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

R. Kissmann\textsuperscript{1}, O. Reimer\textsuperscript{1}, and F. Niederwanger\textsuperscript{1}

\textsuperscript{1}Leopold Franzens Universität Innsbruck
The PICARD Code

**Numerical solution**

- Solution of steady state transport equation:

\[
- \nabla \cdot (D \nabla \psi_i - \vec{v}\psi_i) - \frac{\partial}{\partial p} p^2 \frac{\partial}{\partial p} \frac{1}{2} \psi_i + \frac{\partial}{\partial p} \left\{ \frac{\partial}{\partial p} \left[ \frac{\partial}{\partial p} \psi_i \right] - \frac{\xi}{\tau} (\nabla \cdot \vec{v})\psi_i \right\} = q(\vec{r}, p) - \frac{1}{\tau_f} \psi_i - \frac{1}{\tau_r} \psi_i
\]

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**

**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

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

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:

Cartesian grid coordinates:

\[
\mathcal{D} = \begin{pmatrix}
D_{xx} & D_{xy} & D_{xz} \\
D_{xy} & D_{yy} & D_{yz} \\
D_{xz} & D_{yz} & D_{zz}
\end{pmatrix}
\]

Components of diffusion tensor for general case:

\[
\begin{align*}
D_{xx} &= D_{\parallel} \cos^2 \theta \sin^2 \phi + D_{\perp} (\cos^2 \phi + \sin^2 \theta \sin^2 \phi) \\
D_{yy} &= D_{\parallel} \cos^2 \theta \cos^2 \phi + D_{\perp} (\sin^2 \phi + \sin^2 \theta \cos^2 \phi) \\
D_{zz} &= D_{\parallel} \sin^2 \theta + D_{\perp} \cos^2 \theta \\
D_{xy} &= (D_{\perp} - D_{\parallel}) \cos^2 \theta \sin \phi \cos \phi \\
D_{xz} &= (D_{\perp} - D_{\parallel}) \sin \theta \cos \theta \sin \phi \\
D_{yz} &= (D_{\perp} - D_{\parallel}) \sin \theta \cos \theta \cos \phi
\end{align*}
\]

where $\theta = \arccos(\hat{e}_z \cdot \vec{B})$ and $\phi = \arccos(\hat{e}_x \cdot (-\vec{B}_{xy}))$
Diffusion in X-shape Magnetic Fields

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

Results I

- Fit possible with new set of propagation parameters
- Adapted propagation parameters:
  - $D_0 = 2.1 \cdot 10^{24} \text{ m}^2 \text{ s}^{-1}$
  - $\nu_A = 3 \cdot 10^4 \text{ m} \text{ s}^{-1}$
- Distinct impact on spatial distribution (see Fig. 4: increase of arm-interarm contrast by factor $\sim 2$)

Results II

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

Gamma-ray Emission

Fig 5: $\sim 1$ 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).

Bibliography