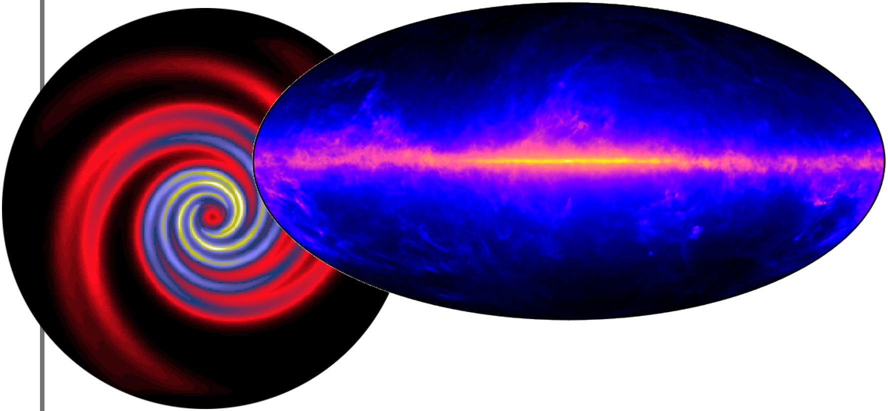
Picard & Galactic CR Propagation



CRISM 2014 – Ralf Kissmann

Reminder: Description of CR Transport

Transport Equation

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

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Individual Terms

- CR sources

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  $\rightarrow$ input for gamma rays

Solution

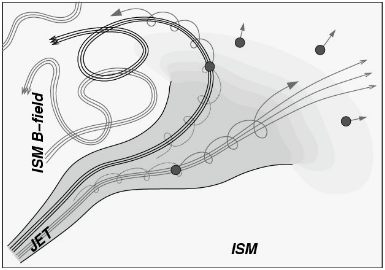
- Simplifications $\rightarrow$ analytical
- General case $\rightarrow$ numerical

Galactic Propagation Codes

Major Codes

- semi-analytical:
  - Usine

Transport in ISM



(by Heinz & Sunyaev (2002))

Galactic Propagation Codes

Major Codes

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- fully numerical
  - GALPROP

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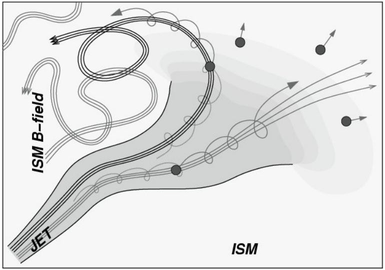

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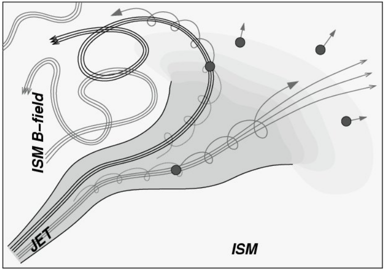

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Other Approaches

- Büsching et al.
- Effenberger et al.
- Hanasz et al. (PIERNIK)

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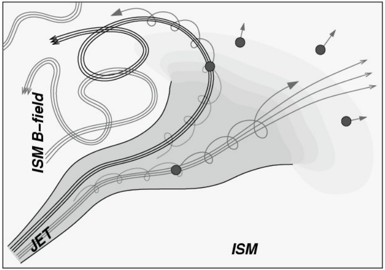

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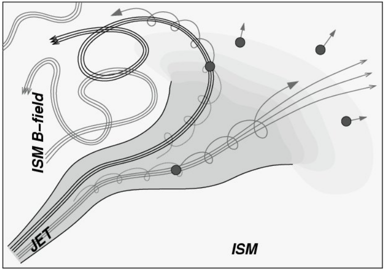

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Physics in Numerical Propagation Codes

Transport Processes

- Convection
- Diffusion
- Momentum diffusion

Physics in Numerical Propagation Codes

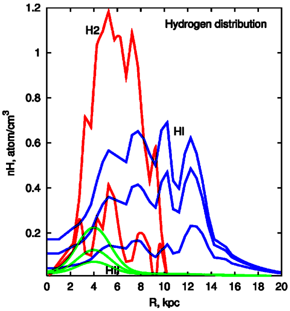
Transport Processes

- Convection
- Diffusion
- Momentum diffusion

Galaxy Model

- Matter distribution
- ISRF
- Magnetic field

Hydrogen Distribution



(From Galprop website)

Physics in Numerical Propagation Codes

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Interaction with ISM

- Spallation cross sections
- Energy loss processes
- Nuclear network

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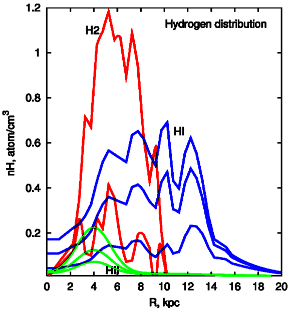

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Secondaries

- Secondary CRs
- Gamma rays

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Solution Process

CR source distribution

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Solution Process

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$\Downarrow$

Transport solver

Physics in Numerical Propagation Codes

Transport Processes

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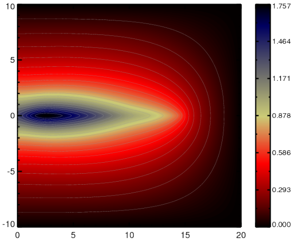
CR Distribution



Secondaries

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$\Downarrow$

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Physics in Numerical Propagation Codes

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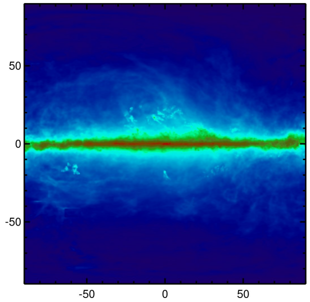
Gamma Ray Emission



Secondaries

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Solution Process

CR source distribution

⇓

Transport solver

⇓

CR distribution

⇓

Gamma ray emission

Issues in Galprop

Transport Equation

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Physics Issues

- Physics as parameters

Issues in GALPROP

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Transport Parameters

- Source distribution $q(\mathbf{r}, p)$
- Diffusion tensor $\mathcal{D}$
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- Physics as parameters
  - Constant in time
  - Constant in space
  - $\rightarrow$ Parameter tuning

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Technical Issues

- Solver
- Local structure ↔ spatial resolution
- Consistency

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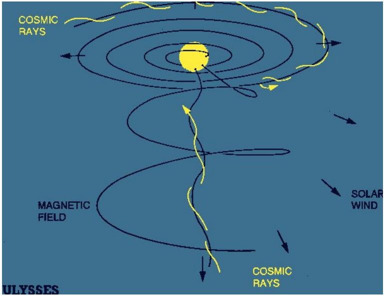
Diffusion in Galprop

- Isotropic
- No spatial variation

CRs Inside the Heliosphere



(From Ulysses website)

Example I: Diffusion

Diffusion in Galprop

- Isotropic
- No spatial variation
- Alternatives:
  - Dragon, Picard
  - Effenberger et al.

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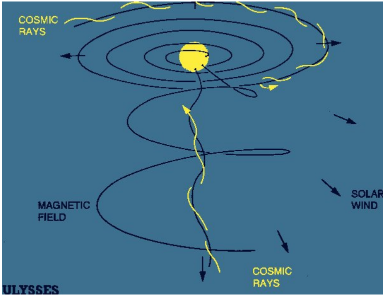

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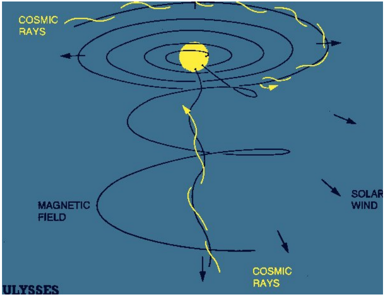
Field Aligned Diffusion

$$\mathcal{D}_B = \begin{pmatrix} D_{\|} & 0 & 0 \\ 0 & D_{\perp,1} & 0 \\ 0 & 0 & D_{\perp,2} \end{pmatrix}$$

CRs Inside the Heliosphere



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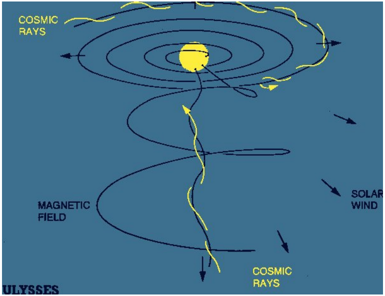

(From Ulysses website)

Diffusion in Cartesian Coordinates

$$\mathcal{D} = \begin{pmatrix} D_\parallel \cos^2\psi + D_\perp \sin^2\psi & \left(D_\parallel - D_\perp\right)\sin\psi\cos\psi & 0 \\ \left(D_\parallel - D_\perp\right)\sin\psi\cos\psi & D_\parallel \sin^2\psi + D_\perp \cos^2\psi & 0 \\ 0 & 0 & D_\perp \end{pmatrix}$$

Example I: Diffusion

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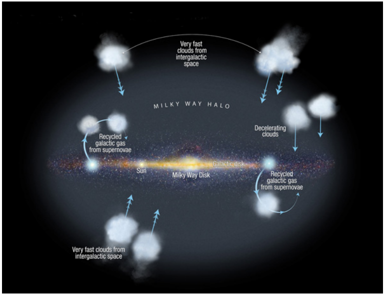
Boundary conditions?

- Diffusion $\leftrightarrow$ advection
- Energy dependence
- GALPROP:
  - Restricted to box
  - $\psi = 0$ at boundary

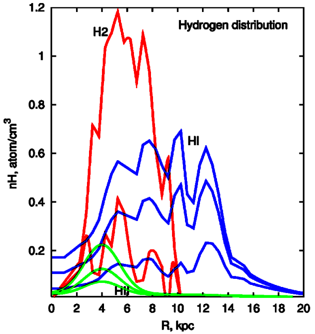
The Galaxy



(artist sketch by NASA)

Example II: Consistency

Gas for Propagation



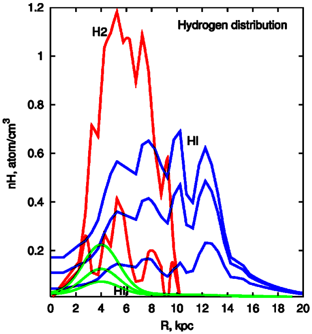
(From Galprop website)

Example II: Consistency

Propagation

- Azimuthally symmetric

Gas for Propagation



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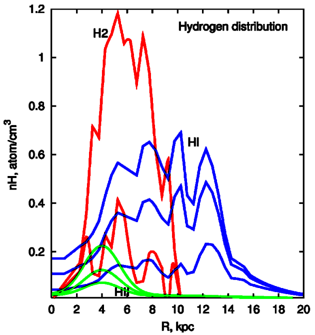

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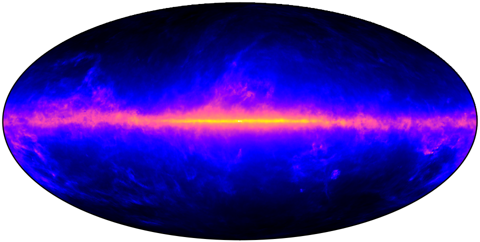
Gamma Ray Emission



(Picard results for 100 GeV gamma rays)

Example II: Consistency

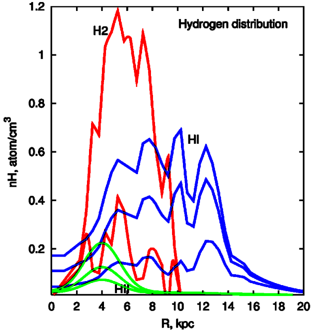
Propagation

- Azimuthally symmetric

Gamma Ray Computation

- Ring-distribution for gas

Gas for Propagation



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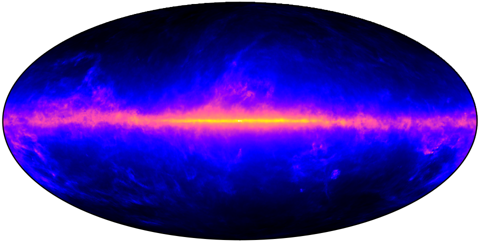

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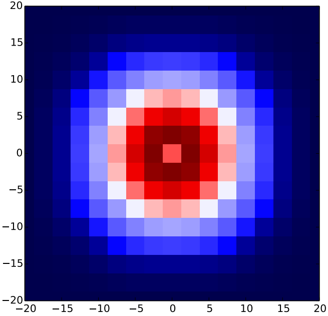
But: CR distribution



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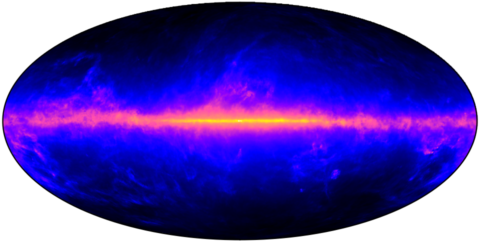

(PICARD results for 100 GeV gamma rays)

Solving the Transport Equation

Transport Equation

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Type of Equation

- Diffusion-advection equation

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Abbreviation

$$\frac{\partial \psi}{\partial t} = s(\mathbf{r}, p) + \nabla \cdot (\mathcal{D} \nabla \psi - \mathbf{v}\psi) + \frac{\psi}{\tau}$$

Solving the Transport Equation

Transport Equation

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Abbreviation

$$\frac{\partial \psi}{\partial t} = s(\mathbf{r}, p) + \nabla \cdot (\mathcal{D} \nabla \psi - \mathbf{v}\psi) + \frac{\psi}{\tau}$$

Possible Solutions

- Time-dependent
- Steady state

Solving the Transport Equation

Transport Equation

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

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Standard Approach

- Time integration
  - Solve multiple time steps
  - Characteristic time-scales
  - Convergence to steady state

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→ Time-integration solver

Standard Approach via Time-Integration

Possible Solvers

- SDEs / Monte Carlo
  - (Pseudo-) particles

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Standard Approach via Time-Integration

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  - Explicit

Explicit schemes

$$\frac{\partial \psi}{\partial t} = f(\psi) \rightarrow \frac{\psi^{n+1} - \psi^{n}}{\Delta t} = f(\psi^{n})$$

- Easy to solve
- Time step restriction

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Implicit schemes

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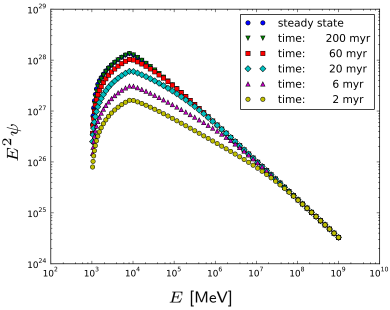
Time Evolution of Spectrum



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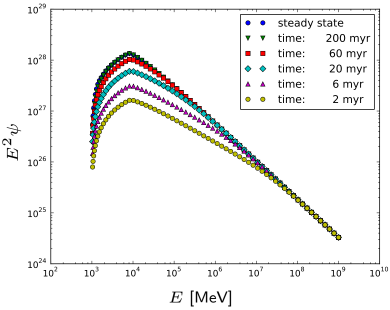

Characteristic time: ∼50 yrs

The GALPROP solver

Numerical Implementation

- Crank-Nicolson discretisation
- Time-integration
- Dimensional splitting
- Decreasing timesteps

Galprop

The GALPROP solver

Numerical Implementation

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Problems

- Check for convergence?

Galprop

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Galprop

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The GALPROP solver

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Galprop

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Numerical Implementation

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Galprop

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- Check for convergence?
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- Crank-Nicolson discretisation
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Galprop

$\rightarrow$ Let's do better

How to do better

A Different Approach

- Solve steady state problem

Simplified Transport Equation

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$$0 = s(\mathbf{r}, p) + \nabla \cdot (\mathcal{D}\nabla\psi - \mathbf{v}\psi) + \frac{\psi}{\tau}$$

Difficulty

- Discretisation

Discretisation in 1D

$$\begin{aligned}\nabla\mathcal{D}\nabla\psi &= D_{xx}\frac{\partial^2\psi}{\partial x^2} \\ &\simeq D_{xx}\frac{\psi_{i+1} - 2\psi_i + \psi_{i-1}}{\Delta x^2}\end{aligned}$$

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Descretisation in 2D

$$\begin{aligned}\nabla\mathcal{D}\nabla\psi =& D_{xx}\frac{\partial^2\psi}{\partial x^2} + D_{yy}\frac{\partial^2\psi}{\partial y^2}\\ \simeq& D_{xx}\frac{\psi_{i+1,j} - 2\psi_{i,j} + \psi_{i-1,j}}{\Delta x^2}\\ &+ D_{yy}\frac{\psi_{i,j+1} - 2\psi_{i,j} + \psi_{i,j+1}}{\Delta y^2}\end{aligned}$$

How to do better

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Simplified Transport Equation

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Difficulty

- Discretisation
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  - $\rightarrow$ Band-diagonal matrix
- Iterative solver
  - Multigrid
  - BICGStab

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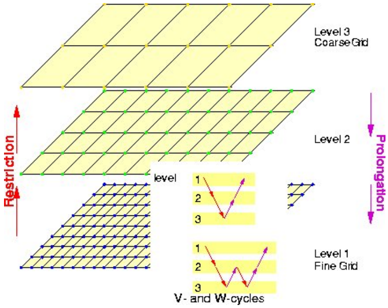
Multigrid Illustration



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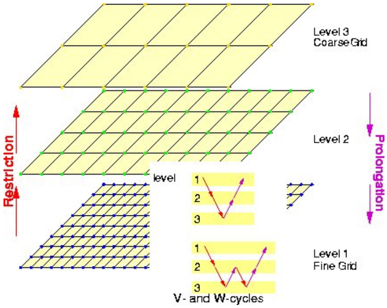
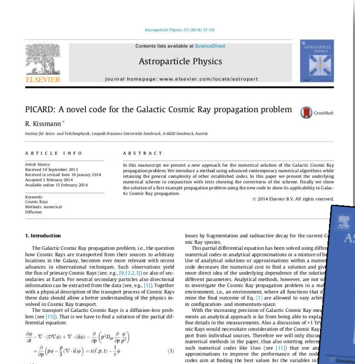


Multigrid Implementation

- Red-black Gauss-Seidel
- Alternating plane Gauss-Seidel

Cosmic Particle Transport:

THE NEXT GENERATION



Astroparticle Physics 55 (2014) 37–50

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

PICARD: A novel code for the Galactic Cosmic Ray propagation problem

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ARTICLE INFO

Article history:
Received 10 September 2013
Received in revised form 16 January 2014
Accepted 3 February 2014
Available online 15 February 2014

Keywords:
Cosmic Rays
Methods: numerical
Diffusion

ABSTRACT

In this manuscript we present a new approach for the numerical solution of the Galactic Cosmic Ray propagation problem. We introduce a method using advanced contemporary numerical algorithms while retaining the general complexity of other established codes. In this paper we present the underlying numerical scheme in conjunction with tests showing the correctness of the scheme. Finally we show the solution of a first example propagation problem using the new code to show its applicability to Galactic Cosmic Ray propagation.

1. Introduction

The Galactic Cosmic Ray propagation problem, i.e., the question how Cosmic Rays are transported from their sources to arbitrary locations in the Galaxy, becomes ever more relevant with recent advances in observational techniques. Such observations yield the flux of primary Cosmic Rays (see, e.g., [9,12,2,3]) or also of secondaries at Earth. For neutral secondary particles also directional information can be extracted from the data (see, e.g., [1]). Together with a physical description of the transport process of Cosmic Rays these data should allow a better understanding of the physics involved in Cosmic Ray transport.

The transport of Galactic Cosmic Rays is a diffusion-loss problem (see [15]). That is we have to find a solution of the partial differential equation:

$$\frac{\partial\psi}{\partial t} - \nabla\cdot(D\nabla\psi) + \nabla\cdot(\vec{u}\psi) - \frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2}\right) + \frac{\partial}{\partial p}\left(\dot{p}\psi - \frac{p}{3}(\nabla\cdot\vec{u})\psi\right) = s(\vec{r},p,t) - \frac{1}{\tau}\psi \quad (1)$$

losses by fragmentation and radioactive decay for the current C mic Ray species.

This partial differential equation has been solved using differ numerical codes or analytical approximations or a mixture of b Use of analytical solutions or approximations within a numer code decreases the numerical cost to find a solution and giv more direct idea of the underlying dependence of the solutio different parameters. Analytical methods, however, are not su to investigate the Cosmic Ray propagation problem in a rea environment, i.e., an environment, where all functions that d mine the final outcome of Eq. (1) are allowed to vary arbit in configuration- and momentum-space.

With the increasing precision of Galactic Cosmic Ray mea ments an analytical approach is far from being able to expla fine details in the measurements. Also a discussion of >1 Te mic Rays would necessitate consideration of the Cosmic Ray port from individual sources. Therefore we will only discus numerical methods in the paper, thus also omitting referen such numerical codes like Usine (see [11]) that use an approximations to improve the performance of the cod codes aim at finding the best values for the variables in

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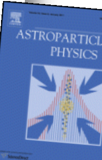

Features of Picard

Solver

- Steady-state solution
- Explicit time integrator
- MPI-parallel
  - $\rightarrow$ High resolution
- Improved nuclear network
- Speed

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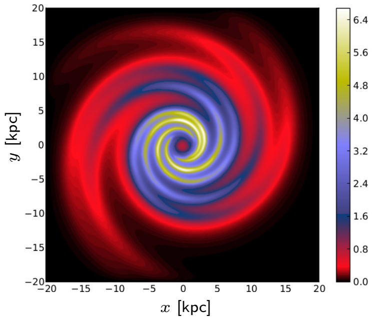
Example Resolution

- Standard GALPROP
  - → 2D (1 kpc × 100 pc)
- PICARD
  - → 3D (up to ∼75 pc^3)

Example Simulation Results



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Physics

- 3D source distributions
- Anisotropic diffusion
- tbd...

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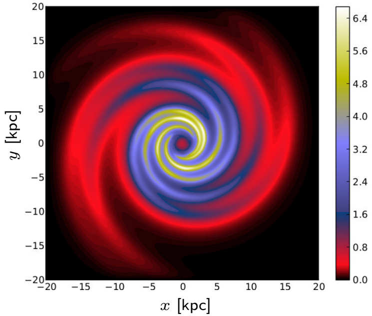

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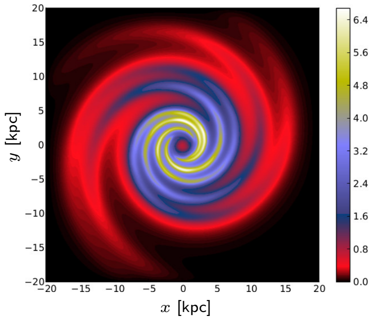

Example results:
Milkyway as spiral galaxy

Milkyway as a Spiral Galaxy

Model setup

- Spiral arm source dist.
- Standard GALPROP parameters
- Electrons / protons $\leftrightarrow$ Nuclear network

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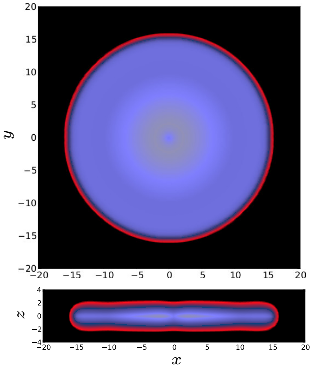
- Different source distributions

$\rightarrow$ 1 TeV electrons

Axi-symmetric Model



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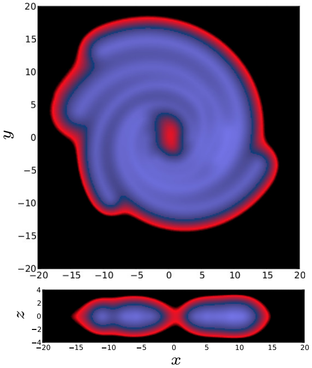

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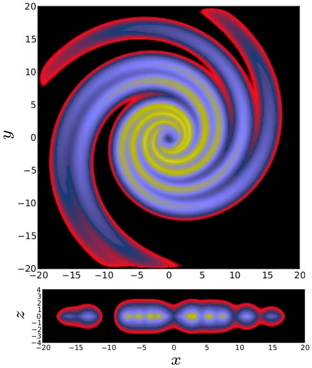
Other Four Arm Model



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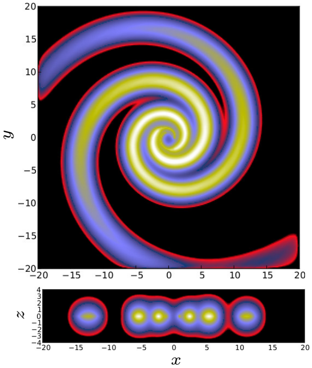

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- Differences ↔ normalisation
  ↔ Vicinity of Earth

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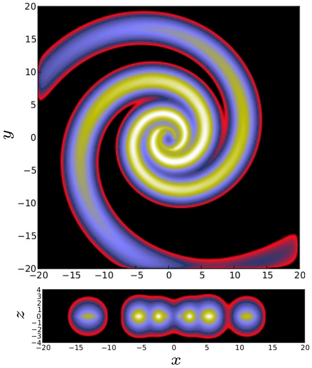

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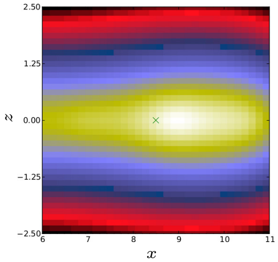

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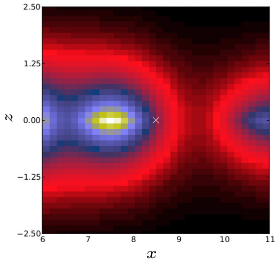

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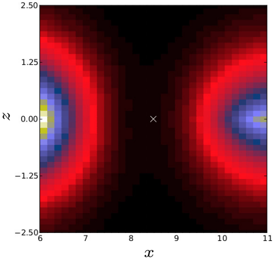

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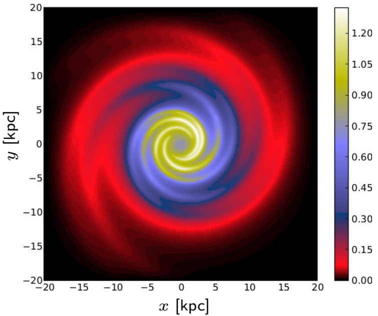
- Differences $\leftrightarrow$ normalisation
  $\leftrightarrow$ Vicinity of Earth
- Secondaries

Distribution of Carbon



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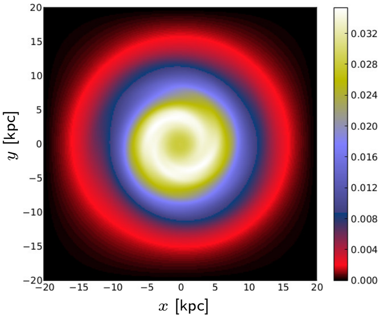

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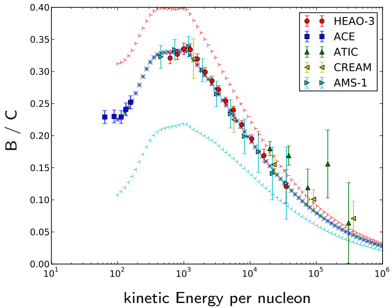
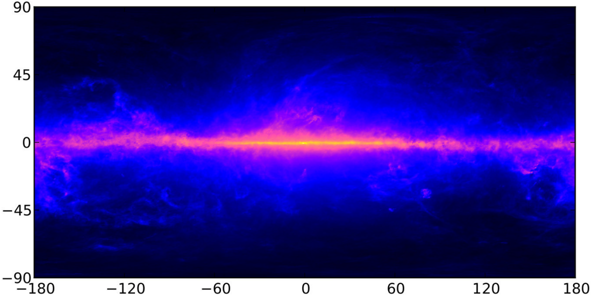
B/C Ration



Gamma Rays with PICARD

Axi-Symmetric Configuration

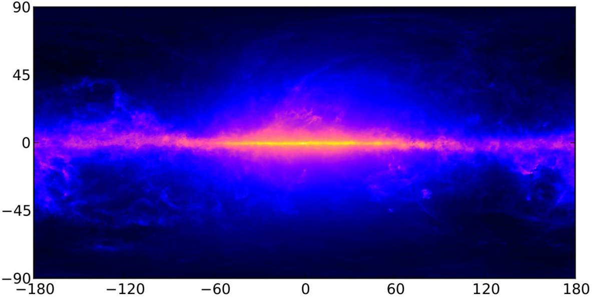


Gamma Ray Data

- 100 MeV

Gamma Rays with Picard

Four-Arm Configuration



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Gamma Rays with Picard

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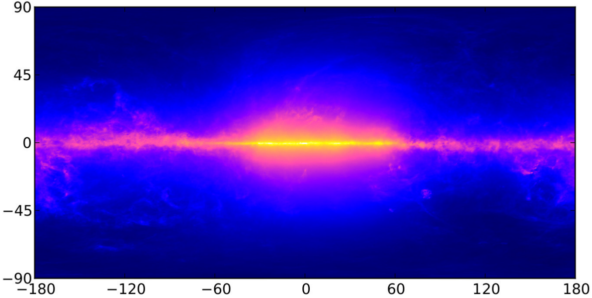


Gamma Ray Data

- 100 MeV

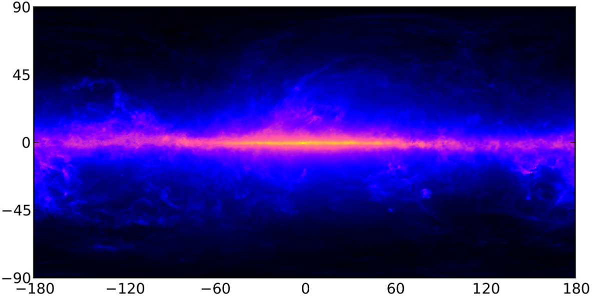
Gamma Rays with PICARD

Gamma Ray Data

- 100 MeV
- 100 GeV

Gamma Rays with PICARD

Axi-Symmetric Configuration

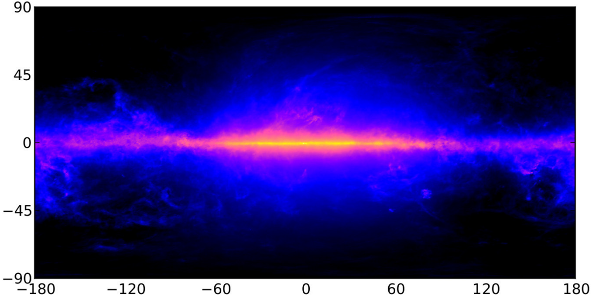


Gamma Ray Data

- 100 MeV
- 100 GeV

Gamma Rays with Picard

Four-Arm Configuration

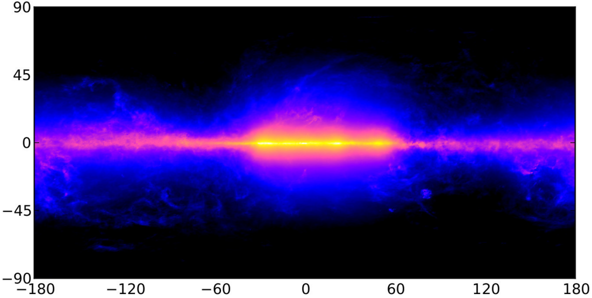


Gamma Ray Data

- 100 MeV
- 100 GeV

Gamma Rays with Picard

Two-Arm Configuration

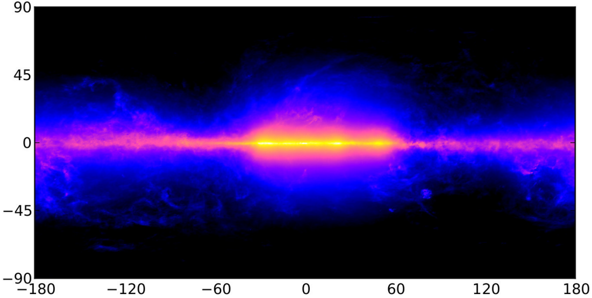


Gamma Ray Data

- 100 MeV
- 100 GeV

Gamma Rays with PICARD

Two-Arm Configuration



Preliminary Conclusion

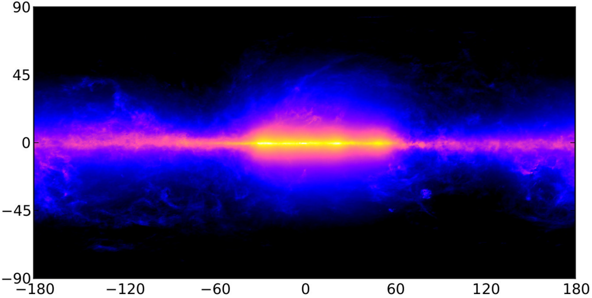
- Increase of IC component

Gamma Ray Data

- 100 MeV
- 100 GeV

Gamma Rays with PICARD

Two-Arm Configuration



Preliminary Conclusion

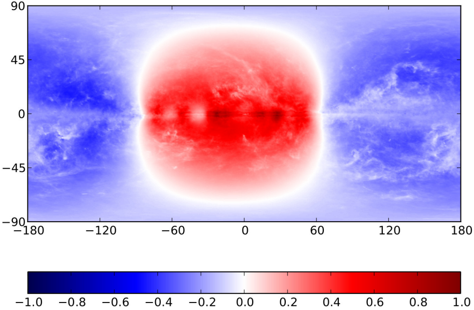
- Increase of IC component
- Two-arm model excluded?

Gamma Ray Data

- 100 MeV
- 100 GeV

Gamma Rays with PICARD

Residual - Four Arm Configuration



Preliminary Conclusion

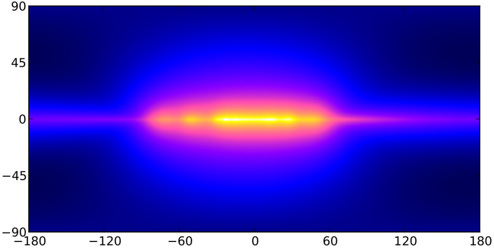
- Increase of IC component
- Two-arm model excluded?
- Axi-symmetric model?

Gamma Ray Data

- 100 MeV
- 100 GeV

Conclusion

Inverse Compton & Spiral Arms

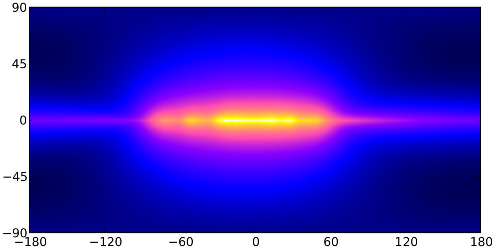


Galactic Propagation

- New generation of models
- Different improvements under way

Conclusion

Inverse Compton & Spiral Arms



Application of PICARD

- Principal CR data ✓
- GeV photons (✓)
- TeV photons
- Electrons / DM

Galactic Propagation

- New generation of models
- Different improvements under way