PROCEEDINGS OF SCIENCE

Galactic Diffuse Gamma-Ray Emission From 3D Cosmic-Ray Transport Models

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Ralf Kissmann*, **Olaf Reimer, and Felix Niederwanger**
Leopold Franzens Universität Innsbruck, Austria
E-mail: `ralf.kissmann@uibk.ac.at`

The PICARD code for the numerical solution of the Galactic cosmic-ray propagation problem allows for high-resolution 3D models that can acknowledge localised structures within our Galaxy. Using PICARD, we address the impact of different transport physics processes on the flux and distribution of diffuse Galactic gamma rays: we investigate models with a cosmic-ray source distribution aligned with different arrangements of the Galactic spiral arms, under consideration of a recently updated interstellar radiation field model, and those assuming anisotropic cosmic-ray diffusion governed by an improved Galactic magnetic field model. The choice of changing the different transport parameters is most readily visible in the inverse-Compton channel, which shows features not present in commonly-used axisymmetric transport models.

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[*] Speaker.

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The Picard Code

Numerical solution

- Solution of steady state transport equation:

$$-\nabla\cdot(\mathcal{D}\nabla\psi_i - \vec{v}\psi_i) - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi_i + \frac{\partial}{\partial p}\left\{\dot{p}\psi_i - \frac{p}{3}(\nabla\cdot\vec{v})\psi_i\right\} = \\ = q(\vec{r},p) - \frac{1}{\tau_f}\psi_i - \frac{1}{\tau_r}\psi_i$$

  via Picard cosmic-ray propagation code (Kissmann, 2014)

- Solution of discretised equations via dedicated numerical methods:
  - **Multigrid** (red-black Gauss-Seidel or alternating plane Gauss-Seidel)
  - **BICGStab**-Solver

⇒ Solution accuracy determined by user-defined discretisation error only

- Very-high resolution 3D simulations (demonstrated up to 75 pc scale resolution)
- Model Setup
  - Source-distribution model based on four-arm Galaxy model by Steiman-Cameron et al. (2010) – see also in Werner et al. (2015)
  - Parameters adapted to Earth-bound cosmic-ray observations (see Kissmann et al., 2015)
- Ability to include anisotropic spatial diffusion (see also Effenberger et al., 2012a)

Spiral-Arm Models

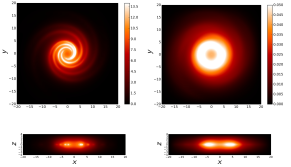


Fig 1: Flux of ∼10 GeV Galactic cosmic rays in the Galactic plane (top) and in the $x - z$-plane (bottom). Results are shown for ^{12}C (left) and for ^{10}B (right) for a four-arm source distribution.

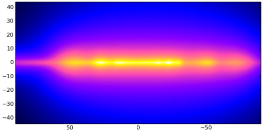
Effects on CR nuclei

- Confinement near sources for primaries (Kissmann et al., 2015)
- Strong spatial variation of B/C relative to spiral arms
- B/C ratio governed by
  - spatial diffusion
  - re-acceleration
  - position relative to spiral arms

→ B/C no global measure in 3D models any longer

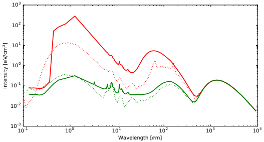
Impact on Gamma Rays

- Local structures (spiral-arm tangents)
- On-arm vs. off-arm contrast (see Kissmann et al., 2017)
- Harder spectra at spiral-arm tangents



New developments in PICARD

New Radiation Field

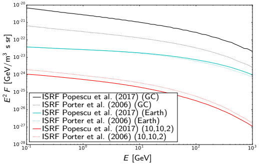


Properties

- For description see Popescu et al. (2017)
- Higher flux in Galactic center
- More details in dust regime

Impact of new ISRF

- Substantial changes in Galactic center:
  - Increase of IC energy losses → reduced high-energy electron flux
  - Factor ∼10 increase of IC emissivity
- Reduced IC emissivity in halo



Changes for observable gamma-ray flux

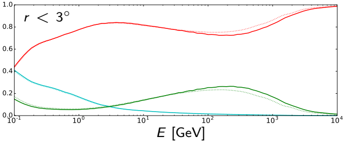


Fig 2: Relative contribution of different gamma-ray production channels in GC region (red: pion-decay emission, green: IC emission, blue: bremsstrahlung). Results for Porter et al. (2006) ISRF given as dotted lines.

Anisotropic Spatial Diffusion

Comparison of two **diffusion models**:

- Isotropic diffusion with $\mathcal{D} = D_0 \hat{I}$
- Diffusion within complex Galactic magnetic field model from Ferrière and Terral (2014)

Diffusion tensor for anisotropic diffusion models:

magnetic field coordinates: Cartensian grid coordinates:

$$\mathcal{D} = \begin{pmatrix} D_{\|} & 0 & 0 \\ 0 & D_{\perp} & 0 \\ 0 & 0 & D_{\perp} \end{pmatrix} \rightarrow \mathcal{D} = \begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{pmatrix}$$

Components of diffusion tensor for general case:

$$\begin{aligned}
D_{xx} &= D_{\|} \cos^2\theta \sin^2\phi + D_{\perp}\left(\cos^2\phi + \sin^2\theta \sin^2\phi\right) \\
D_{yy} &= D_{\|} \cos^2\theta \cos^2\phi + D_{\perp}\left(\sin^2\phi + \sin^2\theta \cos^2\phi\right) \\
D_{zz} &= D_{\|} \sin^2\theta + D_{\perp} \cos^2\theta \\
D_{xy} &= \left(D_{\perp} - D_{\|}\right) \cos^2\theta \sin\phi \cos\phi \\
D_{xz} &= \left(D_{\perp} - D_{\|}\right) \sin\theta \cos\theta \sin\phi \\
D_{yz} &= \left(D_{\perp} - D_{\|}\right) \sin\theta \cos\theta \cos\phi
\end{aligned}$$

where $\theta = \arccos\left(\vec{e}_z \cdot \vec{B}\right)$ and $\phi = \arccos\left(\vec{e}_x \cdot \left(-\vec{B}_{xy}\right)\right)$

Diffusion in X-shape Magnetic Fields

Anisotropic Diffusion: Transport Results

Model magnetic field

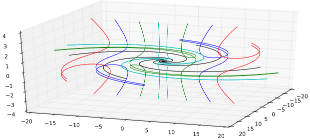


Fig 3: X-shape magnetic field model used in this study. Vertical dimension is stretched by factor 2

- Spiral magnetic field in Galactic plane
- X-shape field in halo

→ Ferrière and Terral (2014) model Dd

- Using $D_{\|} = 10D_0$, $D_{\perp} = D_0$

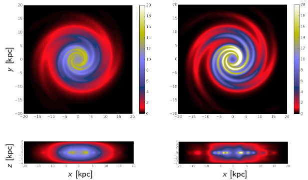


Fig 4: 1 GeV ^{12}C flux in the Galactic plane (top) and the vertical plane (bottom) for a model with isotropic diffusion (left) and one with anisotropic diffusion in an X-shape magnetic field (right).

Results I

- Fit possible with new set of propagation parameters

→ Adapted propagation parameters:
  - $\tilde{D}_0 = 2.1 \cdot 10^{24}$ m^2 s^{-1}
  - $v_A = 3 \cdot 10^4$ m s^{-1}

- Distinct impact on spatial distribution (see Fig. 4: increase of arm-interarm contrast by factor ∼ 2)

Results II

- Lower flux in Galactic center (up to factor 2.5)
- Position dependent diffusion & Galactic center physics (Gaggero et al., 2017)
  → impact of field-aligned diffusion?
- Higher gamma-ray flux from spiral-arm tangents (see Fig. 5)

Anisotropic Diffusion: Gamma-ray Emission

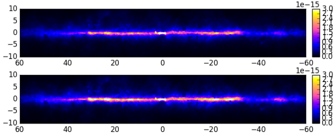


Fig 5: ∼1 TeV total diffuse gamma-ray emission for a model with isotropic diffusion (top) and a model with anisotropic diffusion along an X-shape magnetic field (bottom).

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