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Time Variability of Galactic CRs and the Diffuse TeV Gamma-Ray Emission Predicted with GALPROP

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Using the 3D simulation software GALPROP, we modelled the Galactic cosmic ray (CR) diffusion and investigated the time variability of the gamma-ray flux along the Galactic plane using a distribution of stochastically placed CR sources. These CR sources more accurately represent the formation rate and finite lifetimes compared to the steady-state CR injections models that are typically assumed. Our results show that the leptonic component of the gamma-ray emission is highly sensitive to the assumed electron injection and spectral characteristics. Furthermore, the leptonic component is heavily dependent on the positions of the sources due to the rapid synchrotron cooling of the very-high-energy electrons. At 1 TeV the total gamma-ray flux along the Galactic plane can vary by as much 50% due only to the stochasticity of the CR source placement. Therefore, the large-scale gamma-ray emission that CTA will observe may be significantly influenced by gamma rays local to CR accelerators. The diffuse emission that CTA observes will be heavily impacted by the gamma-ray variability, with the variability in the large-scale gamma-ray emission having important implications for any background modelling that CTA performs. Hence, we will also provide the first look at the time-dependent morphology in the multi-TeV gamma-ray structures in the Milky Way and quantify the variation over time and Galactic longitude.

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1. Introduction

Cosmic ray (CR) particles are accelerated up to PeV energies and can diffuse through the Milky Way (MW) for millions of years, resulting in a diffuse 'sea' of CRs. The CRs lose energy and emit non-thermal broad-band emissions due to interactions with the various components of the interstellar Medium (ISM); the interstellar gas, the interstellar radiation field (ISRF), and the Galactic magnetic field (GMF). Observations of these emissions are essential to understanding how the CRs are accelerated up to these energies and for understanding how they travel through the MW. γ-ray observations also provides insights to the spatial distributions of the ISM components.

The standard procedure for Galactic diffusion calculations is to inject CRs based on a smoothly-varying source distribution. In reality, CRs are injected into the ISM by individual sources with finite lifetimes. The observed diffuse CR sea is then created from the ensemble of all CR accelerators. Due to the CR spectra softening as the CRs diffuse away from their sources, and as the Galactic CR sources exist for some finite length of time, there will be some energy where the fluctuations due to individual sources will outshine the diffuse flux of CRs. The magnitude of the temporal variations will depend on the distribution of the CR sources, the inection spectra of the CR sources, the creation rate of the CR sources, and the lifetimes of the CR sources.

Temporal variation in the CRs will necessarily impart a component of temporal variation onto the γ-ray sky. Regions of the MW that have significant variations in their CR intensities will be inherently more variable in γ rays. Accurately modelling CR porpagation and VHE γ rays would require precise position and spectral information on all CR accelerators in the MW within $\sim$1 kpc of the Solar location. As this data is not currently known, any temporal variation that we observe is an additional modelling uncertainty that remains to be quantified. This uncertainty impacts all CR propagation codes and their VHE γ-ray emission predictions.

Previous results from [1] found that for γ-ray energies above 1 TeV the electron IC emissions had an increasing contribution to the total γ-ray flux observed along the Galactic plane. Adittionally, features in the local CR electron flux will have a strong dependence on the proximity to nearby CR electron accelerators. Hence, for the CR electrons with energies >10 TeV the placement of the individual sources has an impact on both local CR measurements as well as estimates of the >10 TeV diffuse Galactic γ-ray emission.

In this contribution we use the time-dependent solution available in the Galprop CR propagation package [2, 3] to quantify the variations in both the CR and γ-ray fluxes as a function of energy. We will quantify this uncertainty only for a single combination of ISM distributions; however, we do not expect the degree of uncertainty to change dramatically across the available range of reasonable models. We will also quantify the impacts that the temporal variability will have on future observations of the diffuse γ-ray emission such as, for exmaple, by CTA.

2. Modelling Setup

The Galprop framework [4, 5] is a widely employed CR propagation package that now has over 25 years of development behind it. For this paper, we use the latest release (v57), where an extensive description of the current features is given by [3].

2.1 Input Distributions

One of the critical inputs for a Galprop run is the CR source distribution, i.e. the locations in the MW where the CRs are injected. Under the steady-state assumption the source distribution represents the relative amplitude of the injection spectra of CRs at a given location. In this work we use the time-dependent solution, which instead utilises the source distribution as a synthetic probability density function to stochastically place individual/discrete CR injection sites across the MW [2, 3]. The CR source distribution is defined as a sum of a disc-like component and a spiral-arm component. The components are given an equal weighting such that half of the local CR flux comes from each of the two components. For a description of the construction of the two components, see [1] and references therein.

The propagation and emissions of VHE CR electrons and positrons are largely controlled by the interstellar radiation field (ISRF) and the Galactic magnetic field (GMF). Futhermore, the pair-absorption effects on the >10 TeV γ rays are completely regulated by the ISRF spatial and spectral distribution. Here we utilise the 'R12' ISRF model and the 'PBSS' GMF model (see [1], and references therein). Both of these models were chosen due to their inclusion of the Galactic spiral arms.

For descriptions on the input ISM gas distribution and the CR propagation parameters see [1], and references therein.

2.2 Modelling Parameters

The critical condition is that the chosen combination of the inputs described above reproduces the local CR spectra. To ensure that the local spectra are reproduced, the propagation parameters and source spectra are optimised following [1]. We use the XY limits of ±20 kpc and the Z limits of ±6 kpc. We use the previous IAU recommended distance from the GC to the Solar location of $R_s = 8.5$ kpc, such that it agrees with the other models used in the simulation. The Solar location in our coordinate system is given by $(X, Y, Z) = (8.5, 0, 0)$ kpc. For runtime efficiency we use a non-linear grid (tan spatial grid). For the CRs, we use ten bins per decade ranging from 1 GeV/nuc to 10 PeV/nuc. For the γ rays, we use give bins per decade ranging from 1 GeV to 1 PeV. The γ-ray skymaps use a seventh-order HEALPix [6] isopixelisation, giving a pixel size of $27.5'$.

For the time-dependent solution we do not define the individual CR accelerator source types, e.g. SNRs, PWNe, stellar clusters, and binary sources. The relative CR contribution between the various source types in the MW is not currently constrained adequately. Instead, we approximate some 'average' source, which is largely based on SNRs as they are believed to be the principal CR source class. The source parameters are tuned under the steady-state and diffuse assumptions, which injects CRs based on the smoothly-varying source distribution and does not model individual sites of injection. The CR spectra for the steady-state solution is then applied to each individual source in the time-dependent solution.

For the time-dependent solution, the rate and lifetime of the CR injection regions must also be considered. As mentioned above, instead of simulating impulsive and continuous sources separately, or even each individual source type (e.g. SNR, PWNe, etc.) separately, we chose to simplify the situation into one 'average' source type for simplicity. The source creation rate and the source lifetime are additional free parameters which do not impact the CR normalisation condition.

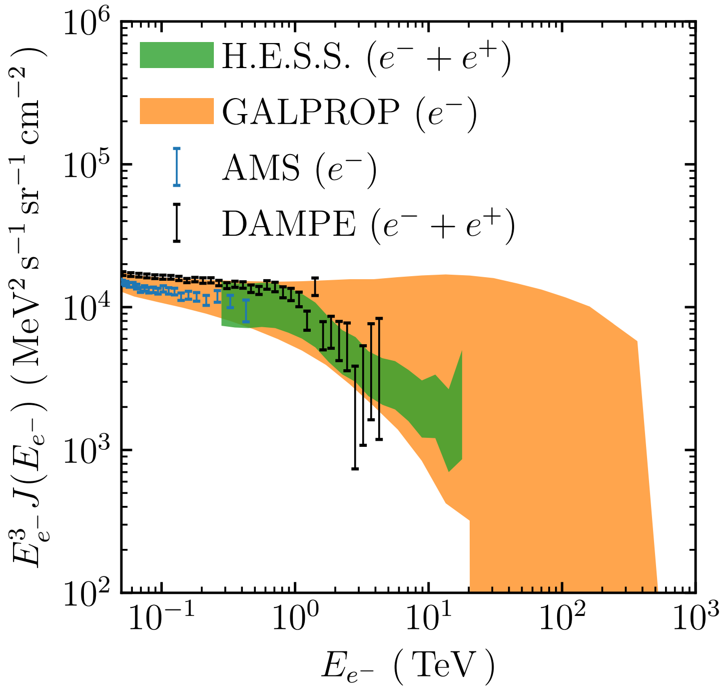

Figure 1: The variation in the simulated GALPROP electron kinetic energy spectrum above 50 GeV taken at the Solar location over a 5 Myr period is shown in orange. The preliminary H.E.S.S. combined electron and positron spectrum is from [7], the AMS electron spectrum is from [8], and the DAMPE combined electron and positron spectrum is from [9].

However, the degree of variation will be impacted. There is no tight contraint on the estimates of the rates and lifetimes of the various classes of CR accelerator in the MW. For this work we follow [2] and take a creation rate of one CR accelerator every 100 yr and a single source lifetime of 100 kyr.

We run the CR diffusion until the CR flux density across the entire MW has reached a steady sate. After this point, all variations in the CR and γ-ray flux will be due to the placement of the CR sources and centred around the steady-state flux values. The steady-state flux for the energy range of interest required 100 Myr of simulation time. After the steady-state fluxes have been reached, we run CR diffusion for an additional 5 Myr. All results shown here use only these final 5 Myr for the analyses, with a 25 kyr step between outputs.

3. Results

Recent observations from DAMPE [9] and the preliminary results from H.E.S.S. [7] show a potential cut-off/break at ~1 TeV for the combined electron and positron flux. Any TeV cut-off in the electron spectrum is explained naturally by the short (<500 pc) cooling distances of the VHE electrons – any local measurement can only probe the local environment. Figure 1 shows the combined electron and positron flux DAMPE and H.E.S.S., as well as the electron flux from AMS [8]. An envelope of the variation in the local electron flux from GALPROP is shown for a 5 Myr period. The GALPROP electron flux shows a potential cutoff at all timesteps, with the cut-off energy

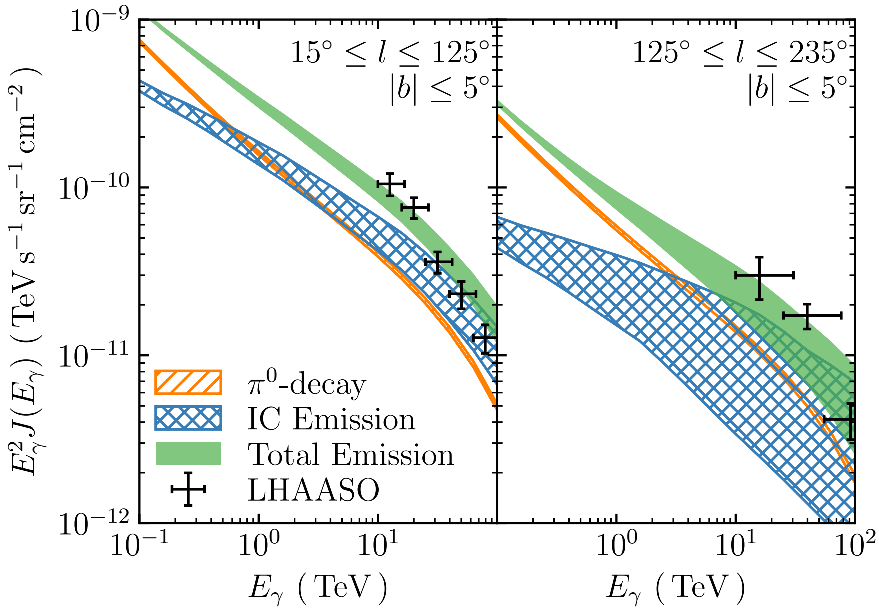

Figure 2: The variation in the simulated Galprop γ-ray spectra for a 5 Myr period for the inner ($15^\circ \leq l \leq 125^\circ$, $|b| \leq 5^\circ$) and outer ($125^\circ \leq l \leq 235^\circ$, $|b| \leq 5^\circ$) LHAASO regions. The π^0-decay emission is shown by the orange hatched bands, the IC emission is shown by the blue hatched bands, and the total emission is shown by the green shaded region. The LHAASO flux points are from [10], and are shown by the black points.

varying between ~800 GeV and 60 TeV, depending on the proximity between Earth and the nearest electron accelerator at any given timestep. At 10 TeV the local electron flux varies by up to a factor of ten.

As the TeV protons (and heavier nuclei) are completely diffuse, there is little variation in the local hadronic spectra. The integration over the line-of-sight for the γ-ray calculations further reduces the variability in the hadronic γ rays. The γ-ray flux for two of the LHAASO regions is shown in Figure 2. For all Galactic longitudes, the pion-decay emission is constant over the 5 Myr simulation period. For the leptonic emission, the variability in the electrons is imparted onto the IC emissions. As the γ-ray energy increases, so does the variability of the IC emission. Furthermore, for the outer LHAASO region the line-of-sight integral contains less of the ISM, and so is more sensitive to variations in the electron density at any given location.

For γ-ray energies >1 TeV in the inner LHAASO region, and for >10 TeV for the outer LHAASO region, the IC emission can equal the pion-decay emission for some epochs. For the inner LHAASO region the IC emission dominates over the pion-decay for γ-ray energies above 10 TeV for all epochs in the simulation. The dominance of the IC emission for the inner Galaxy agrees with the results from [1]. Furthermore, the total γ-ray emission is within the uncertainties of the LHAASO diffuse flux estimates [10] for all timesteps in the simulation.

We applied a sliding window analysis to the Galprop results, with the longitudinal profile shown in Figure 3. The sliding window is defined by the Galactic latitude range $-1.5^\circ \leq l \leq +1.0$, spans $\Delta w = 15^\circ$ is Galactic longitude, with the windows being spaced $\Delta s = 1^\circ$ apart (for a

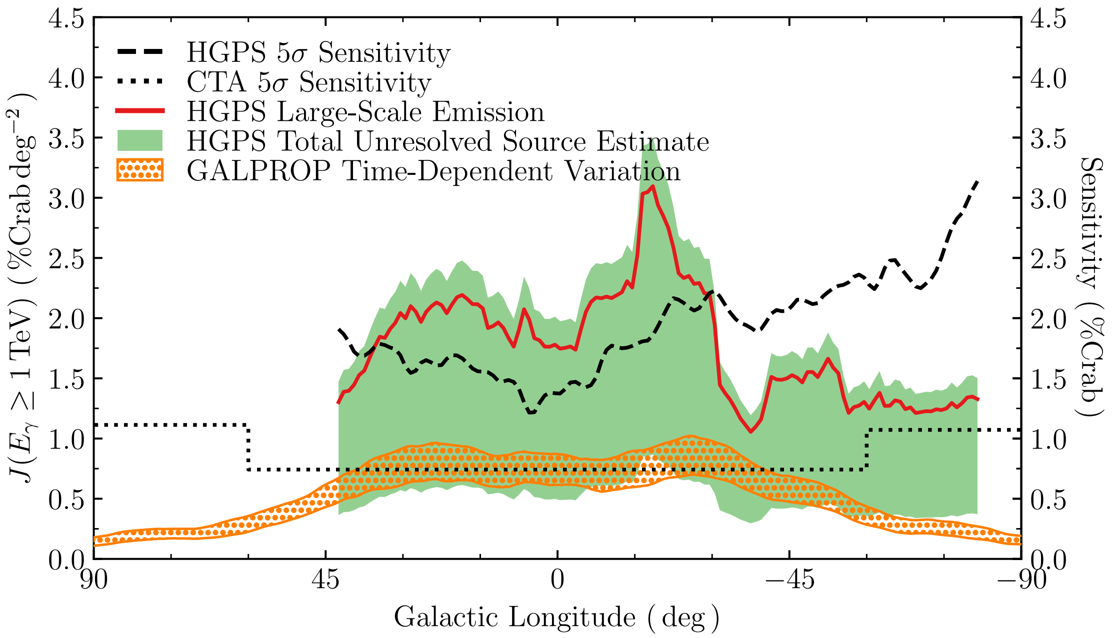

Figure 3: The longitudinal profile for the HGPS emission after catalogued sources are subtracted (see [1]) is shown in red. Accounting for the unresolved source contribution to the diffuse emission in the HGPS emission (see [1], and references therein) is shown by the green shaded band. The variation in the simulated GALPROP γ-ray spectra for a 5 Myr period is shown by the orange hatched band. All profiles are created using a sliding window analysis (see [1], and references therein) and are integrated for γ-ray energies >1 TeV, and are shown in units of %Crab deg^{-2}. The 5σ sensitivity for the HGPS is shown by the dashed black line and the sensitivity for the planned CTA GPS is shown by the dotted black line, with both sensitivities given in units of %Crab.

description of the chosen sliding window parameters, see [1]). Also shown is the large-scale γ-ray emission from the HGPS [11] after subtracting the γ-ray emission from catalogued γ-ray sources. Estimates of the unresolved γ-ray source component to the large-scale emission observed in the HGPS vary between 13% to 60% (see [1], and references therein). The longitudinal profile after accounting for the unresolved sources and after accounting for the flux uncertainty of the HGPS is shown in green. The residual emission found after accounting for both the catalogued and unresolved source components is an estimate of the large-scale diffuse emission in the TeV energy regime.

4. Discussion

The electron flux at the Solar location is not representative of the Galactic CR flux. This is especially true for the VHE CR electrons, where the local population probes only the nearest ~100–500 pc region. The local CR electron flux, and the break observed in the TeV energy regime, can arise naturally from a population of discrete CR electron accelerators. The local CR electron spectrum, especially for energies above 100 GeV, can only be considered a snapshot in time. These results also imply that there is no electron accelerator near the Solar location at the current time.

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Hence, it would be incorrect to normalise the CR electron injection spectrum to the local observed electron spectrum for kinetic energies above 100 GeV.

The energy of the electron spectral cutoff, as well as the strength of the cutoff, will depend on the electron injection spectrum. Currently, we considered only an average CR source class that injects both hadrons and leptons into the ISM. Considering the hadronic and leptonic sources separately may be necessary in future work, and will likely increase the observed variation in the γ-ray fluxes.

Current diffuse model comparisons to LHAASO implicitly add a collection of unresolved CR hadron accelerators with hard spectra to explain the LHAASO emission. A hadronic class of sources with these properties has not yet been observed. However, the IC emission component found in Figure 2 in the LHAASO energy range adequately describes both the spectral shape and intensity of the LHAASO flux points. The IC emission found here can be considered as leptonic emission from an ensemble of unresolved CR electron accelerators. An unresolved leptonic component to the large-scale LHAASO emission agrees with the large number of >100 TeV electron accelerators found by the LHAASO collaboration.

For the >1 TeV longitudinal profile (Figure 3), the variation found from injecting CRs from localised and randomly-placed CR sources is similar to the modelling uncertainty found across a grid of source distributions, ISRF models, and GMF models [1]. For further discussion on the Galprop emission and the comparison to the HGPS, see [1].

The variation in the Galprop CR spectra and γ-ray emission depends on the CR source parameters, particularly the source lifetime and source creation rate. These will be investigated further in future work.

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