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Nuclear and Particle Physics Proceedings 291–293 (2017) 9–14

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Gamma-ray and Neutrino Diffuse Emissions of the Galaxy at very High Energy

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Abstract

Several independent analyzes of Fermi-LAT results found evidences of a spatial dependent cosmic ray (CR) spectral index which is not accounted for by conventional models of CR transport in the Galaxy. Moreover, several experiments have established the presence of a CR spectral hardening above few hundred GeV. We show that these results may have a relevant impact on the γ-ray and neutrino diffuse emissions of the Galaxy above the TeV. Indeed a phenomenological model which adopts a spatial dependent diffusion coefficient, so to account for those features, also reproduces the γ-ray excess found by Milagro at 15 TeV and the spectrum measured by H.E.S.S. and Fermi-LAT in the Galactic ridge. The same model predicts a neutrino emission along the Galactic plane which is significantly larger than expected on the basis of conventional models. This emission is compatible with ANTARES upper limits and is a natural target for KM3NeT.

Keywords: *Cosmic rays; gamma-ray and neutrino astronomy*

1. Introduction

The last few years brought a wealth of new data in high energy astrophysics. The IceCube experiment opened the era of high energy neutrino astronomy finding, in several data samples [1, 2, 3, 4], significant excesses respect to the atmospheric background. Moreover the ANTARES collaboration put interesting complementary constraints on the neutrino flux from the inner plane of our Galaxy [5]. Also "more conventional" channels, as those provided by charged cosmic rays (CR) and γ-rays, brought new interesting results. Some of those results display anomalies which require to modify the way the γ-ray and neutrino high energy diffuse emissions of the Galaxy are conventionally modeled.

This is the case of the CR hardening found by Pamela [6] and AMS-02 [7] at about 250 GeV/nucleon and of the excess in the γ-ray diffuse emission found by Fermi-LAT in the inner Galactic plane (IGP) [8] respect to the conventional propagation models. In fact, while few degrees away from the GP the diffuse emission is well described by the Fermi-LAT benchmark model based on GALPROP [9], for Galactic latitudes $|b| \lesssim 5°$, and above few GeV, its spectrum diverge significantly from those expectations. It was found [10] that the excess is related to a dependence of the primary CR proton spectral index on the Galactocentric radius which was confirmed by the Fermi-LAT collaboration [11]. This is at odd with conventional models which, assuming uniform source and propagation properties, do not predict such a behaviour. Those findings were independently confirmed by another group [12] making the need for a theoretical understanding even more compelling.

A possible interpretation [13], which has been recently proposed in terms of non-linear CR propagation, may have problems explaining the γ-ray excess to rise with energy above 10 GeV. A different approach has been undertaken by the authors of [10] introducing a radial dependence for both the spectral index $\delta(R)$ setting the rigidity dependence of the CR diffusion coefficient and the advection velocity. This was implemented with

https://doi.org/10.1016/j.nuclphysbps.2017.06.003

the DRAGON[1] numerical code [14] which is built to account for spatial depend CR transport. The comparison between DRAGON and experimental data turned into a new phenomenological model (KRAγ) reproducing the Fermi-LAT γ-ray diffuse spectrum over the whole sky.

In this contribution we will compare the prediction of the KRAγ model with several γ-ray data set above the TeV. These will include the flux measured by Milagro at $\sim$ 15 TeV in the IGP [16] as well as the spectrum measured by H.E.S.S. [17] in the Galactic ridge. We will show as the well known (though often forgotten) discrepancies between those experimental results and the predictions of conventional models are absent for the KRAγ model.

We will then use the same model to compute the neutrino diffuse emission of the Galaxy above the 10 TeV, showing that it is significantly larger than that computed with GALPROP [18] and compare our results with recent IceCube and ANTARES results.

2. The KRA$_\gamma$ model

The model KRA$_\gamma$ proposed in [10] assumes that the exponent δ, setting the rigidity dependence of the CR diffusion coefficient, has a linear dependence on the Galactocentric radius (R): $\delta(R) = AR + B$. The parameters A and B are tuned to consistently reproduce CR and γ-ray data. In particular the combination $A = 0.035$ kpc^{-1} and $B = 0.21$ gives $\delta(R_\odot) \simeq 0.5$ so to reproduce recent boron to carbon ratio (B/C) data (see e.g. [19]) and allows to reproduce the angular distribution and spectrum of the Galactic diffuse emission measured by Fermi-LAT (see Figs. in [10]). In particular the model reproduces the radial dependence of the CR spectral index determined by the Fermi-LAT collaboration (see Fig.s 7 and 8 in [11]). The model also adopts a convective wind for $R < 6.5$ kpc with velocity $V_C(z)\hat{z}$ (z is the distance from the GP) vanishing at $z = 0$ and growing as $dV_c/dz = 100$ km s^{-1} kpc^{-1} as motivated by the X-ray ROSAT observations and helps keeping the *CR* density in the IGP region at the observed level.

The setup was implemented with DRAGON, a numerical code designed to compute the propagation of all CR species [14, 15] in the general framework of position-dependent diffusion.

The model also accounts for the CR nuclei spectral hardening at $\sim$ 250 GeV/n inferred from Pamela and AMS-02 data. This it is assumed to be present in the whole Galaxy and it is effectively implemented as a feature in the CR source term. Although such feature has almost no effect on the γ-ray spectrum in the energy range measured by Fermi, we will see that, together with inhomogeneous diffusion, it has a quite relevant impact above the TeV.

In order to extend the range to which the KRA$_\gamma$ model can be applied up to the energies probed by IceCube, a proper CR primary spectrum has to be used. In [20] we assumed proton and Helium source spectra (heavier nuclei give a negligible contribution) such that the propagated spectra at Solar System circle agrees with CR data between 10 TeV and few PeV. In particular we used CREAM [21] as well as KASCADE [23] and KASCADE-Grande data [24]. In order to deal with the large scatter in the KASCADE-Grande data we considered two values of the exponential cut-off energy required to reproduce the observed knee in the propagated spectra, namely $E_{\rm cut} = 5$ and 50 PeV.

Concerning γ-ray production cross-sections in $p-p$ scattering, we used the parametrization reported in [22] which properly accounts for its energy dependence (which is significant above the TeV). We disregard γ-ray opacity due to the interstellar radiation field since it is negligible on Galactic distances up to few tens of TeV.

Finally, we notice that although the KRA$_\gamma$ is a phenomenological model, a physically motivated scenario which reproduces its main features (namely a value of δ which decreases with R) has been recently proposed in terms of anisotropic diffusion and implemented with the DRAGON 2 code [15].

3. Comparison with γ-ray data above the TeV

So far, only few data are available for the diffuse γ-ray emission from the IGP region aboe the TeV. Here we will consider the Milagro data in the IGP and H.E.S.S. data from the Galactic ridge. As we mentioned in the Introduction both data sets display significant discrepancies respect to the predictions of conventional CR models. Other data sets, as those taken by ARGO-YBJ [25], are relative to regions where the predictions of KRA$_\gamma$ and conventional models are too close and both in agreement with data.

Let's start with the comparison with Milagro result. This water Cherenkov experiment measured the γ-ray flux in the sky window with $|b| < 2^\circ$ and $30^\circ < l < 65^\circ$ at a median energy of 15 TeV. This was found to be 4σ above the flux computed with the 2008 state of art conventional model based on GALPROP. A better agreement was found with an *optimized* model based on EGRET data which however has been excluded by

[1]https://github.com/cosmicrays