PROCEEDINGS OF SCIENCE

Spectral Shape of Galactic Cosmic Rays: Modeling and Implications on Diffusive Gamma-Ray Emission

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We model the hadronic gamma-ray production in the Galaxy using an updated phenomenological description of the cosmic ray spectra and different Galactic gas templates. We find a persistent discrepancy in both normalization and spectral shape between the predicted gamma-ray flux and observations by LHAASO. We conclude that the local cosmic-ray proton flux measured by LHAASO overshoots the Galactic gamma-ray emission observed in the TeV-PeV sky, calling for a revision of current cosmic ray models.

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1. Introduction

Recently, the Large High Altitude Air Shower Observatory (LHAASO) measured the cosmic-ray (CR) proton spectrum in the energy range known as the "knee" [1]. This has provided for the first time a continuous observation of CR proton flux, linking observations of other ground-based observatories (such as IceTop [2], KASCADE [3, 4] and GRAPES-3 [5]) with measurements by direct missions (PAMELA [6], AMS-02 [7, 8], DAMPE [9, 10], CALET [11, 12], CREAM [13] and ATIC-2 [14]).

The same collaboration has provided an updated measurement of high-energy (TeV-PeV) Galactic diffuse gamma-ray emission [15, 16] using in combination the Water Cherenkov Detector Array (WCDA) and the Square Kilometer Array (KM2A). This diffuse gamma-ray emission is primarily generated by the interaction of cosmic rays (mainly protons and helium) with the gas present in our Galaxy. We construct a phenomenological model of Galactic cosmic rays based on the most recent CR data and evaluate its implications on the predicted secondary diffuse gamma-ray flux. We discuss the conditions under which both observations can be brought into agreement.

2. Galactic Cosmic Rays Model

We adopt the parameterization introduced in [17] to describe the proton and helium fluxes as:

$$\phi_A(E) = \left[K_A \left(\frac{E}{E_0} \right)^{-\alpha_1(A)} \right] S_A(E)\,, \tag{1}$$

where the label A (here A = H or He) refers to the considered nucleus, and K_A is a normalization factor with units (GeV cm^2 s sr)$^{-1}$ at an arbitrary energy E_0. On the other hand, the function $S_A(E)$, given by

$$S_A(E) = \Pi_i \left[1 + \left(\frac{E}{E_{b,i}(A)} \right)^{\frac{1}{\omega_i(A)}} \right]^{-\Delta\alpha_i(A)\,\omega_i(A)} \tag{2}$$

models the spectrum at larger energies by introducing a series of breaks located at energies $E_{b,i}(A)$ with spectral index changing by $\Delta\alpha_i(A) = \alpha_{i+1}(A) - \alpha_i(A)$ over an energy-width $\omega_i(A)$ in logarithmic scale.

We fit the available data for both components, combining measurements by direct missions and ground-based experiments. Our best-fit results are shown with a black line in the lower panel of Fig. 1 alongside observational data. The spectral breaks in the helium and proton fluxes are found, within uncertainties, at roughly the same rigidity R, as expected if the origin of the breaks is governed by rigidity-dependent processes such as acceleration or transport.

We model the spectra of heavier elements by assuming one heavy element dominates and shares the same rigidity dependence as helium, differing only by a normalization factor. We consider that in the low-energy regime the total heavy element contribution relative to that of helium is roughly constant and given by $\eta = \phi_{\rm heavy}(E)/\phi_{\rm He}(E) = \sum_{A>4}(K_A/K_{\rm He})$. We estimate this contribution from observations of the all particle flux $\phi_{\rm tot}(E)$ measured by LHAASO [18] and other detectors (HAWC [19], Tunka [20], KASCADE [3, 4] and IceTop [2]). In particular, we note $\eta = [\phi_{\rm tot}(E) - \phi_{\rm p}(E) - \phi_{\rm He}(E)]/\phi_{\rm He}(E) \sim 1.7$, from observational data.

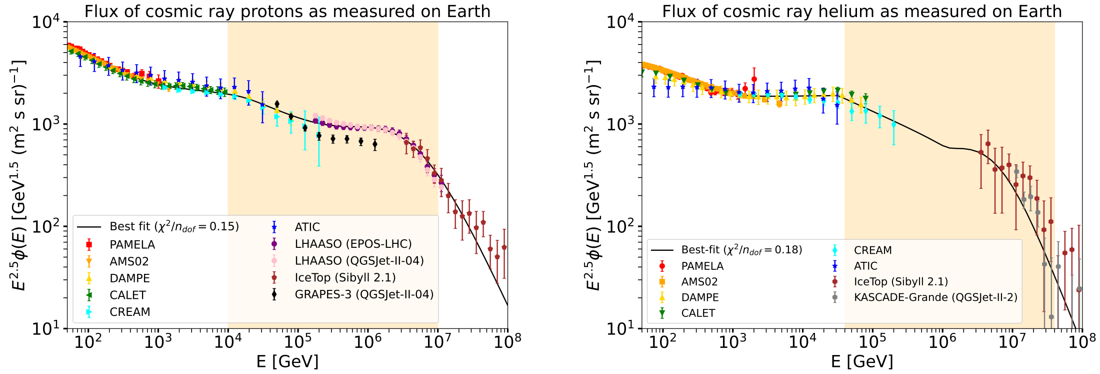

Figure 1: Flux of galactic cosmic ray protons (left panel) and helium (right panel) as a function of energy per nuclei. Observation data by direct detection experiments (PAMELA [6], AMS-02 [7, 8], DAMPE [9, 10], CALET [11, 12], CREAM [13] and ATIC-2 [14]) as well as ground-based observatories (GRAPES-3 [5], IceTop [2], KASCADE-Grande [4] and LHAASO [1]) shown with colored scatter points. Best-fits of our model are represented with solid black lines. Shaded areas correspond to the energy range of interest for the production of TeV-PeV γ-rays.

Although helium and heavy elements play a relevant role in shaping the CR all-particle spectrum, they are much less significant for assessing the diffuse γ−ray flux. Indeed, γ−ray production by hadronic interactions is primarily determined by the total CR nucleon flux, which is given by

$$\phi_{\rm CR}(E_n) = \sum_A A^2\, \phi_A(AE_n) \tag{3}$$

where E_n is the energy per nucleon. The combined effect of the prefactor A^2 and the shift in energy $E = AE_{\rm n}$ is to suppress helium and heavy element contributions (at a given nucleon energy) with respect to that of hydrogen. Therefore, the γ−ray diffuse emission essentially probes the CR proton spectrum and in particular the position of the CR proton knee.

Following the discussion in [21], the CR nucleon flux can be written as:

$$\phi_{{\rm CR},\odot}(E_{\rm n}) = \phi_{\rm p}(E_{\rm n}) + (1+k)\, \phi_{\rm He,\,CR}(E_{\rm n}) \tag{4}$$

where $\phi_{\rm He,CR}(E_{\rm n}) = A_{\rm He}^2\, \phi_{\rm He}(A_{\rm He}E_{\rm n})$ is the helium contribution to nucleon flux and the factor

$$k = \eta \left(\frac{A}{A_{\rm He}}\right)^{2-\alpha_1(He)} \tag{5}$$

takes into account heavy elements contributions, dominated by a nuclei of mass number A. We obtain a conservative range for k by taking $A = 12$ (carbon) and $A = 56$ (iron) as extreme values.

3. Galactic Diffuse Gamma-Rays

The diffuse γ-ray emission resulting from CR interactions with the interstellar medium can be expressed as [22, 23]:

$$\phi_\gamma(E_\gamma, \hat{n}_\gamma) = \int_{E_\gamma}^{\infty} dE_{\rm n}\, \frac{d\sigma}{dE_\gamma}(E_{\rm n},\, E_\gamma) \int_0^{\infty} dl\, \phi_{\rm CR}(E_{\rm n}, \mathbf{r}_\odot + l\,\hat{n}_\gamma)\, n_g(\mathbf{r}_\odot + l\,\hat{n}_\gamma)\, e^{-\tau(l,E_\gamma)}. \tag{6}$$

Here, $d\sigma/dE_\gamma$ is the differential cross section for γ-ray production in nucleon-nucleon collisions, $n_g(\mathbf{r})$ is the Galactic gas density distribution, $r_\odot = 8.5$ kpc is the position of the Sun and $\tau(l, E_\gamma)$ represents the optical depth due to pair production on background radiation field photons (we restrict to the dominating Cosmic Microwave Background radiation). We adopt the AAFRAG parameterization [24, 25] for the photon production cross section, which we find to be in closest agreement with the approach of [26], based entirely on accelerator data fits.

Directional dependence of diffuse γ-rays is mainly determined by the distribution of gas and CRs in the Galaxy. For simplicity, in this work we initially assume that CR are uniformly distributed in the Galaxy and later address how potential deviations from this assumption could impact our results.

The interstellar gas is mainly composed of atomic (H) and molecular hydrogen (H_2), whose distributions are traced by the 21-cm [27] and CO [28] emission lines. We include both components in our analysis by the map provided by the GALPROP code[1] [29].

Alternatively, the gas distribution can be inferred from the dust opacity ($\tau_{\rm D}$, obtained at 353 GHz), measured by Planck Collaboration[2] [30]. This quantity can be used as a tracer for the hydrogen gas column density ($N_{\rm H}$) since dust is uniformly mixed with neutral gas. The dust-to-gas conversion factor is calibrated on experimental data; for our analysis, we use $X_{\rm D}^{-1} \equiv \left(\frac{\tau_{\rm D}}{N_{\rm H}}\right) = 1.18 \times 10^{-26}\ {\rm cm}^2$, as reported by [31].

To account for heavier elements in the gas, we scale the hydrogen density by a factor of 1.42 in both models, reflecting the Solar System composition, assumed to be representative of the entire Galactic Disk [32].

4. Results and Discussion

The diffuse γ-ray fluxes computed using the methodology discussed in the previous section are presented in Fig. 2 for both sky regions probed by LHAASO and after applying the same mask used by the collaboration in [16]. Two shaded bands, which represent our uncertainty in CR composition and contribution of heavy elements, illustrate our predictions based on different assumptions for the interstellar gas distributions. The blue band is obtained by using the gas distribution provided with the GALPROP code. The green band is based instead on the gas column density inferred from the Planck dust opacity (τ_D) map.

The predictions obtained using the Planck dust map show a better agreement with LHAASO measurements, especially in the lateral region ($|b| < 5°$ and $125° < l < 235°$). In this sky region, the blue shaded band, derived from the GALPROP gas model, systematically exceeds the data points for gamma-ray energies $E_\gamma > 30$ TeV. This trend is also observed in the inner region, with $15° < l < 125°$; however, in this case, both predictions fail to adequately reproduce the LHAASO data below $E_\gamma < 30$ TeV.

The uncertainty in the proton flux can potentially affect our conclusions. Previous measurements by KASCADE [3, 4] reported a significantly lower proton flux than IceTop in the ~PeV energy range. A recent work in Ref. Luque *et al.* [33] highlighted that the $\gamma-$flux measured by LHAASO-KM2A was incompatible with the IceTop proton flux dataset while in good agreement

[1] galprop.stanford.edu
[2] esa.int/Science_Exploration/Space_Science/Planck

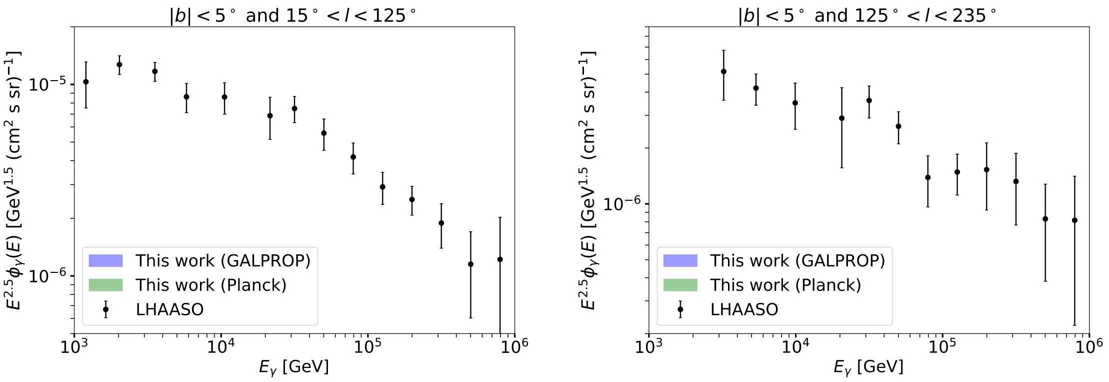

Figure 2: Diffuse gamma-ray flux in LHAASO inner ($|b| < 5°$, $15° < l < 125°$, top panel) and lateral ($|b| < 5°$, $125° < l < 235°$, bottom panel) Galaxy regions. The γ-flux expectations obtained from our model are shown by blue (GALPROP gas model) and green (Planck gas model) shaded bands. Observational data by LHAASO [16] are added with black points.

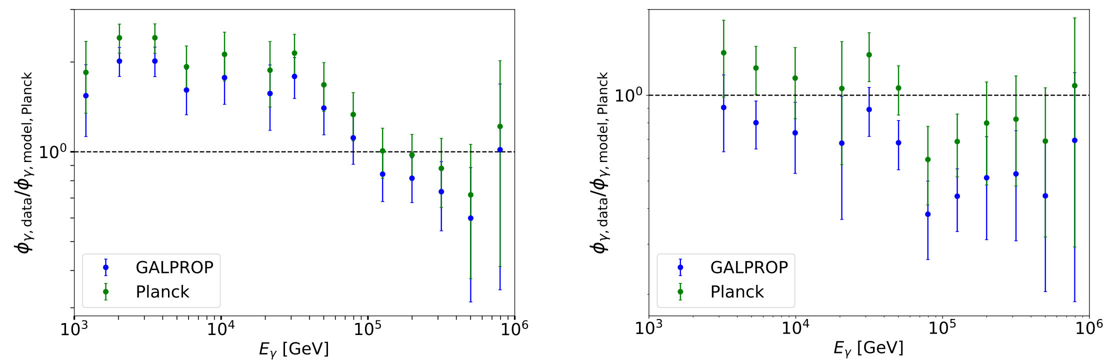

Figure 3: Ratio of measured and expected γ-fluxes (for GALPROP and Planck gas distribution scenarios) in LHAASO inner ($|b| < 5°$, $15° < l < 125°$, left panel) and lateral ($|b| < 5°$, $125° < l < 235°$, right panel) Galaxy regions as a function of gamma-ray energy. Dashed black line represents scenario were measurement data and expectations from our model perfectly agree.

with the KASCADE data. Conversely, the helium flux lacks measurements between 100 TeV and a few PeV, providing another potential source of uncertainty in all models so far.

Another possibility that has been discussed in Cataldo *et al.* [23], Vecchiotti *et al.* [34] is that the cosmic ray density is not uniform in the Galaxy but resembles the distribution of sources (mainly supernova remnants, SNR), motivated by a possible confinement in the proximity of the sources. However, including this variation in our analysis would cause a reduction of the gamma ray flux of up to 20% in the lateral region (in the most optimistic scenarios) while it would increase the prediction in the inner region, worsening the tension.

In order to better investigate the mismatch among data and predictions, we plot in Fig. 3 their ratio as a function of the γ-ray energy in both LHAASO sky regions, for both gas models considered (shown in different colors). We observe a discrepancy between data and predictions reflected not only in the overall normalization but also in the energy dependence of the ratios.

We consider all sources of uncertainty that could account for the discrepancy of the predicted spectral shape. The adoption of other cross-sections would increase the γ-flux while predicting a slightly harder slope. An additional diffuse component contributing to the LHAASO measurement would require a lower γ-ray flux produced by CRs. Therefore, both options would enlarge the discrepancy found in this work. Another alternative not fully explored in this work is the additional γ-ray absorption by interstellar radiation field (ISRF). Absorption by ISRF is, however, believed to be small according to present estimates, see e.g.Vernetto and Lipari [35].

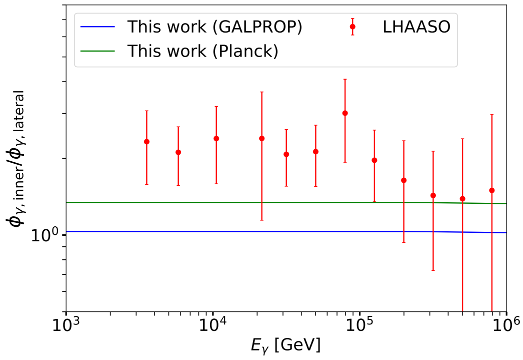

Figure 4: Ratio of γ-fluxes in inner and lateral Galaxy regions as a function of gamma-ray energy. Ratio obtained from expectations by our model using GALPROP galactic gas map [29] and Planck galactic dust opacity map [31] displayed with blue and green solid lines, respectively. Ratio computed with observation data by LHAASO [16] shown with black scatter points.

Another diagnostic we consider is the ratio between the observational data of γ-fluxes in the inner and lateral regions, plotted in Fig. 4. We also include the expected ratio between the γ-ray fluxes from the two regions obtained by using GALPROP (Planck) gas distribution with a blue (green) line. If we assume that the CR spectrum in the two regions is the same, this ratio is approximately energy independent and determined by the amount of targets in two regions.

Previous works [22, 23, 36–42] have explored the possibility of a spatial-dependent CR spectrum, based on the fact that Fermi-LAT $\gamma-$ray data at GeV energies suggest CR spectral hardening in the direction of the Galactic center. We note, however, that diffuse γ-ray observations by LHAASO do not distinguish between these spatial-dependent CR transport models and the conventional scenario (as was already noted in Vecchiotti *et al.* [34]), being well compatible with a constant within uncertainties.

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