Publ. Astron. Obs. Belgrade No. 91 (2012), 249 - 254 *Contributed paper*

COSMOLOGICAL COSMIC-RAY CONTRIBUTION TO THE EXTRAGALACTIC GAMMA-RAY BACKGROUND

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Abstract. The extragalactic gamma-ray background measured by The Fermi Gamma-Ray Space Telescope is substantially different from previous measurements. Fermi has clarified that the dominant emission mechanism comes from cosmic-ray interactions with interstellar gas in normal galaxies. We present a constraint of cosmological cosmic-ray contribution to the extragalactic gamma-ray background. Even though normal galaxies seem to be dominant component, they still fall short to explain measured gamma-ray background at highest energies, thus another source has to be taken into consideration. Using models of evolution of cosmic accretion shock, we calculate pionic gamma-ray source-function for cosmological cosmic rays independent of redshift. We show that cosmological cosmic rays could even dominate the extragalactic gamma-ray background at highest energies. We also show that measured background can well be explained by these two cosmic-ray components - normal star-forming galaxies and cosmological cosmic rays.

1. INTRODUCTION

Existence of cosmological cosmic rays is still hypothetical as they are yet to be detected. By observing extragalactic gamma-ray background (EGRB) it may be possible to learn more about this cosmic-ray (CR) population, and/or constrain their maximal contribution to the EGRB. CRs that originate from structure-formation processes were already considered as contributing component of the EGRB (see e.g. Prodanović & Fields 2004). However, since history of these sources is unknown, in order for their maximal contribution to EGRB to be constrained, it had to be assumed that all of these CRs originate from a single redshift. Here we revisit this analysis but with also implementing source evolution. Namely, we consider accretion shocks that arise during the formation of the largest scale structures such as filaments, to be accelerating CRs (so called structure-forming cosmic rays or SFCRs). We use Pavlidou & Fields (2006) evolution model of structure-formation shocks and assume that it directly reflects on the evolution of SFCRs. This way we can calculate for the first time the evolved source function of cosmological CRs, which gives us their summarized contribution (from all redshifts) to the EGRB. With a more realistic model that includes source evolution, and with the new EGRB *Fermi* data (Abdo *et. al.* 2010), we can now obtain a stronger constraint on the SFCR contribution to the EGRB.

2. GAMMA-RAY BACKGROUND

The dominant component of diffuse gamma-ray sky comes from the Galactic disk. Since diffuse gamma-rays were also detected away from the Galactic disk and even in directions towards Galactic poles, it became clear that an extragalactic gamma-ray component is also present (e.g. Hunter et al. 1997). EGRB was first detected via SAS-2 satellite and then with EGRET and *Fermi* LAT (see e.g. Abdo *et. al.* 2010). There are many extragalactic sources that can contribute to the EGRB. There are point sources like unresolved star-forming galaxies which are guaranteed to contribute (Pavlidou & Fields 2002), active galactic nuclei and blazars (e.g. Stecker & Salamon 1996, Narumoto & Totani 2007) which are the brightest extragalactic sources. Also, there could potentially be some truly diffuse sources contributing to the EGRB, like interactions of CRs that originate from the process of formation of large scale structures, or even annihilation or decay of dark matter.

Contribution of unresolved normal galaxies to the EGRB turned out to be dominant (Fields, Pavlidou & Prodanović 2010). Specifically, CRs accelerated in supernova remnants of star-forming galaxies interact with the gas of the host galaxy and produce gamma-rays mainly via

$$\mathrm{p_{cr}} + \mathrm{p_{ism}} \rightarrow \pi^0 \rightarrow \gamma + \gamma, \tag{1}$$

the so called pionic γ-rays. In this equation $\mathrm{p_{cr}}$ represents a cosmic-ray proton, $\mathrm{p_{ism}}$ a proton from interstellar medium and π^0 is a pion. Even though normal galaxies are much fainter than blazars, they are by far more common and thus their contribution to the EGRB is greater. However, another source of γ-rays has to be considered in order to produce a better fit at the high energy end of the observed spectrum, where there is indication that the spectrum breaks. Here we consider SFCRs as that source, which produce γ-rays through the same above mentioned process. We use the observed break in the EGRB spectrum to place stronger upper limit on the SFCR contribution to the EGRB. Since SFCRs are still a hypothetical cosmic-ray population that is yet to be observed, this new constraint will help us build a better picture of their origin and history, which in turn provides another insight into the process of formation of large-scale structures, and constrains any other subdominant source.

3. COSMOLOGICAL COSMIC-RAYS

Gamma-ray intensity in some direction at energy ϵ (see e.g. Prodanović & Fields 2004) can be calculated from:

$$I(\epsilon) = \frac{1}{4\pi} \int \Gamma(\epsilon) n_{\mathrm{H}}(\mathbf{r}) \mathrm{d}s \tag{2}$$

where ϵ is rest-frame energy, $\Gamma(\epsilon)$ is pionic γ photon production rate per hydrogen atom and n_{H} is local density of hydrogen atoms. In this equation absorption and reflection of γ-rays is neglected because they are very small at energies $\epsilon \gtrsim 20\,\mathrm{GeV}$ (see e.g. Madau & Phinney 1996, Salamon & Stecker 1998). In the case of extragalactic emission radiation comimg from different redshifts gamma-ray intensity becomes:

$$I(\epsilon_{\mathrm{obs}}) = \frac{1}{H_0} \int \frac{n_{\mathrm{H,com}}(z)\Gamma[(1+z)\,\epsilon_{\mathrm{obs}}, z]}{(1+z)\mathcal{H}(z)}\, \mathrm{d}z \tag{3}$$

where $n_{\rm H,com}$ is the co-moving hydrogen density, $\epsilon_{\rm obs}$ is the observed gamma-ray energy and

$$\mathcal{H} = H(z)/H_0 = \sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_\Lambda} \tag{4}$$

is dimensionless expansion rate of the Universe. Cosmological constant and matter density parameters are Ω_Λ and $\Omega_{\rm m}$ respectively. Pionic γ-ray source function $\Gamma(\epsilon)$ can be represented by semi-analytical formula (Pfrommer & Enßlin 2003) where the redshift dependance follows from energy dependance:

$$\Gamma(z) = \mathrm{C}(z)\left[\left(\frac{2\epsilon_{\rm obs}(1+z)}{m_{\pi^0}}\right)^{\delta_\gamma} + \left(\frac{2\epsilon_{\rm obs}(1+z)}{m_{\pi^0}}\right)^{-\delta_\gamma}\right]^{-\alpha_\gamma/\delta_\gamma} = \mathrm{C}(z)q_\gamma(z) \tag{5}$$

The α_γ is the SFCR spectral index, which is equal to the high-energy end slope of the pionic γ-ray spectrum they produce (Dermer 1986). Following the work of Fields & Prodanović (2005) and Suzuki & Inoue (2002) the value of the spectral index that we used is $\alpha_\gamma = \alpha_{\rm p} = 2.2$ which corresponds to CRs accelerated in strong shocks. Spectral index is used to define the source function shape parameter $\delta_\gamma = 0.14\,\alpha_\gamma^{-1.6} + 0.44$. Pion mass is taken to be $m_{\pi^0} = 135$MeV and C is the normalization parameter. The normalization will be set by maximizing the SFCR spectrum with respect to the EGRB, where normal-galaxy contribution taken from Fields, Pavlidou & Prodanović (2010) was first subtracted from the EGRB. The redshift-dependant function q_γ encodes the shape of the γ-ray spectrum. Figure 1 shows a single-redshift maximal SFCR source function, calculated and plotted for a range of redshifts. We see that the EGRB spectrum at the highest energies is well matched with a slope $\alpha_\gamma = 2.2$.

Structure-formation process evolves over a range of redshifts, and thus SFCRs that originate from it, should also evolve. However, since the evolution of SFCRs as γ-ray sources is unknown, the evolution of formation of large scale structures will serve as its tracer.

3. 1. THE EVOLVED SOURCE FUNCTION

During the formation of large scale structures, shock waves of very large dimensions are being created. One type of these shock waves are accretion shock waves. They are created when gravitationally collapsed objects accrete more material. Although these shocks are described with a range of Mach numbers depending on the mass of the collapsed structure, we have for now assumed that all accretion shocks are strong, in order to obtain the upper limit on the SFCR contribution to the EGRB.

The analytic model of Pavlidou & Fields (2006) describes the overall evolution of accretion shocks, and we use that as our evolution tracer. In their work, the (baryonic) mass current density J_1 is defined as the rate at witch mass crosses surface of a single shock around the structure of mass m at an epoch z (in units $M_\odot\,{\rm yr}^{-1}\,{\rm Mpc}^{-3}$).

$$J_1 = \frac{\Omega_{\rm bar}}{\Omega_{\rm mat}}\frac{{\rm d}m}{{\rm d}t} \tag{6}$$

This tells about the power that goes into accretion shocks at a given redshift, and will in turn tell us about the relative flux of SFCR γ-rays from different redshifts. We use

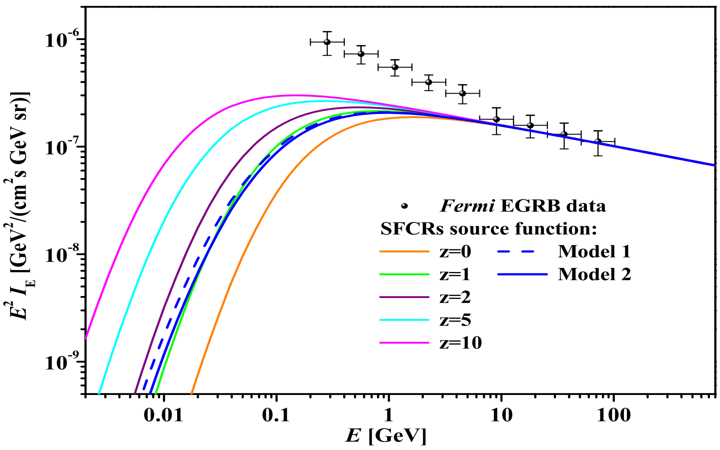

Figure 1: SFCR source functions calculated for several redshifts and evolved source functions derived from two models, one where accreted baryons have uniform density and one where matter of different density and temperature is being accreted. Curves are maximized so they don't go over the data (see e.g. Fields, Pavlidou & Prodanović 2010)

WMAP values for matter density (omega) parameters ($\Omega_{\rm bar} = 0.04$ for baryons and $\Omega_{\rm mat} = 0.27$ for matter).

For calculation of integral mass current density J (co-moving mass current density crossing shock surfaces of any Mach number at a given cosmic epoch) Pavlidou & Fields (2006) consider two models. The first model assumes that all objects accrete baryons of uniform density and temperature. The result of this is that at a given redshift all objects with the same mass have the same Mach number. The second model is more realistic and considers environmental and filament effects. This means that matter of different density and temperature is being accreted by different objects. The evolution of the mass current density in the model of Pavlidou & Fields (2006) is represented on Figure 2. If the shock strength is assumed to be the same for all sources and redshifts like we have assumed, then the shape of of the SFCR γ-ray source spectrum will be the same for all accreting structures at equal redshift. Further more, if cosmic-ray acceleration efficiency is taken to be the same for all accretion shocks, then the evolution of the SFCR γ-ray sources will be a copy of the mass current density evolution of accretion shocks.

Integral mass current J derived from these two models then tells us about the density of the sources with z. This now allows us to find the evolved SFCR source function from $n_{\rm H}(z)\Gamma(z,\epsilon) \propto J(z)q_\gamma(z)$ that represents summarized contribution of γ-rays from all redshifts and is thus much more appropriate to be compared to the observed EGRB spectrum. Our results are presented on Figure 3. Dashed curves correspond to the two limiting cases of the normal galaxy contribution to the EGRB from Fields, Pavlidou & Prodanović (2010). Solid curves represent our SFCR contribution upper limits where different normalizations correspond to subtracting the guaranteed contribution of the normal galaxies (two mentioned limiting cases) from the EGRB. In Figure 3 we also present summarized contribution of these two sources

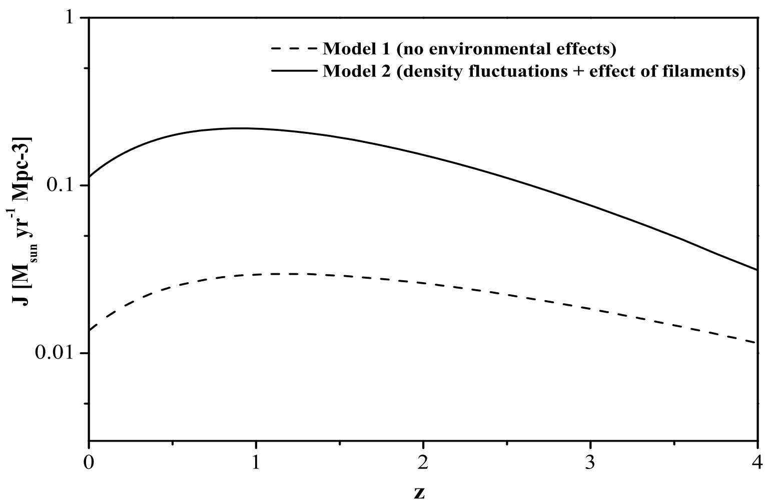

Figure 2: Co-moving integral mass current density J derived from two models (see e.g. Pavlidou & Fields 2006).

and it is clear that their summarized contribution fits well the observed *Fermi* LAT data.

The maximal SFCR contribution to the EGRB is different in different energy ranges. When considering the entire observed energy range, SFCRs make from $54-88\%$ of the total EGRB. The presented range of the maximal SFCR contribution comes from the two limiting cases for normal-galaxy contribution to the EGRB (see Fields, Pavlidou & Prodanović 2010), which we have subtracted from the EGRB data in order to derive the SFCR contribution. The largest contribution of SFCRs is at the highest energies after the break in the spectrum where SFCRs make from $59-96\%$ of the EGRB. Below this break, SFCR contribution is lower and makes $29-46\%$ and the dominant contribution comes from of unresolved normal galaxies.

4. DISCUSSION

Although new estimates show that unresolved normal galaxies are dominant component of the EGRB (see e.g. Fields, Pavlidou & Prodanović 2010), there is indication that another source is needed at highest energies where a spectral break is apparently present. One source that could potentially contribute is the hypothetical population of CRs that originate from the process of large-scale structure formation. The contribution of this source was already estimated but the limit was very weak due to unrealistic approximation that all sources come from a single redshift. Here we present a new constraint that includes evolution of SFCRs as γ-ray sources. If SFCRs mostly originate from strong shocks of structure formation, then the high-energy end of the observed EGRB can be well fitted with the shape of the SFCR gamma-ray spectrum (Figure 3). Normalization is still a free parameter and thus this is an upper limit to the SFCR contribution to the EGRB. Also in the Figure 3 we can see that the combined contributions of unresolved normal galaxies and SFCRs fit the data

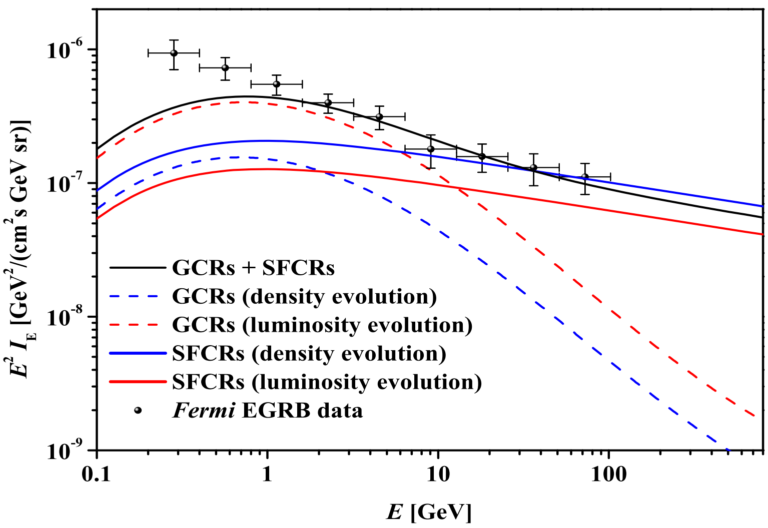

Figure 3: Contribution of unresolved normal galaxies, cosmological cosmic rays and the best fit of the summarized SFCR and GCR contributions.

much better than any of these two sources by it self. Combined contribution can also explain the break in the observed EGRB. Finally, we note that, even though the new constraint is stronger than previous ones, especially since source evolution is implemented for the first time, this is still a very crude, though instructive, model. A more detailed model where more realistic sources of SFCRs will be considered (with shock strength distributions and stronger normalization constraint) is in preparation.

Acknowledgments

I would like to thank Tijana Prodanović for the insights and many useful advice.

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