High-Energy Gamma-Rays from the Milky Way: 3D Spatial Models for the CR and Radiation Field Densities $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$

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What is GALPROP?

- Tool for modelling and interpreting cosmic-ray (CR) and non-thermal emissions data
- Key ideas: self-consistent modelling and realism
- Self-consistency: different kinds of data (CR data, radio, gamma rays) are inter-related because the measured CRs propagate in the ISM losing energy, which produce broadband EM emissions and other secondaries that are also measured
- Realism: objective to include as much realism into the underlying models for the ISM and CR sources, and propagation phenomenology – based on extensive collection of astronomical and nuclear/particle data with minimal simplifying assumptions
- GALPROP combines these into a framework that can be downloaded/installed locally, or run from a web-browser at the GALPROP website: galprop.stanford.edu
Cosmic Rays and Interstellar Emission

GALPROP +

ISM

diffusion
energy losses
reacceleration
convection
etc.

He CNO

P

CR species:
- Only 1 location
- modulation

PAMELA

20 GeV/n

helio-modulation

BESS

PSF

HESS

Chandra

Fermi

ACE

TeV Particle Astrophysics 2017

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Developments and New Release

- Numerous technical and physics improvements
- Spatial variations in propagation for diffusion via diffusion coefficient and Alfvén speed (reacceleration)
- Generalised source distribution and spectral models: separately specified spatial densities and spectra for each CR species
- 2D/3D gas models
- 2D/3D interstellar radiation field models
- Arbitrary positioning of observer – useful for modelling also other galaxies
- Improved solvers for propagation equations, parallel and vectorised – dramatically decreases time for 3D calculations
- New integrator for non-thermal intensity map calculations – includes pair absorption on ISRF models (user-specified)
- Other improvements both large and small, including coupling to HelMod code – enabling tracing CRs from Heliopause (LIS) to Earth … no more “force-field” approximation for solar modulation
3D models for the Interstellar Emission

- New release of GALPROP (v56) + 3D CR source density models + 3D ISRF models
- 3 CR source density models: CR power injected according to `Pulsars’ (2D), 50% Pulsars + 50% spiral arms, 100% spiral arms. Propagation parameters adjusted for each to reproduce measurements of CR data: protons, secondaries, leptons from AMS-02, PAMELA, HEAO-3
- 2 ISRF models: one with spiral arms, star-forming ring, central bulge; one with smooth disc with inner hole, ellipsoidal bar … both calculated with FRaNKIE code and tested to reproduce near- to far-infrared data (shorter wavelengths not so useful because of strong dust extinction). Both model inputs for the stellar luminosity and dust spatial distributions taken from literature: R12 (Robitaille et al. 2012) and F98 (Freudenreich 1998)

Cosmic Rays

- Source spectra modelled with broken power laws in rigidity
- Assume diffusive reacceleration model with 6 kpc halo and fit usual propagation parameters for each source distribution
- Normalisation for the propagated CR intensities is made to CR data (AMS-02, PAMELA, HEAO-3)

CR energy density at plane

Pulsars
ISRF Models: R12 and F98

Intensity at Solar system for $|b| < 5^\circ$

- Full radiation transport modelling using FRaNKIE code
- R12 includes stellar disc, ring, bulge, 4/2 major/minor arms + dust disc with inner hole toward GC
- F98 includes `old’ and `young’ stellar discs that are warped, spheroidal bar, and warped dust disc with inner hole toward GC
- R12 generally reproduces more structured features in the local intensity data, but both R12 and F98 ISRF models are consistent with data
ISRF Models: R12 and F98

- R12 and F98 produced noticeably different integrated energy density distributions that reflect the stellar and dust distributions.
- In and about the inner Galaxy there is a factor ~5 difference between the models, even though locally they are both reasonably consistent with the data.
Interstellar Emissions

Fractional Residual: \[
\frac{(\text{SA100-R12}) - (\text{SA0-Std})}{\text{SA0-Std}}
\]
SA100 = 100% sources in spiral arms

- Reference case: 2D (SA0) + Std ISRF from GALPROP
- Fractional residual maps \([(\text{model-ref})/\text{ref}]\) for other combinations: SA50-R12, SA50-F98, SA100-R12, SA100-F98
- CR src and ISRF models with arms produce a density-squared effect because of enhanced CR and ISRF energy densities in these regions, produces `doughnut' in residual maps and the effect is energy-dependent

SA100-R12 @ 10.6 MeV
SA100-R12 @ 1.2 GeV
FERMI-LAT OBSERVATIONS OF HIGH-ENERGY $\gamma$-RAY EMISSION TOWARDS THE GALACTIC CENTER

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All-Sky Residuals 1-3.16 GeV

Data-baseline (Pulsars)

Ajello et al. `16 (no masks)
All-Sky Residuals 1-3.16 GeV

Data-baseline (Pulsars)

Ajello et al. `16 (no masks)
Interpreting the scaling results

Gamma-ray intensity

CR energy density in-plane

Red curves: No CR bulge
Black curves: With CR bulge
Dot: IC
Dash: $\pi^0$
Dash-dot: Brem
Solid: total
Injected CR power for the `bulge/bar' is ~25x smaller than the arms for the residuals shown. Can be done with CR nuclei/leptons or leptons only.

Ajello et al. `16 (no masks)
Summary of Fits for 15° x 15° RoI

Fit to data requires increase over baseline. Interpretation with 2D models unclear – 3D bulge/arm models provide more physical basis for understanding these results.
Coming soon: 3D atomic and molecular gas models

- Forward-folding model fitting method
- ML fit to HI LAB and DHT CO surveys
- Build model iteratively: 2D disc, add warp, bulge/bar, flaring (outer Galaxy), spiral arms
- Spiral location and shape same for HI and CO but scale-heights and normalisations differ
- Each arm has free normalisation in model fitting method
Effect of 3D gas models for gamma-ray data analysis

- Ratio of 3d/2d gas model, same CR source distribution (SA0/Pulsars)

3d/2d fractional difference @ 1 GeV
Summary

- GALPROP is officially of drinking age in the US (21+ years development)!
- New release v56 with many additions and optimisations: specific focus improving performance for full 3D CR and interstellar emission calculations.
- New 3D models for ISM density distributions have been developed: ISRF (Porter et al.) and Gas (Johannesson et al.).
- Modelling with upcoming GALPROP release using 3D CR source and ISRF densities show new features in residual maps compared to 2D-based reference calculations.
- The 3D models provide a plausible explanation for the puzzling results from the analysis based on 2D axisymmetric models.
- CR sources in spiral arms and central bulge/bar in combination with 3D ISRF models are required.
- Coming soon: results with 3D gas and CR sources
- Check out galprop.stanford.edu and galprop.stanford.edu/webrun for configuration files and data products and facility to run code via browser