Can the TeV gamma-ray sky probe the galactic cosmic ray distribution?

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Abstract. We evaluate the diffuse gamma-ray flux at TeV energies produced by hadronic interactions of cosmic rays with the gas contained in the galactic disk. We consider different assumptions for the cosmic ray distribution, including the recently emerged possibility of a harder cosmic ray spectrum in the inner Galaxy. We show that observational data provided by Argo-YBJ, HESS, HAWC and Milagro, can already discriminate among different hypotheses. The constraints can be strengthened if the contribution of sources not resolved by HESS is taken into account.

1. Introduction

Cosmic rays (CR) that propagate in different regions of the Galaxy interact with the ambient gas through hadronic processes and produce a diffuse flux of high energy (HE) gamma and neutrinos. The distribution of cosmic rays in the Galaxy is still uncertain and this affects the expectations for the diffuse emission. Recent analyses, see e.g. [1, 2], pointed out that the CR spectrum in the inner Galaxy may be harder than the local one. This could clearly have a dramatic effect at TeV energies and above. It would enhance the expected HE emission with respect to standard expectations and, moreover, it would produce a different angular distribution of HE photons from the Galactic plane with respect to lower energy observations. In this work, following the approach described in Ref. [3], we test expectations for the galactic HE gamma-ray emission against existing observational data in the TeV domain. We consider, in particular, the observations provided by Argo-YBJ [4], HESS [5], Milagro [6] and the preliminary results by HAWC [7].

2. The diffuse gamma flux

We calculate the diffuse HE gamma flux by using the phenomenological approach introduced in [8, 9] that allows us to implement different assumptions for the CR space and energy distribution in a simple and direct way, including the possibility of a position dependent CR spectral index. The CR nucleon flux is given as a function of position and nucleon energy by:

$$\varphi_{\text{CR}}(E, r) = \varphi_{\text{CR}, \odot}(E) g(r) h(E, r)$$

where $\varphi_{\text{CR}, \odot}(E)$ represents the local flux, $g(r)$ is an adimensional function (normalized to one at the Sun position $r_{\odot}$) introduced to describe the spatial distribution of CR while the function

$$h(E, r)$$

represents the hardness of the CR spectrum.
\( h(E, \mathbf{r}) \), given by:

\[
h(E, \mathbf{r}) = \left( \frac{E}{E_0} \right)^\Delta(r)
\]

with \( E_0 = 20 \text{ GeV} \) and \( \Delta(\mathbf{r}_\odot) = 0 \), introduces a position-dependent variation \( \Delta(r) \) of the CR spectral index.

We describe the local CR nucleon flux \( \varphi_{\text{CR,}\odot}(E) \) according to the data driven parameterization \cite{10}. The function \( g(\mathbf{r}) \) is obtained as the solution of 3D isotropic diffusion equation with constant diffusion coefficient, see Eqs.(2.3-2.5) of Ref. \cite{3}. We assume stationary CR injection by a population of sources distributed in the Galaxy according to the Supernova Remnants (SNR) number density given by \cite{11}. We consider two extreme assumptions for the diffusion length, \( R = 1\text{ kpc} \) and \( R = \infty \), in order to provide a conservative estimate of the uncertainty connected with CR spatial distribution in the Galaxy. When \( R = \infty \), the function \( g(\mathbf{r}) \) is expected to coincide, a part from boundary condition effects, with the CR distribution predicted by standard propagation codes. The assumption \( R = 1\text{ kpc} \) is intended to describe the opposite situation in which CR are confined relatively close to their sources. Finally the function \( \Delta(\mathbf{r}) \) in Eq.(2) is modelled as:

\[
\Delta(r, z) = \Delta_0 \left( 1 - \frac{r}{r_\odot} \right)
\]

with \( r_\odot = 8.5 \text{ kpc} \), in galactic cylindrical coordinates. The standard assumption (i.e. no CR spectral hardening) corresponds to \( \Delta_0 = 0 \). The possibility of CR spectral hardening in the inner Galaxy is implemented by taking \( \Delta_0 = 0.3 \) since this assumption allows us to reproduce the trend with \( r \) observed by \cite{2, 12, 13} for \( r \leq 10 \text{ kpc} \). In more external regions, the evidence for a variation of CR energy distribution is much weaker and we assume that \( \Delta(r) \) is constant.

The predictions for the diffuse HE gamma-ray flux at \( E_\gamma = 1 \text{ TeV} \) in the different scenarios are displayed in Fig. 2 of Ref. \cite{3} It is shown that CR hardening may be responsible for a factor \( \sim 2 \) increase of the diffuse emission in the longitude range \( |l| \leq 60^\circ \) that can be potentially probed by TeV scale gamma-ray observations, as it is explained in the following.

3. The sources contribution

The total flux of HE gammas produced in our Galaxy can be written as:

\[
\varphi_{\gamma,\text{tot}} = \varphi_{\gamma,\text{diff}} + \varphi_{\gamma,S} + \varphi_{\gamma,\text{IC}}
\]

where \( \varphi_{\gamma,\text{diff}} \) is the diffuse flux, \( \varphi_{\gamma,S} \) is the flux produced by sources and \( \varphi_{\gamma,\text{IC}} \) indicates the contribution due to Inverse Compton (IC) emission by diffuse HE electrons. With the term ‘sources’, we refer here to all the contributions produced within or close to an acceleration site by freshly accelerated particles that potentially have (a part from cut-off effects) harder spectra than the diffuse component. In the energy range of interest (\( E \geq 1 \text{ TeV} \)), we assume that the IC contribution is negligible, moreover the gamma-ray sky gets a comparable contribution by sources and diffuse emission and it is difficult to isolate the two components. For this reason, we construct a complete model that includes both contributions and we compare it with the total flux observed by the various gamma-ray experiments.

In the longitude range of interest (\( |l| \leq 60^\circ \)), TeV gamma-ray sources have been extensively studied by the HESS experiment. The HESS-GPS catalogue \cite{14} includes 78 VHE sources measured with an angular resolution of 0.08° and a sensitivity \( \simeq 1.5\% \) Crab flux for point-like objects. Extended sources are described with Gaussian profiles in \( l \) and in \( b \). The source spectrum is calculated in the energy range 0.1 \( \leq E_\gamma \leq 100 \text{ TeV} \) by using a power law or a power-law with an exponential cutoff with the best-fit parameters given by \cite{14}.
The total gamma-ray fluxes as a function of the Galactic longitude $l$. Blue lines correspond to the predicted flux due to diffuse emission and resolved sources in the "standard" scenario for CR propagation while red lines implement CR spectral hardening. Solid (dashed) lines are obtained by assuming a CR diffusion length equal to $R = 1$ kpc ($R = \infty$). The green dotted line represents the contribution of resolved sources.

The flux $\varphi_{\gamma,S}^{(r)}$ that is calculated by using the HESS source catalogue includes by construction only resolved sources. The total flux produced by sources should include also the contribution due to very faint and/or extended sources that are not resolved by HESS. We can express the total source contribution as

$$\varphi_{\gamma} = \varphi_{\gamma,S}^{(r)} (1 + \eta)$$

where the parameter $\eta$, that depends in principle on the observation direction and energy, quantifies the relative contribution of unresolved objects to the total source flux. At TeV energies, we naturally expect that unresolved sources accounts for a relevant fraction of the total signal because a small portion of the Galaxy is resolved by HESS while sources are expected to be distributed in the entire Galaxy. By taking into account that HESS sensitivity limit for extended objects is $\approx 10\%$ of the CRAB flux integrated above 1 TeV \cite{14}, the $\eta$ parameter can estimated as a function of the assumed sources intrinsic luminosity $L$, see \cite{3}. In the angular region $|l| \leq 60\degree$ and $|b| \leq 3\degree$, we obtain $\eta \approx 60\%$ by assuming that source are distributed as SNRs in the Galaxy \cite{11} and have intrinsic luminosity $L = L_{\text{CRAB}}$. The parameter $\eta$ is a decreasing function of $L$. As a consequence, the above value represents a lower limit of the luminosity-averaged unresolved contribution unless the source luminosity distribution extends well above $L_{\text{CRAB}}$.

4. Results
The sum of the flux produced by diffuse component and resolved sources provides a lower estimate of the total emission that can be compared with the observational determinations of the total gamma-ray flux at TeV energies obtained by HESS \cite{5}, HAWC \cite{7}, Argo-YBJ \cite{4} and
Milagro [6]. This comparison is reported in Fig. 1. We re-binned the data from HESS, HAWC and Milagro over longitudinal bins $\delta l \sim 10^\circ$ that are comparable with Argo-YBJ angular resolution. The data points are reported in Fig. 1 in the bin midpoint and have vertical error bars that include systematic and statistical errors of the measured fluxes. The two errors are summed in quadrature and correspond to 30% for HESS [14], 50% for HAWC [7], 27% for Argo-YBJ [4] and 36% for Milagro [6]. The grey dashed lines are obtained by performing a moving average of the experimental data with the previously discussed $\delta l$. The red and blue curves displayed in Fig. 1 give the sum of the gamma-ray flux produced by sources in HESS catalogue and diffuse emission, averaged in the galactic latitudinal windows considered by each experiment. The red lines take into account CR spectral hardening hypothesis while blue lines correspond to the standard assumption. Solid and dashed lines are obtained (in both cases) by assuming that the CR spatial distribution follows that of SNRs with smearing radius (i.e. diffusion length) equal to $R = 1$ kpc and $R = \infty$, respectively. The green dotted lines in the various panels show the contribution to the total flux which is ascribed only to sources resolved by HESS.

The results reported in Fig. 1 allow us to reach the following important conclusions:

i) The main features of the gamma-ray signal in the TeV domain are reproduced by our model both as function of the observation angle and energy;

ii) The resolved sources emission accounts for a large fraction of the total flux in the TeV domain;

iii) The predicted fluxes in the presence of CR hardening saturate or exceed the observed signal in certain regions of the Sky.

In particular, the largest prediction considered in this work, which is obtained by including CR spectral hardening and by assuming that the CR spatial distribution follows that of SNRs with $R = 1$ kpc smearing radius (red solid lines), account for 95%, 104%, 104% and 118% of the total signal observed by Argo-YBJ, HESS, HAWC and Milagro in the angular ranges indicated in Fig. 1, respectively. This is hardly acceptable on physical basis considering that an additional non negligible contribution is expected to be provided by non-resolved sources and IC.

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