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

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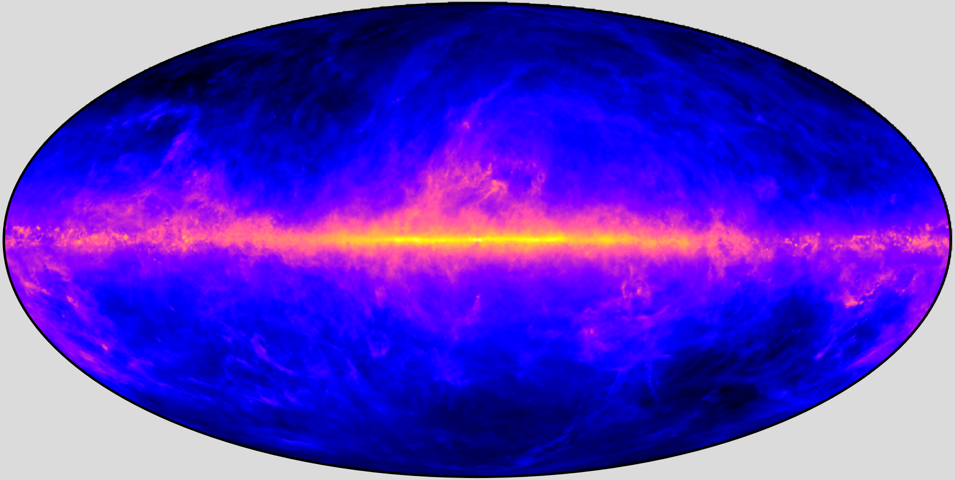


The Picard Code

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

$\Rightarrow$ 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

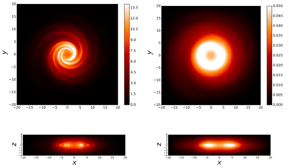


Fig 1: Flux of $\sim$10 GeV Galactic cosmic rays in the Galactic plane (top) and in the $x - z$-plane (bottom). Results are shown for ^{12}C (left) and for ^{10}B (right) for a four-arm source distribution.

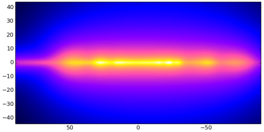
Effects on CR nuclei

- 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

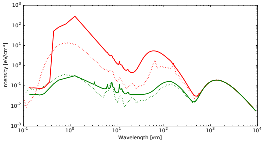
$\rightarrow$ B/C no global measure in 3D models any longer

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 Radiation Field

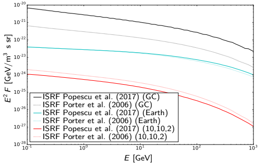


Properties

- 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 $\rightarrow$ reduced high-energy electron flux
  - Factor $\sim$10 increase of IC emissivity
- Reduced IC emissivity in halo



Changes for observable gamma-ray flux

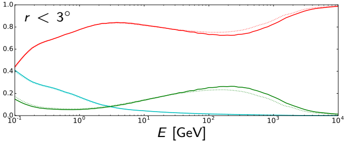


Fig 2: Relative contribution of different gamma-ray production channels in GC region (red: pion-decay emission, green: IC emission, blue: bremsstrahlung). Results for Porter et al. (2006) ISRF given as dotted lines.

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:

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

Components of diffusion tensor for general case:

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

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

Bibliography

Model magnetic field

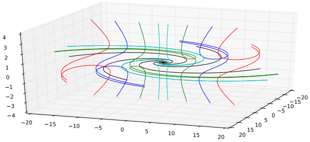


Fig 3: X-shape magnetic field model used in this study. Vertical dimension is stretched by factor 2

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

→ Ferrière and Terral (2014) model Dd

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

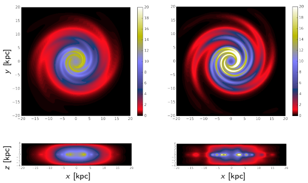


Fig 4: 1 GeV ^{12}C flux in the Galactic plane (top) and the vertical plane (bottom) for a model with isotropic diffusion (left) and one with anisotropic diffusion in an X-shape magnetic field(right).

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)

Gamma-ray Emission

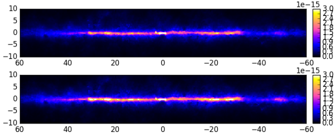


Fig 5: ∼1 TeV total diffuse gamma-ray emission for a model with isotropic diffusion (top) and a model with anisotropic diffusion along an X-shape magnetic field (bottom).

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