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Cosmic-Ray Source Grammage Dominates The Diffuse Gamma-Ray Sky

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Recent secondary-over-primary cosmic-ray (CR) ratio measurements by DAMPE and CALET show a hint of a flattening above ($\sim$) TV rigidities. It is plausible - and theoretically well-motivated - that CRs accumulate additional grammage inside the source environment leading to a constant grammage in addition to the Galactic one. In this contribution, we explore this scenario, quantifying the contribution of these cocoon regions onto the secondary diffuse emissions such as gamma-rays and neutrinos. Interestingly, we find that, assuming a source grammage of $\sim 0.4\frac{\mathrm{gr}}{\mathrm{cm}^2}$, compatible with the grammage accumulated by CRs in the downstream regions of Supernova Remnant shocks, and fitted against high-energy B/C measurements, the corresponding gamma-ray emission must substantially contribute to the diffuse gamma-ray flux providing a natural explanation of the gamma-ray hardening observed in the inner Galaxy. Our results may also additionally reproduce the recently published TeV-PeV gamma-ray measurements from the LHAASO and Tibet observations. We also discuss the implications of our calculation for the neutrino fluxes in light of the recent Galactic neutrino flux measured by the IceCube collaboration.

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1. Introduction

Recently, several experimental facilities have measured a diffuse gamma-ray flux from GeV up to PeV energies, along several different directions in our Galaxy [1–4]. These diffuse fluxes allows us to probe the cosmic ray (CR) physics in Galactic regions not accessible by CR experiments. In fact, the gamma-ray Galactic Diffuse Emission (GDE) is expected to be produced by hadronic collisions between CRs propagating in the Galactic environment and interstellar medium. While the GDE measurements generally support the standard picture of CR transport dominated by advection (diffusion) at low (high) energies, there are important inconsistencies (see [5] for details). In particular, the gamma-ray flux near the Galaxy center is larger than theoretically expected assuming a uniform CR distribution along the galactic plane and normalizing to the local CR spectrum [6, 7]. Some authors have suggested the possibility that the larger gamma-ray spectrum can be explained by unresolved leptonic sources such as pulsar wind nebulae or TeV halos [8, 9]. However, the IceCube Collaboration found high-energy neutrino emission associated with the Galactic disc [10], constraining the potential role of leptonic sources. Some authors have speculated that the CR transport in the Galaxy center could be different than in the outer part of the galaxy, enhancing the gamma-ray yield in the center of the Galaxy [11–13]. However, these effects should not be visible above ~ TeV energies in the LHAASO spectrum. Therefore, the gamma-ray measurements currently challenge our CR physics knowledge. In this contribution, we propose that CRs might be trapped in *cocoons* where can accumulate source grammage before being injected into the intergalactic environment. Source grammage is theoretically expected to be accumulated in different Galactic environments such as Supernova remnants (SNRs) and star clusters [14, 15]. Thus, our scenario can naturally explain all the measurements (see [5] for more details).

2. Model Assumptions

We assume that the cocoons have the same distribution as SNRs [16]. Then, the CR distribution in each point of the Galaxy reads (see [5] for more details)

$$f_{\mathrm{CR}}(p,r,z) = Q_{\mathrm{CR}}(p,r,z)\tau_{\mathrm{c}}(p) = Q_{\mathrm{CR}}(p)\rho(r,z)\frac{\chi_c(p)}{m_p n_{\mathrm{gas}} c}, \tag{1}$$

where n_{gas} is the gas density in the cocoon, $\rho(r,z)$ is the cocoon density, $\chi_c(p)$ is the source grammage accumulated by CRs.

The gamma-ray and neutrino production rate, in each point of the Galaxy, reads

$$\begin{aligned} Q_{\gamma,\nu}(E,r,z) = \frac{\rho(r,z)}{m_p} \sum_{i=\mathrm{H,He}} \int_{E_{\mathrm{th,i}}}^{+\infty} dE_i Q^E_{\mathrm{CR,i}}(E_i)\,\chi_c(E_i) \times \\ \times \frac{d\sigma^i_{\gamma,\nu}}{dE_i}(E_i,E) = \rho(r,z) Q_{\gamma,\nu}(E), \end{aligned} \tag{2}$$

where $Q^E_{\mathrm{CR}}(E) = 4\pi p^2 Q_{\mathrm{CR}}(p(E))\frac{dp}{dE}$, and $\frac{d\sigma^i_{\gamma,\nu}}{dE_i}(E_i,E)$ is the differential cross-section from [17] publicly available in `github.com/aafragpy/aafragpy`. The final angle-integrated flux from cocoon contributions reads

$$\Phi^{\text{cocoon}}_{\gamma/\nu}(E) = \frac{Q_{\gamma/\nu}(E)}{4\pi} \int d\Omega \int_0^\infty ds\, \rho(s,\Omega), \tag{3}$$

For the source grammage, we use a model-independent approach, and so we assume

$$\chi_c(R) = \chi_{c,0}\, e^{-\frac{R}{R_0}}\,. \tag{4}$$

where R is the particle rigidity and we fix $R_0 = 20\,\text{TV}$.

3. Results

The source grammage contributes to the primary over secondary CR ratio. In order to quantify which is the source grammage allowed by the data, we use the approach as [18, 19]. In particular, we insert an injection term into the secondary CRs transport equation and we fit the B/C data [20–22]. Fig. 1 shows the best-fit scenario. The fit finds a non-zero $\chi_{c,0}$ in the range of $[0.3 - 0.6]\,\text{g cm}^{-2}$,

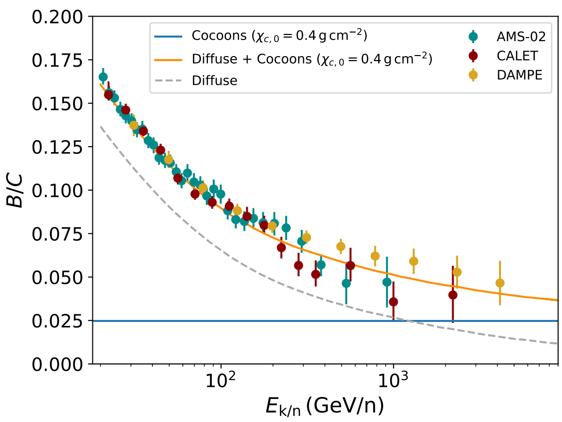

Figure 1: B/C in terms of the kinetic energy per nucleon. The solid orange line represents the best fit, while the grey dashed line represents the Galactic grammage, while the solid blue line represents the cocoons contribution with $\chi_{c,0} = 0.4\,\text{g cm}^{-2}$. Data from [20–22]. Image taken from [5].

with a best-fit value $\chi_{c,0} = 0.4\,\text{g cm}^{-2}$.

Fig. 2 shows the total gamma-ray spectrum (galactic diffuse + cocoons) compared with the experimental data [4], both for the inner and outer parts of the Galaxy. The galactic diffuse gamma-ray spectrum is taken from [23]. For the inner part, the fluxes are scaled in order to take into account the LHAASO mask of the galactic disc [24]. We obtain a satisfactory description of the gamma-ray spectrum where the cocoons mainly contribute to the $\lesssim 10\,\text{TeV}$ excess where the diffuse-only emission cannot explain the measurements. In this approach, we do not need either a diffusion coefficient to vary within the galactic disk or a population of unresolved leptonic sources. Our results have also impact over the high-energy neutrino sky. Fig. 3 reports the angle-integrated neutrino flux (galactic diffuse + cocoons) compared with the ICeCube measurements reported in [10]. While the comparison is not completely consistent because of the specific template analysis used by IceCube to evaluate the galactic diffuse flux, our theoretical prediction lies in ballpark of the measurements.

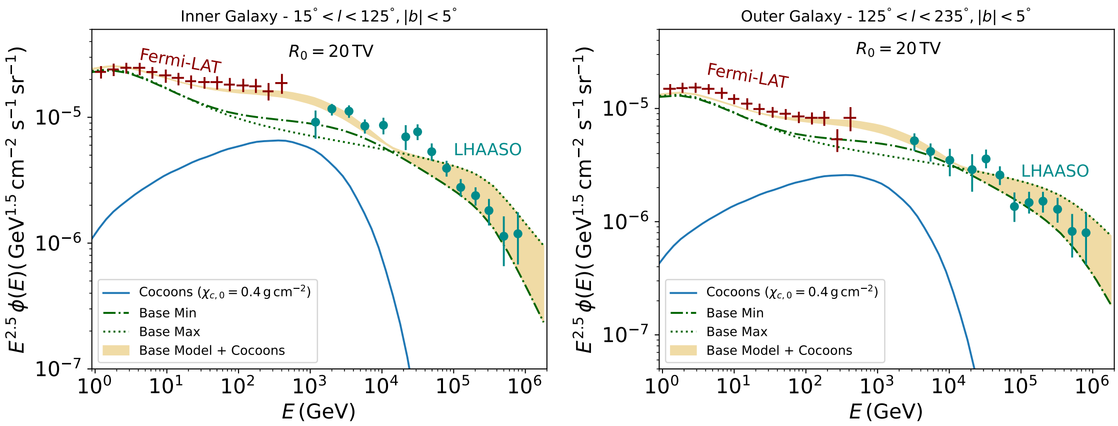

Figure 2: Left: Inner galaxy gamma-ray flux as a function of the energy for the DGE + cocoons contributions (golden band) and for the cocoons only (blue line). The result is scaled to account for the LHAASO mask in the galactic disc. **Right**: Same as left panel, but for the outer galaxy. In both panels, the gamma-ray SEDs are compared with Fermi-LAT and LHAASO data reported by [4]. Image taken from [5].

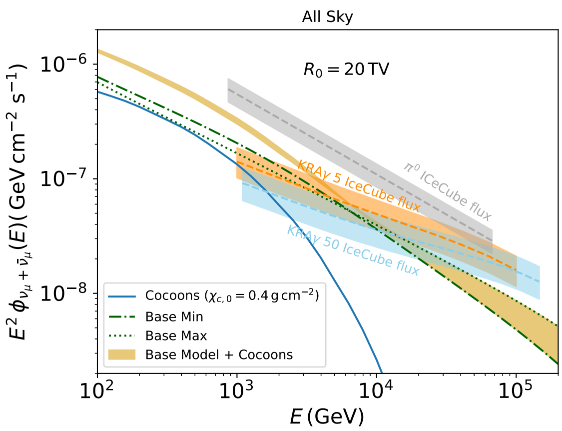

Figure 3: All-sky neutrino SEDs as a function of energy, comparing the total emission (DGE + cocoons, shown by the golden band) and the cocoon-only contribution (blue line). These predictions are evaluated against the IceCube flux measurements [10], derived using the π^0 template from [7] and the KRAγ 5 and 50 templates described in [23]. Image taken from [5].

We point out that the cocoons only marginally contribute to the overall neutrino flux because the chosen value of R_0 strongly suppresses the neutrino yield at higher energies. However, our model cannot reproduce a flux level of $\sim 2 \cdot 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$ at $\sim 100\,\mathrm{TeV}$ [25]. However, It is still unclear whether this flux level is a genuine feature of the Galactic neutrino spectrum or merely an artifact of the power-law assumption adopted by the IceCube Collaboration.

4. Conclusions

Several experiments have demonstrated that there is a discrepancy between diffuse Galactic gamma-ray and the local CR fluxes. Despite large systematic and statistical measurements uncertainties, these findings point out that our understanding of the microphysical conditions of Galactic CR transport is tremendously lacking. In this contribution, we have proposed the existence of extended *cocoons* around CR sources, capable of trapping CRs up to $\sim 3 \cdot 10^5$ yr. This scenario modifies the standard picture by introducing a source grammage of $\sim 0.4\,\mathrm{g/cm^2}$, but it explains the flattening of the B/C at high energies. We have also demonstrated that cocoons strongly contribute to the gamma-ray DGE around $\sim 1\,\mathrm{TeV}$, explaining the hardening of the gamma-ray spectrum towards the inner Galaxy. These results might revolutionise our understanding of Galactic CRs pointing towards the processes that govern their transport. Indeed, the most plausible manifestation of cocoons may be star-cluster wind bubbles, where CRs below $\sim$ 10 TeV escape via advection, while at higher-energy diffusion processes kick in [26]. More concretely, our results pave the way for using DGE measurements to scrutinize specific cosmic ray transport models that shape the energy-dependent source grammage accumulated by CRs inside their sources. Although we have employed a model-independent approach, more refined measurements in the future will further enhance these studies. Finally, the upcoming KM3NeT neutrino telescope in the Mediterranean Sea will have an unprecedented sensitivity and a field of view along the Galactic plane [25, 27, 28]. Therefore, it will strongly probe the neutrino emission along the Galactic disk and independently test our scenario.

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