Modelling the TeV Diffuse Emission with GALPROP

Peter Marinos

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The University of Adelaide
Supervisors: A. Prof. Gavin ROWELL and Dr. Sabrina EINECKE

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Introduction and Motivation

- H.E.S.S. Collaboration et al. 2014 had the first detection of large-scale γ-ray emission at these energies
- H.E.S.S. Collaboration et al. 2018 included another analysis, but was unable to make conclusions on the diffuse emission due to analysis constraints
- Neronov et al. 2019 compared the HGPS to Fermi-LAT
- No one has compared the HGPS to cosmic ray simulations as of yet

GALPROP Basics

- GALPROP numerically solves the transport equation in 3D
- Cosmic-rays are propagated through the Galaxy, and γ-ray skymaps are created
- GALPROP's input parameters can be varied, and the effects on the diffuse emission can be discerned
- Using version 56.0.2870 in the steady-state mode

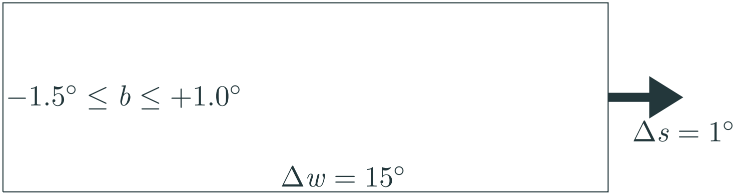
Transport Equation

The three-dimensional transport equation, which gives the density per unit of total particle momentum, is written as:

$$
\begin{aligned}
\frac{\partial \psi}{\partial t} = \; & q(\vec{r}, p) && \texttt{Source Term} \\
& + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) && \texttt{Diffusion and Advection} \\
& + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi && \texttt{Fermi Acceleration} \\
& - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V} \psi) \right] && \texttt{Radiative Loss and Adiabatic Expansion} \\
& - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi && \texttt{Nuclear Fragmentation and Radioactive Decay}
\end{aligned}
$$

Analysis Method

- The analysis had to be compatible with both GALPROP and the HGPS
- Sliding window with width $\Delta w = 15°$, spaced $\Delta s = 1.0°$ apart
- Latitudes are restricted to $-1.5° \leq b \leq +1.0°$
- Take the average flux of all pixels within the window



- CRs are injected into the galaxy based on a source distribution, $\rho(r, \theta, z)$
- ρ is the superposition of the galactic disk and spiral arms
- The fraction between the disk and arms can be adjusted

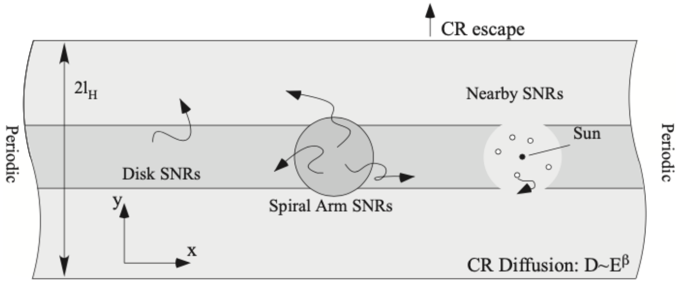
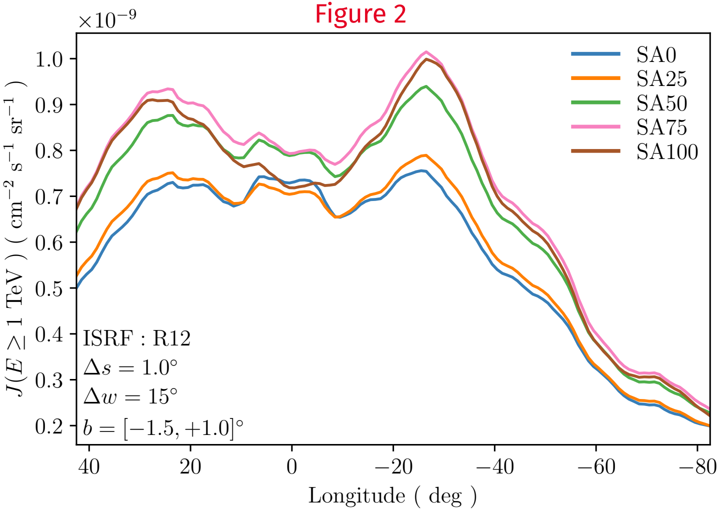


Figure 1: Side-on illustration of the galactic plane showcasing the difference between disk and spiral arm sources.
Image from Shaviv et al. 2009

Varying Source Distributions within GALPROP, Part (ii)

Figure 2



- Average flux within a window, integrated above 1 TeV
- SA% denotes the percentage of CRs injected into the spiral arms
- The variation between the source distributions is up to 30%

Varying the Interstellar Radiation Field within GALPROP, Part (i)

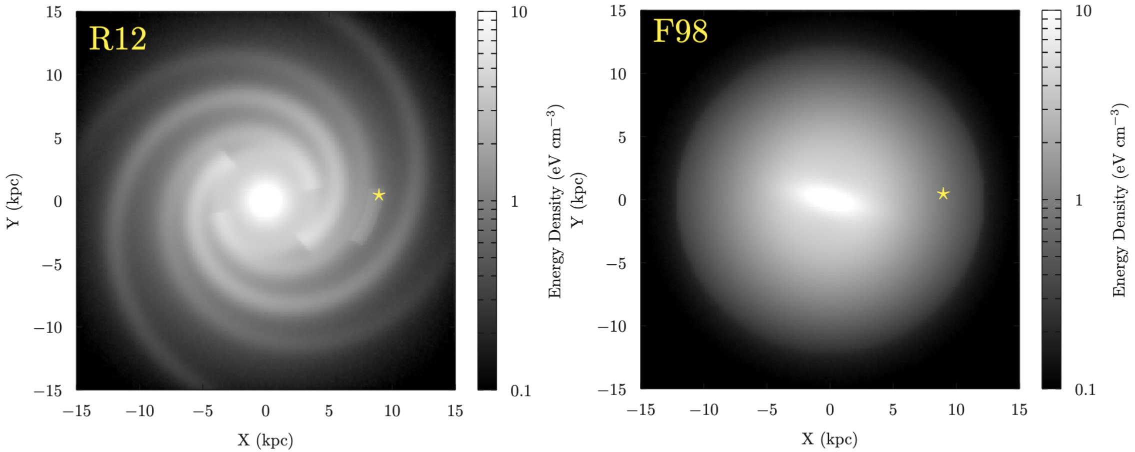


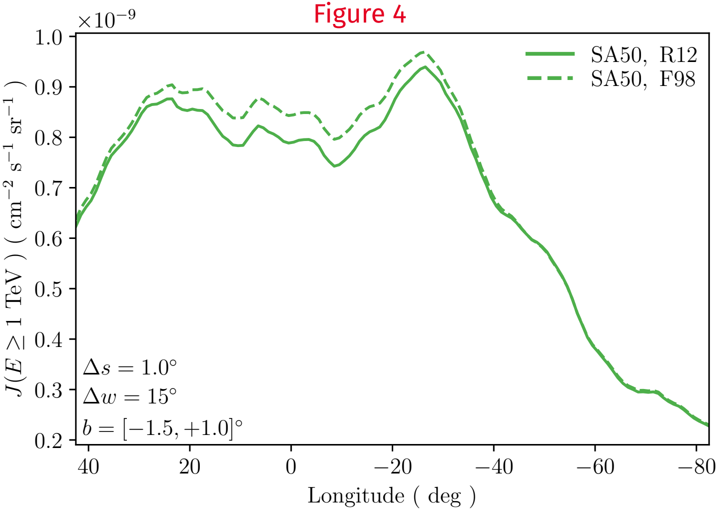
Figure 3: The integrated energy density of the two interstellar radiation field (ISRF) models. The yellow star marks the location of the Solar system.

Image from Porter et al. 2017

Varying the Interstellar Radiation Field within GALPROP, Part (ii)

- Average flux within a window, integrated above 1 TeV
- R12: axisymmetric bulge and spiral arms (Robitaille et al. 2012)
- F98: non-axisymmetric bulge (Freudenreich 1998)
- The variation between the ISRF models up to 15%

Figure 4



HGPS Basics

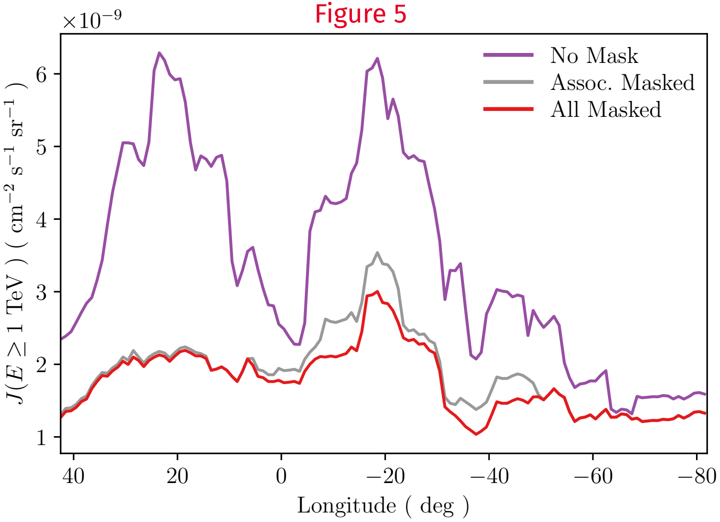
- The H.E.S.S. galactic plane survey (HGPS) includes 2673 hours of data
- Covers longitudes from $l = 250°$ to $l = 65°$, and latitudes $b \leq |3°|$
- Public map is the flux integrated above $1\ \mathrm{TeV}$
- Two containment radii are public, $0.1°$ and $0.2°$

Masking Sources from the HGPS, Part (i)

- We are interested in the diffuse emission, so sources must be masked
- Created two masks;
  - Mask A: Only sources with a CR-accelerator association are masked
  - Mask B: All sources are masked
- Masking sources follows the recipe in H.E.S.S. Collaboration et al. 2018

Masking Sources from the HGPS, Part (ii)

Figure 5

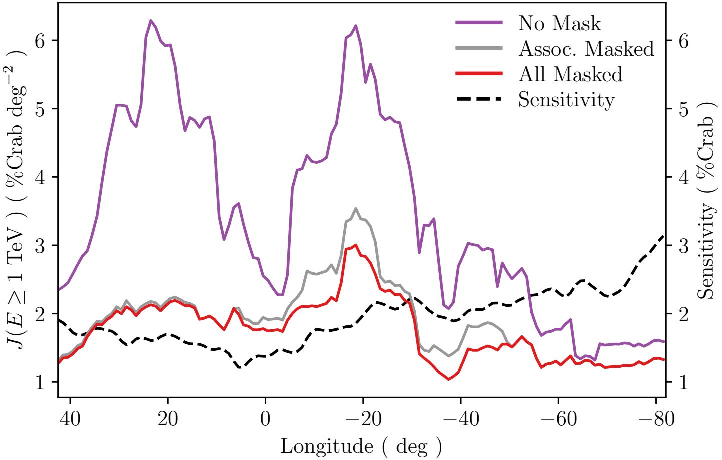


- Flux integrated above 1 TeV as measured in the HGPS
- Integration radii equal to $0.2°$

Sensitivity of the HGPS

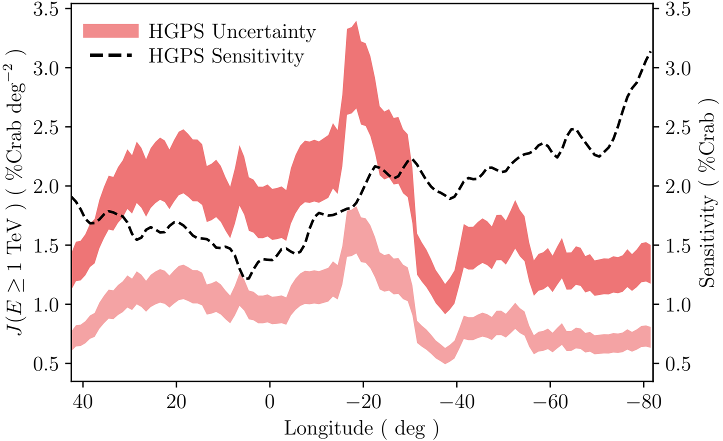
- Flux integrated above 1 TeV in units of $(\%\mathrm{Crab}/\mathrm{deg}^2)$
- HGPS sensitivity shown for the 5σ level, in units of $(\%\mathrm{Crab})$
- Both the flux and the sensitivity are for a $0.2°$ integration radius
- $\Phi_{\mathrm{crab}}(E \geq 1\ \mathrm{TeV}) = 2.26 \cdot 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Figure 6



Unresolved Source Contribution to the HGPS

Figure 7



- The HGPS has a systematic uncertainty in the flux of 30%
- Steppa et al. 2020 estimate that unresolved sources contribute between 13% and 32% to the flux

Application to CTA

- CTA will be ten times more sensitive than H.E.S.S., and will be able to resolve many more sources even with the lower observation time
- The CTA survey will cover much more of the sky, allowing further comparisons to TeV models
- Will allow more robust conclusions on, and improvements to, TeV models

Sensitivity of the Proposed CTA Survey

- CTA sensitivity shown for the 5σ level for the full 10-year plan (1620 observation hours)
- The CTA sensitivity adapted from Science with the Cherenkov Telescope Array (2018) by the CTA Consortium

Figure 8

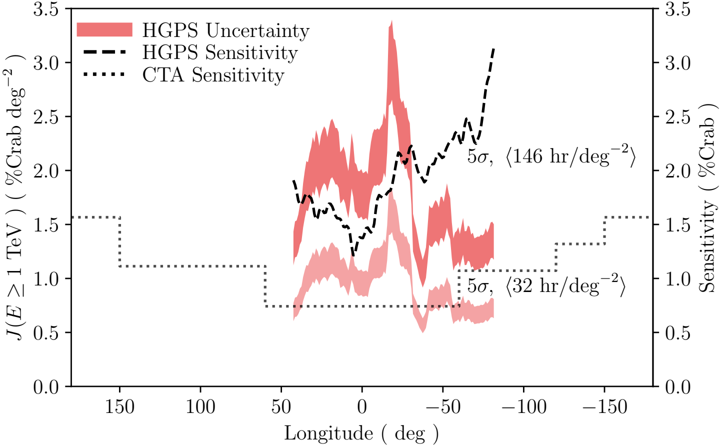


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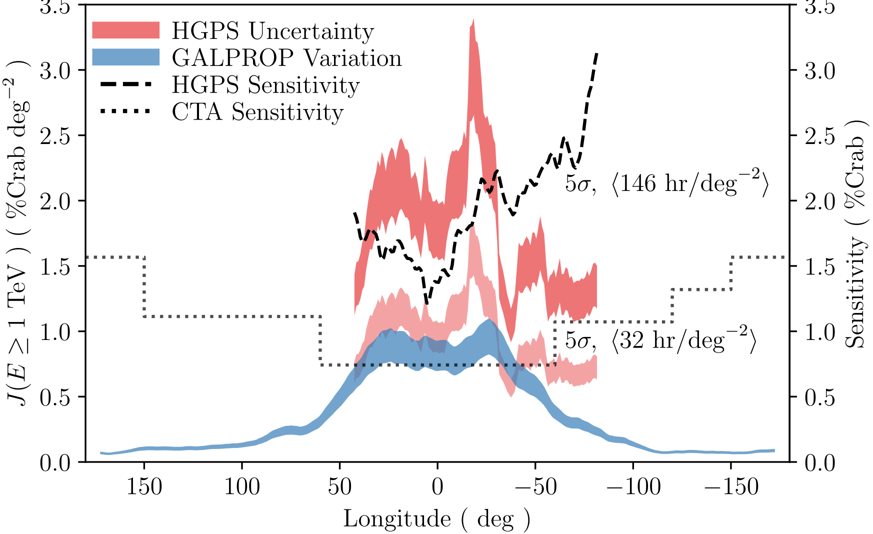
Figure 9



Summary

- Tested the variation in different GALPROP models by altering the source distribution and ISRFs
- Discrepancy between GALPROP and HGPS are possibly explained by unresolved sources
- CTA should be able to resolve these sources and answer this question
- Possible changes to GALPROP will give a more accurate representation of the γ-ray sky, including time-dependence

EXTRA: Integration Radii Differences

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