979, Pohl et al. 1997, Blandford & Königl 1979, Scheuer & Readhead 1979, Reynolds 1982). Therefore, they show a strongly anisotropic beaming pattern. The bulk of the energy as well as the highest photon energies are scattered into a small cone centered on the jet axis. We will discuss an idealised model of these sources in Sect. 2.

It is apparent that every source that is able to produce gamma radiation will contribute to the EGRB if the source is not resolved by present-day detectors. The EGRET detector, even though today by far the best, leave much room for this possibility. In this case blazars viewed from all possible angles can contribute to the EGRB. Calculating the blazars' contribution to the EGRB on the basis of observations of those blazars that can be observed directly can be misleading under certain circumstances. On this subject see for example Erlykin & Wolfendale 1995. With regard to the anisotropic beaming pattern, blazars with jet axis pointing roughly toward the observer are far more likely to be observed than others. But these others also contribute to the EGRB, and they outnumber the aligned ones, even though direct observation may not be possible. Here we will calculate the contribution of "misaligned blazars" to the EGRB. On the basis of an idealised model (Sect. 2), we will model the EGRB (Sect. 3). We will then demonstrate that this way it may be possible to predict the at present only poorly known high energetic end of the EGRB that could in principle be used to resolve the question of its origins in the future (Sect. 4). Our model was picked for easy exposition, to see properties that are helpful clarifying the central point of the argument. The calculations could and should be repeated on the basis of other models.

2. Model of the active galactic nulei

Our calculations are based on a slightly altered version of the blazarmodel presented by Dermer et al. 1992, (DSM) (See also Schlickeiser 1996.). Near the center of an active galactic nucleus

Send offprint requests to: B. Weferling is a black hole surrounded by an accretion disk. A jet is formed along the rotation axis of the black hole. It is still uncertain as to which kind of material these jets consist of and which physical processes form these structures (see e.g. Blandford & Rees 1978). In this work we assume the jet plasma to consist of a mixture of electrons and positrons. Unless mentioned otherwise, in the following we will refer to both electrons and positrons, even when we only speak of electrons, because in all the calculations they can be handled the same way. We assume furthermore that this plasma moves along the jet in separated components called blobs. Accretion disk photons illuminate these blobs. (In fact, some other target photon sources can and should be considered in more detailed models. For example, stars, dust clouds, the microwave background, synchroton radiation, and others can be such sources, see e.g. Böttcher et al. 1996). These target photons react with the plasma electrons. Because the electrons are highly relativistic, they scatter the photons to higher energies by inverse Compton scattering, thus producing the gamma rays. Fig. 1 of DSM shows the model diagram. For the calculation of the observable gamma-ray flux of such a source and to model the EGRB we assume the following:

(1) The highly relativistic electrons have an isotropic energy distribution in the rest frame of the blob (BF).
(2) The core of the AGN emits target photons isotropically in the observer's frame (OF).
(3) The target photons enter the blob directly from behind. This is a good approximation if the blob is sufficiently far from the core. (Dermer & Schlickeiser 1993.) (This assumption produces a characteristic beaming pattern which is useful for the explanation of some principal effects we will discuss later; therefore, we do not consider more realistic assumptions here.)
(4) The target photons are monoenergetic with the energy $\bar{\epsilon}^*$. (All energies are in terms of the electron rest energy if not noted otherwise and asterisks refer to quantities in the OF, whereas an index s referes to scattered quantities.) This assumption is a good approximation because earlier studies of the inverse Compton process (e.g. Schlickeiser 1979) have revealed only a slight dependence of the Compton scattered photon flux on the target photon energy distribution.
(5) The blob is optically thin to Thompson scattering along the jet axis. Under the circumstances considered, the inverse Compton process can always be treated as a Thompson scattering.
(6) The target photons are moving inside the jet on trajectories parallel to the jet axis. This is realistic if the blob is sufficiently far from the core.
(7) The energy distribution of the electrons in the blob is given by a restricted power law:

$$n_e(\gamma) = n_0\gamma^{-s}$$

for

$$1 \ll \gamma_1 \leq \gamma \leq \gamma_2$$

and zero otherwise.
(8) The distribution of the orientations of the jet axes of blazars is isotropic. This is in accordance with the cosmological principle.

We then obtain the scattered inverse Compton flux as received by an observer (see DSM):

$$S_s^{rec}(\epsilon_s^*) = \frac{V_b\sigma_T\Phi_0 n_0}{8\pi r^2}D^2\eta^{\frac{(s+1)}{2}}(\frac{\epsilon_s^*}{\bar{\epsilon}^*})^{\frac{(1-s)}{2}} \quad (1)$$

for $\eta\bar{\epsilon}^*\gamma_1^2 \leq \epsilon_s^* \leq \eta\bar{\epsilon}^*\gamma_2^2$, and zero otherwise. Therein ϵ_s^* is the observed scattered energy, V_b the volume of the blob, σ_T the Thompson scattering cross section, Φ_0 the target photon flux, n_0 the electron density, r the distance of the blob from the core. Furthermore, D denotes the familiar Doppler factor:

$$D = [\Gamma(1 - B\mu_s^*)]^{-1} \quad (2)$$

and we have used the abbrevation:

$$\eta = \frac{1 + \beta B - \mu_s^*(\beta \cdot B)}{(1 + B)\Gamma^2(1 - B\mu_s^*)^2} \simeq D^2(1 - \mu_s^*) \quad (3)$$

with Γ the blob's Lorentz factor, Bc the bulk velocity of the blob (c the velocity of light) and βc the velocity of the electrons; μ_s^* is the cosine of the angle between the blob's velocity vector (jet axis) and the direction to the observer. The latter approximation holds for $\beta \simeq 1$. The cutoffs of the spectrum described by Eq. (1) are due to the cutoffs in the electron energy distribution and can easily be modelled more realistically. We furthermore find the dependence of the scattered photon energy on the viewing angle to be

$$\epsilon_s^* = \bar{\epsilon}^*\eta\gamma^2 \ . \quad (4)$$

The total amount of scattered energy as a function of the viewing angle is in principle given by

$$F_1(s, \mu_s^*) = D^{3+s}(1 - \mu_s^*)^{(s+1)/2} \ . \quad (5)$$

According to the DSM-model Eqs. (4) and (5) describe the beaming pattern of the blazar, see Figs. 1 and 2. They attain their maximum values in the vicinity of the superluminal direction where the superluminal effect is greatest, thus explaining why many alligned blazars are strong gamma ray point sources showing superluminal effects.

3. The contribution of blazars to the EGRB

All unresolved blazars, as far as they produce gamma radiation at all, contribute to the EGRB. As Sect. 2 demonstrates, blazars are very likely to show a strong angular dependence of their gamma radiation. Therefore, it can be misleading to calculate their contribution on the basis of the observations of resolved blazars because their jet axis will tend to be in close alignment with the direction to the observer. The spectra from blazars of all possible viewing angles will combine in their contribution to the EGRB. It is therefore neccessary to calculate a spectrum that is averaged over all viewing angles. We find, based on the

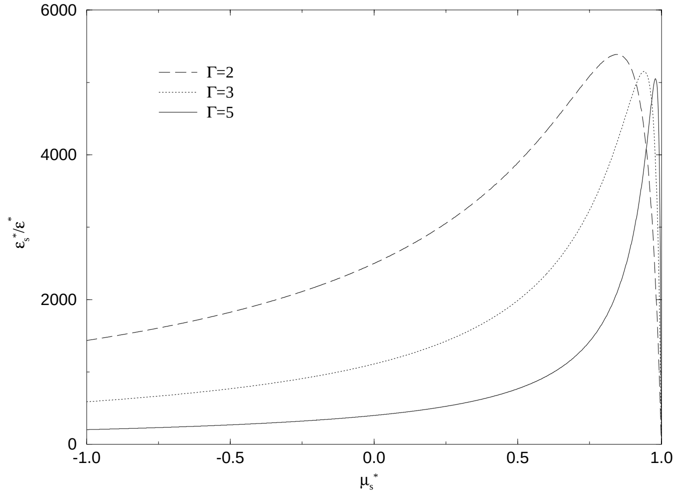

Fig. 1. The beaming pattern of the blazar according to the DSM-model. The figure shows $\epsilon_s^*/\overline{\epsilon}^*$ as a function of the scattering angle for different values of Γ, as given by Eq. (4).

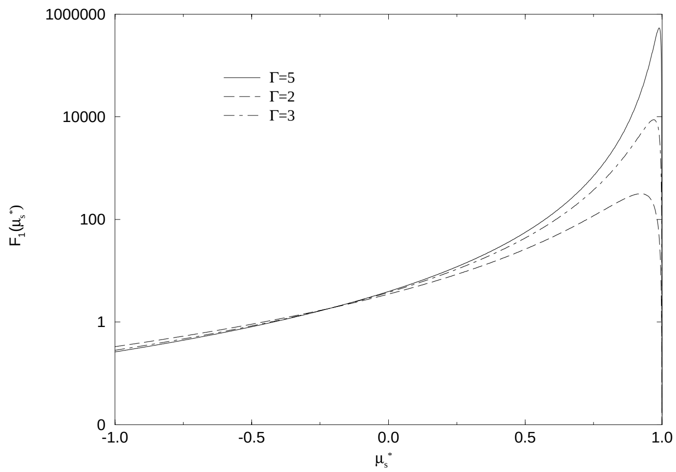

Fig. 2. The beaming pattern of the blazar according to the DSM-model. The figure shows the principal angular dependence of the total amount of scattered energy, given by the function F_1 for different values of Γ, Eq. (5).

results of Sect. 2, that such a spectrum is given by:

$$\overline{S}_s^{rec}(\epsilon_s^*) = \frac{1}{2}\int\limits_{Max[\mu^*_{s,low},-1]}^{Min[\mu^*_{s,high},1]} \frac{V_b\sigma_T\Phi_0 n_0}{8\pi r^2} D^2 \eta^{\frac{(s+1)}{2}} \times \left(\frac{\epsilon_s^*}{\overline{\epsilon}^*}\right)^{\frac{(1-s)}{2}} d\mu_s^* \quad (6)$$

for $\epsilon^*_{s,min} \leq \epsilon^*_s \leq \epsilon^*_{s,max}$ and zero otherwise. The maximal and minimal energies are given by

$$\epsilon^*_{s,max} = \frac{\overline{\epsilon}^*\gamma_2^2}{4(B\Gamma^2 - B^2\Gamma^2)} \quad (7)$$

and

$$\epsilon^*_{s,min} = \frac{2\overline{\epsilon}^*\gamma_1^2}{\Gamma(1+B)} \ . \quad (8)$$

One has to consider the integration limits of the integral in Eq. (6). The limits can get narrower than 1 and -1, according to the beaming pattern given by Eq. (4) they are given by:

$$\mu^*_{s,low} = \frac{2B\epsilon_s^*\Gamma^2 - \overline{\epsilon}^*\gamma_2^2 - \sqrt{w}}{2B^2\epsilon_s^*\Gamma^2} \ , \quad (9)$$

$$\mu^*_{s,high} = \frac{2B\epsilon_s^*\Gamma^2 - \overline{\epsilon}^*\gamma_2^2 + \sqrt{w}}{2B^2\epsilon_s^*\Gamma^2} \ . \quad (10)$$

where we have used

$$w = -4B^2\epsilon_s^*\Gamma^2(\epsilon_s^*\Gamma^2 - \overline{\epsilon}^*\gamma_2^2) + (-2B\epsilon_s^*\Gamma^2 + \overline{\epsilon}^*\gamma_2^2)^2 \ . \quad (11)$$

as an abbrevation.

We can now use these results to calculate the contribution of blazars to the EGRB. We will develop an approach that includes the considerations about the angle-averaged spectrum and will then derive predictions that allows to test the origin of the EGRB s hows up.

Not only blazars of all viewing angles but all possible blazars can contribute to the EGRB. According to the model, the blazars can be distinguished by their inner parameters. In principle, it is necessary to know the number of unresolved blazars producing gamma radiation, as well as how many blazars can be described by a given set of parameters. The function N should give exactly that last number, whereas A should stand for the overall number of blazars which contribute to the EGRB. The global distribution function N is dependent on all intrinsic parameters. In our case:

$$N = N(\Gamma, V_b, r, \overline{\epsilon}^*, n_0, s, \gamma_1, \gamma_2, \Phi_0, \mu_s^*) \ . \quad (12)$$

We can also express the recieved flux of a blazar (Eq. (1)) as:

$$\overline{S}_s^{rec} = S_s^{rec}(\Gamma, V_b, r, \overline{\epsilon}^*, n_0, s, \gamma_1, \gamma_2, \Phi_0, \mu_s^*, \epsilon_s^*) \ . \quad (13)$$

A and N are connected through

$$A = \int\limits_0^\infty \cdots \int\limits_0^\infty \int\limits_{-1}^1 N d\Gamma\, dV_b\, dr\, d\overline{\epsilon}^*\, dn_0\, ds\, d\gamma_1\, d\gamma_2\, d\Phi_0\, d\mu_s^* . \quad (14)$$

The contribution of the blazars to the EGRB is then given by

$$S_{EGRB}(\epsilon_s^*) = \int\limits_0^\infty \cdots \int\limits_0^\infty \int\limits_{Max[\mu^*_{s,low},-1]}^{Min[\mu^*_{s,high},1]} N \times S_s^{rec} d\Gamma \cdots d\mu_s^* . \quad (15)$$

The only dependence of N that we really know for sure is the one on the viewing angle. In this regard all angles are equal. The other dependencies are subject to further studies. We use a simplified approach by regarding these dependencies as deltafunctions. Thus, the central point becomes clear and besides we can easily vary the parameters to model the EGRB. We find that Eq. (15) in that case is equivalent to

$$S_{EGRB}(\epsilon_s^*) = 2 \cdot A \cdot \overline{S}_s^{rec}(\epsilon_s^*) \ . \quad (16)$$

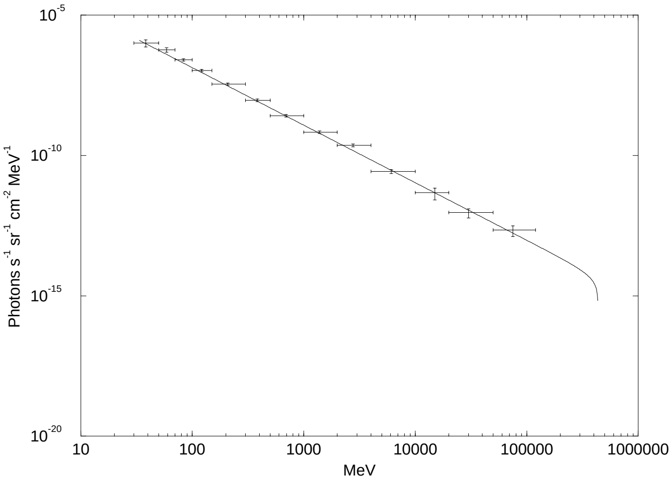

Fig. 3. Our model EGRB for parameter values s=3.1, $\Gamma = 3$, $r = 5.0 \cdot 10^{15}\,cm$, $n_0 = 14.1\,cm^{-3}$, $\overline{\epsilon}^* = 9.8 \cdot 10^{-5}$, $\gamma_2 = 130000$, $\gamma_1 = 1400$, $A = 50 \cdot 10^6$, $V_b = 4.1888 \cdot 10^{48}\,cm^3$, $\Phi_0 = 250\,cm^{-2}\,s^{-1}$. The figure also shows the EGRB as measured by Sreekumar et al. 1998.

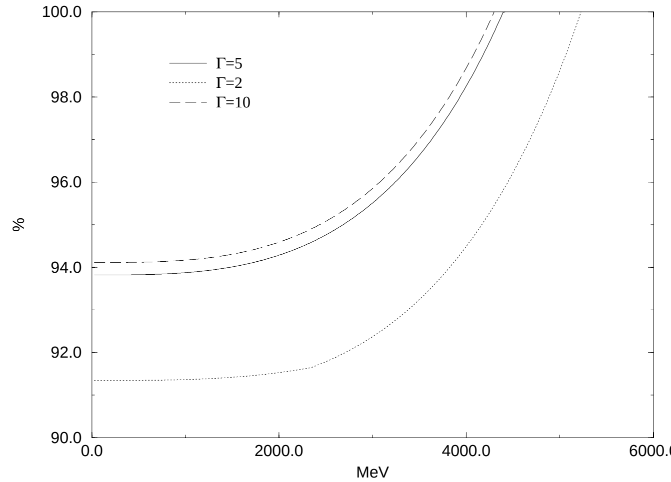

Fig. 4. The figure shows the percentage of energy that is scattered in the direction between $0°$ and $2 \cdot \Theta_{SL}$, with Θ_{SL} the cosinus of the angle under which superluminal effects are greatest, at a given photon energy. We choose $s = 3$, $\gamma_2 = 25000$, $\gamma_1 = 500$ and Γ=2; 5 and 10.

4. Testing the origin of the EGRB

Eq. (16) demonstrates that the contribution of the blazars to the EGRB depends in every case (not just in the simplified one) on the characteristics of the sources' beaming pattern, because the angle-averaged spectrum is involved. In the case chosen, this contribution is proportional to $\overline{S}_s^{rec}(\epsilon_s^*)$, a spectrum that is in principle not plain observable but may play a significant role in the EGRB. If we can find a set of parameters so that the spectrum calculated with Eq. 16 is in accordance with the measured spectrum of the EGRB, we can most importantly verify the hypothesis that blazars could contribute significantly to the EGRB. This is with regard to the correct approach that considers the anisot ropic effects and not just on the basis of the insufficient approach that merely considers the observed blazars. As Fig. 3 shows the answer is yes.

It is possible to model the EGRB according to Eq. (16) in many different ways. We have shown just one possibility. The reason that this modelling is successful under the correct approach, is that for large enough Γ, the radiation of a blazar in the direction of the jet axis is so dominant over the radiation into the other directions that it outweights the effect that the misaligned blazars outnumber the aligned ones by far. Fig. 4 illustrates this argument. Here a blazar is considered to be aligned when $0 \leq \mu_s^* \leq \mu_{SL}$, with μ_{SL} the cosinus of the angle between the jet axis and the direction under which the observed superluminal effects are greatest, Θ_{SL}. A blazar with $\Gamma = 5$ scatters at all photon energies a minimum of nearly 94% of the total scattered energy in directions where the blazar would be considered aligned. This effect is even stronger for higher values of Γ and according to Eq. (6) less dramatic for lower ones. In addition to that one can define the exact meaning of "alligned" in other, less restrictive ways so that the contribution of the misaligned blazars can be well over 10%. So in this limit of large enough Γ the frequently used standard approach seems to be a fair approximation.

But the correct approach shows details that do not show up when the EGRB is modeled in the previous fashion with a direct blazar spectrum, because a direct blazar spectrum is solely an inverse Compton spectrum which can be described by a power law. We see at the high energy end of the calculated spectrum that it loses intensity in a characteristic manner. This is due to the fact that only blazars with a specifically aligned jet axis can contribute at those energies. See Fig. 4. We find the effect mathematically described in Eqs. (6) – (11): the intregral closes over the beaming pattern. In principle, it should be possible to use this effect to test if the blazars make a major contribution to the EGRB. The effect demonstrated here based on a very simple jet-model will play a role regardless of what model is used and what type of blazar population is considered. It is very unlikely that another natural phenomenon shows the same high energy end of its spectrum as that described by a narrowing integral over the very special beaming pattern of an anisotropically radiating blazar. In principle, calculations such as these make predictions about the high energy end of the EGRB that can be verified by better measurements in the future, although they lie outside the possibilities of the detectors today. It should be noted that for more exotic models of the blazars or other forms of the function N, the characteristic breakdown at the high energy end may look different. In addition, it must not directly be connected to the part of the spectrum that can be approximated by a power law. Rather, these connections could in theory be within a wide range of shapes but can be expected to be relatively common due to reasonable restrictions to the parameters; a broken power law could be one of the more likely possibilities. The authors will work on that in the future.

It should also be noted that the same effect shows up not only in the EGRB, but in all kinds of seemingly diffuse radiation that is the superposition of anisotropically radiating point sources.

We propose to examine the effects of the correct approach on the different models of the EGRB presented so far, to determine the predictions they would make. We furthermore propose to measure the high energy end of the EGRB. When the question of its origin will have been solved, and it turns out that blazars are the origins in question, we may turn the argument around and use the EGRB for blazarstudies because they will be strongly restricted by it. The kind of AGN that can in fact exist in the cosmos depends on what we can see in the EGRB.

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