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BL Lac contribution to the extragalactic gamma-ray background

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Very high energy gamma-rays ($E_\gamma > 20$ GeV) from extragalactic gamma-ray sources traversing cosmological distances through the metagalactic radiation field can be converted to electron-positron pairs in photon-photon collisions. The converted gamma rays initiate electromagnetic cascades driven by inverse-Compton (IC) scattering off the cosmic microwave background (CMB) photons, leading to faint gamma-ray halos. We show that including both components, the primary jet emission and the secondary halo emission of faint undetected blazars, radio-loud AGNs can explain the spectral shape and the total flux of the extragalactic gamma-ray background above 300 MeV as measured by EGRET. From this result we can predict the number of BL Lacs as a function of redshift that can be observed by Cherenkov telescopes, depending on their flux limits and energy thresholds. We can also put some meaningful limits on critical jet parameters for extragalactic radio sources, for example the magnetic field in kpc-scale jets of FR I radio galaxies.

1. Introduction

The extragalactic gamma-ray background detected by EGRET (Energetic Gamma-Ray Experiment Telescope) has extended the spectrum of diffuse, isotropic emission up to an energy of ∼50 GeV. Using a gamma-ray luminosity function and an average spectral index from the observed EGRET blazars [1] only 25% to 50% of the gamma background could be explained by blazars.

The idea presented in this paper is to extend the existing models by assuming a population of BL Lacs with a spectral energy distribution such that their flux at EGRET energies is too low to be generally detected, while their very high energy gamma-ray flux is strong. Since most of these sources are at redshifts high enough for pair attenuation to take place, a significant part of their VHE emission is reprocessed by cascades contributing to the diffuse background, but not to the single source counts. We can extend this model assuming the grand unified scheme for *radio-laud* AGNs, where BL Lac and FRI galaxies are the same objects observed at different viewing angles, *and hence surrounded by the same isotropic faint gamma-ray halos due to analogous inner parts of the jets*. FRI galaxies show also high energy *(optical and X-ray) synchrotron* emission in the knots of their kpc scale jets, and *thus* might be able to produce *some additional* gamma-rays *thereby* [2]. Therefore, *here* we discuss *also* the contribution of large scale jet emission of a population of FRI-galaxies *to the extragalactic gamma-ray background*.

In this paper we use a Hubble constant of $H_0 = 71$km s^{-1} Mpc^{-1}, $\Omega_{\rm M}$=0.27 and Ω_Λ=0.73.

2. EGRET blazars

The luminosity function of resolved EGRET sources, extended to the faint end has been computed by [1]. We use their model for undetected blazars changing only the spectral index from $\alpha = 2.1$ to $\alpha = 2.33$. The new spectral index was determined by fitting the reanalyzed EGRET data at < 2.0 GeV. We also include the effect of extragalactic absorption and halo emission. The absorption of the primary photons is calculated using the ”best-fit” model for metagalactic radiation field (MRF) presented in [3], and the re-emission is calculated using an analytical approximation [4] for the IC emission due to the interaction of the electron-positron pairs and the CMB.

3. BL Lac

The main part of the remaining excess of the measured gamma-ray background we ascribe to high-energy peaked blazars (HBL). The spectral energy distribution of these sources between 100 MeV and 30 TeV and their luminosity function in gamma-rays (gamma-LF) is poorly known, and we have to make some theoretical assumptions, which will be discussed in more detail in [4] and [5] and only summarized in this section.

As a template for BL Lacs we use a gamma-ray spectrum with two power laws. The choice of parameters is in agreement with the observations of Mkn501, which is one of the most studied BL Lacs in high energy gamma-rays. Other observed sources like Mkn421 and 1ES1995+650 are showing a very similar spectral shape, so that a spectrum with a spectral index of $\alpha = 1.7$ for $E_\gamma < 3$ TeV and $\alpha = 2.3$ for higher energies is a good approximation for an HBL population.

H1426+428 is a BL Lac which is located at higher redshift (z=0.129) and therefore much more luminous. The spectrum could have a maximum at much higher energies than the high peaked BL Lacs [6]. To take such sources into account we study a contribution of a very small (<10%) population of extreme BL Lacs to the extralagactic gamma-ray background. We assume a spectral index of $\alpha = 1.2$ with a maximum at 10 TeV. The parameters are chosen to fit the calculated intrinsic spectrum and the observations of H1426+428 (ExBL) (see [6]).

To derive the gamma-LF for a population of HBLs we use [7] which combines all available data leading to an X-ray luminosity function for BL Lacs. HBL are X-ray selected BL Lacs showing indications of correlated X-ray/gamma-ray emission. Combining the X-ray LF and a relation between the gamma-ray flux above 3 TeV and X-ray flux at 1 keV from the calculations presented in [8] we are able to derive a gamma-LF which can be written as a broken power law

$$\frac{dN}{dV\,dL_{0,\mathrm{TeV}}} \propto (L_{0,\mathrm{TeV}})^{\alpha_{\mathrm{LF}}} \tag{1}$$

where $\alpha_{\mathrm{LF}} = -1.9$ for $L_{0,\mathrm{TeV}} \leq L_{\mathrm{B}}$ and $\alpha_{\mathrm{LF}} = -2.4$ for $L_{0,\mathrm{TeV}} > L_B$ a break luminosity L_B and no evolution. Including the ExBL population we define that only the bright end ($L_{(\mathrm{TeV})} > 4.2 \cdot 10^{-4}$ 10^{-48}erg s^{-1}) of the LF have ExBL spectra while the main part of the LF is assumed to represent the HBLs.

4. FRI galaxies

We used the data for all FR I radio galaxies with kpc-scale radio jets detected also at higher (X-ray) frequencies. By fitting a broken power-law to the collected radio-to-X-ray synchrotron continua, we reconstructed the template energy distribution of the radiating electrons, from which we computed the unabsorbed γ-ray emission due to inverse-Compton (IC) scattering on the starlight photon field (a detailed description of the model is presented in [9]). The resulting intrinsic IC luminosity *of the 'typical' FR I jet*, $L_\gamma(\varepsilon)$, consists of a power-law part $\propto \varepsilon^{-0.75}$ at photon energies $\varepsilon <$ GeV, break region between 1 GeV and 100 GeV, and a steep power-law for $\varepsilon \geq 100$ GeV. Under the minimum-power hypothesis (corresponding to the equipartition jet magnetic field 300 μG), the bolometric IC jet luminosity should be comparable to the radio luminosity of the source. This enables us to derive the gamma-ray luminosity function for the kpc-scale FR I jets from the radio luminosity function characterizing low-power radio galaxies. We took the latter one in a form discussed by [10],

$$\frac{dN}{dV\, d\log L_\gamma} = \begin{cases} \rho_0 \left(\frac{L_\gamma}{L_{\rm cr}}\right)^{-\alpha} \exp\left(\frac{-L_\gamma}{L_{\rm cr}}\right) (1+z)^k & \text{for} \quad z < z_{\rm cr} \\ \rho_0 \left(\frac{L_\gamma}{L_{\rm cr}}\right)^{-\alpha} \exp\left(\frac{-L_\gamma}{L_{\rm cr}}\right) (1+z_{\rm cr})^k & \text{for} \quad z \geq z_{\rm cr} \end{cases} , \tag{2}$$

and converted it to the cosmological model used in this paper. Note that with the jet magnetic field lower than the assumed equipartition value, jet gamma-ray emission would increase.

5. Results

The results for the various contributions to the extragalactic gamma-ray background are shown in Figure 1. The thin solid line denotes the EGRET blazar contribution. Due to the new spectral index, the change of cosmological parameters, the additional halo emission and the reanalyzed EGRET data, the unresolved EGRET blazars now produce about 78% of the background flux. The dot-dashed line represents the background flux due to the HBL population which can account for about 20%, while the dotted line describes the flux corresponding to an ExBL contribution (which would contribute only 0.5% to the total EGRET flux above 100 MeV).

Comparing the total flux as a sum of the three contributions and the EGRET data, the agreement is acceptable. The primary flux of the BL Lac population produces only a small contribution in the EGRET energy range. The secondary photons can contribute about 20% to the gamma-ray background.

Whipple with an energy threshold of 300 GeV and a flux limit of 10^{-11} cm^{-2} s^{-1} would be able to detect only 30 sources at redshifts $z < 0.2$. This number has to be divided by about a factor of 4 to account for the Imaging-Air-Cherenkov-Telescope (IACT) observation method. So the result is in agreement with the results of the first generation of IACT. The next generation of IACTs should be able to detect a factor of 10 more sources up to redshifts of one or even two, depending on the energy threshold and fluxlimits.

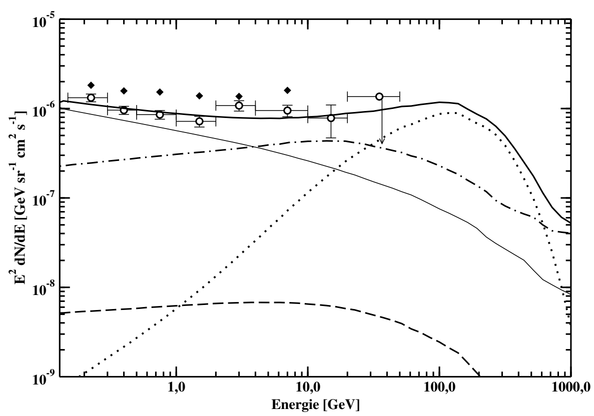

Figure 1. Spectrum of the extragalactic gamma-ray background. The total spectrum is produced by four components: EGRET sources with a spectral index of 1.33 (thin solid line), HBL (dot-dashed line), ExBL (dotted line) and FRI galaxies (dashed line). For all four components the effect of extragalactic absorption and reemission via inverse Compton scattering is taken into account. Data are taken from [13] and [14].

The contribution from large-scale jets of FRI galaxies to the EGRET background is only about 0.5% (see dashed line). Indeed much larger contribution of these objects is not expected, since accordingly to the analysis presented above blazar sources can account for the bulk of the extragalactic gamma-ray background. On the other hand, this result excluded weak (sub-equipartition) magnetic fields within kpc-scale FR I jets, as discussed in [9].

The cascades from strong extragalactic magnetic fields are leading to a diffuse halo around the gamma-ray source. If FRI galaxies and BL Lac objects are the same their halo emission should also be the same as well. This implies that BL Lac objects should also show a halo component due to their large scale jet emission, FRI galaxies should show the halo emission due to the inner jet gamma-ray emission. To calculate the complete halo emission as a contribution to the gamma-ray background, a model for a combined FRI-BL Lac population is needed. This includes consistent assumptions about parameters of small and large scale jets and will be discussed elsewhere.

6. Conclusions

To explain the gamma-ray background at energies higher than 100 MeV an assumption of a steeper spectrum for EGRET blazars is made. This is very plausible given the flux-spectral index relation for blazars [11]. The assumption is that the observed EGRET blazars are the brightest, and therefore they are not necessarily indicative of the general population. The weaker undetected sources with a steeper spectrum would be the main contributors to the gamma-ray background emission. Adding the diffuse halo flux from a high peaked blazar population can then account for the total observed background flux. The spectral shape is also in good agreement and a third component due to extreme blazar cannot be excluded before GLAST is able to detect the gamma-ray background at energies at 100 GeV. Note that BL Lacs cannot explain the data points at 3 GeV and 7 GeV. Assuming the new analysis of EGRET data is correct another contribution is needed to explain this feature, like the flux from neutrino annihilation described in [12].

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