GALPROP code for CR propagation and diffuse emissions

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Contents

✧ Introduction to propagation of CRs
✧ Building a model of the diffuse emission
✧ Effect of anisotropic inverse Compton scattering
✧ A view from far far away: multi-wavelength luminosity of the Milky Way
✧ Bayesian analysis of propagation parameters
✧ GALPROP WebRun
CR Propagation: Milky Way Galaxy

Radio contours: Condon et al. 1998 AJ 115, 1693

1 kpc $\sim 3 \times 10^{21}$ cm

R Band image of NGC891
1.4 GHz continuum (NVSS), 1,2,…64 mJy/ beam

"Flat halo" model (Ginzburg & Ptuskin 1976)
CRs in the Interstellar Medium

ISM

- X,\gamma
- e^\pm
- P
- He
- CNO
- ISRF
- IC
- energy losses
- diffusion
- convection
- production of secondaries
- \pi^0
- brems
- gas
- \pi^0
- solar modulation
- Flux
- 20 GeV/n
- CR species:
  - Only 1 location
  - modulation

WIMP annihilations

ACE

BESS

HESS

Chandra

Fermi

PAMELA

helio-modulation
Components of realistic CR propagation model

✧ Detailed gas distribution (energy losses, $\pi^0$, bremsstrahlung)

✧ Interstellar radiation field (IC, $e^\pm$ energy losses)

✧ Nuclear & particle production cross sections & the reaction network

✧ Gamma-ray production: bremsstrahlung, IC, $\pi^0$

✧ Energy losses: ionization, Coulomb, brems, IC, synchrotron

✧ Solve transport equations for all CR species

✧ Derive the propagation parameters
Transport Equations ~90 (no. of CR species)

\[ \frac{\partial \psi (\vec{r}, p, t)}{\partial t} = q(\vec{r}, p) \text{ sources (SNR, nuclear reactions...)} \]

- **diffusion**
  \[ \nabla \cdot \left[ D_{xx} \nabla \psi - \vec{V} \psi \right] \]

- **diffusive reacceleration**
  \[ \frac{\partial}{\partial p} \left[ p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2} \right] \]

- **E-loss**
  \[ - \frac{\partial}{\partial p} \left[ \frac{dp}{dt} \psi - \frac{1}{3} p \nabla \cdot \vec{V} \psi \right] \]

- **fragmentation**
  \[ - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_d} \]

**convection**
\[ \text{(Galactic wind)} \]

**radioactive decay**
\[ \psi(r, p, t) - \text{density per total momentum} \]

+ **boundary conditions**
Secondary/primary nuclei ratio & CR propagation

Typical parameters (model-dependent):
- \( D \sim 10^{28} \left( \rho / 1 \text{ GV} \right)^{\alpha} \text{ cm}^2/\text{s} \)
- \( \alpha \approx 0.3-0.6 \)
- \( Z_h \sim 4-6 \text{ kpc}; V_A \sim 30 \text{ km/s} \)

Using secondary/primary nuclei ratio (B/C) & radioactive isotopes (e.g. Be\(^{10}\)):
- Diffusion coefficient and its index
- Galactic halo size \( Z_h \)
- Propagation mode and its parameters (e.g., reacceleration \( V_A \), convection \( V_z \))
- Propagation parameters are model-dependent
Relevant CR and gamma-ray (also CR!) instruments

- PAMELA
- BESS-Polar
- d, α
- e+
- e−
- p
- He
- Z ≤ 8
- 8 < Z ≤ 28
- Z > 28
- SUSY
- WIMPs

Energy scales:
- 1 MeV/n
- 1 GeV/n
- 1 TeV/n
Dominating source of gamma rays on the sky. Produced by CR interactions with interstellar gas and radiation field – the so-called diffuse emission. The diffuse Galactic gamma rays are the tracers of CR proton and electron spectra throughout the Galaxy.
Diffuse Galactic Gamma-ray Emission

✧ Origin and propagation of cosmic rays
  - Nature and distribution of CR sources
  - Abundances of primary species
  - Production of secondary species
  - The propagation mode and its relationship to magnetic turbulence in the ISM

✧ Interstellar Medium
  - Distribution of HI, H₂, HII gas
  - Nature of $X_{\text{CO}}$ relation in Galaxy
  - Distribution and intensity of interstellar radiation field and formation of H₂

✧ Foreground against which sources are detected
  - Point sources: limitation on sensitivity
  - Extended sources: disentanglement

✧ Indirect dark matter detection
  - Predicted $\gamma$-ray/CR signals
  - Relies on accurate treatment of standard astrophysical sources

✧ Foreground for isotropic diffuse background
  - Whatever its nature
Fermi-LAT: diffuse gammas

- Conventional GALPROP model is in agreement with the Fermi-LAT data at mid-latitudes (mostly local emission)
- The EGRET “GeV excess” is not confirmed
- This means that we understand the basics of cosmic ray propagation and calculate correctly interstellar gas and radiation field, at least, locally

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Abdo+’09
Diffuse emission at low to high Galactic latitudes

- Pion-decay and inverse Compton emission are two dominant components – allow us to probe the average CR proton and electron spectra along the line of sight
- The GALPROP predictions agree well with the LAT data

Mid-latitudes

Low latitudes

High latitudes

Abdo+’10
Spectrum of isotropic diffuse $\gamma$-ray emission

- Time-dependent: increasingly steepens with time...

index = 2.41 ± 0.05
Diffuse Gammas – Local Spectrum

✧ Mid-latitudes:
\(200^\circ < l < 260^\circ, 22^\circ < b < 60^\circ\)

✧ The spectrum of the local atomic gas emission agrees well with the GALPROP predictions

✧ Confirms that the local proton spectrum is similar to that derived from direct measurements

Abdo+'09
Example: latitude profile of the inner Galaxy
Fractional count residuals: (theory-data)/data

- Agreement for models is overall good but features in residuals are at ~ % level
- Difference between illustrative models due to variations of model parameters

<table>
<thead>
<tr>
<th>Fraction</th>
<th>srs</th>
<th>Zh (kpc)</th>
<th>Rmax (kpc)</th>
<th>TS (K)</th>
<th>mag</th>
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<tbody>
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<td>A)</td>
<td>SNR</td>
<td>4</td>
<td>20</td>
<td>150</td>
<td>5</td>
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<tr>
<td>B)</td>
<td>Lorimer</td>
<td>6</td>
<td>20</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>C)</td>
<td>OB</td>
<td>8</td>
<td>30</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Optically thin HI
Anisotropic IC scattering in the Galaxy

- The formalism and effect of anisotropic IC scattering in the Galaxy: IM & Strong’00
- Varies over the sky
- Gives $\times(0.7-2)$ more gammas vs isotropic approximation
- Has to be taken into account when modeling the diffuse emission

IM & Strong’00
Bulge×10 model (10 kpc halo)

<table>
<thead>
<tr>
<th>anisotropic/isotropic</th>
<th>aniso sum</th>
<th>iso sum</th>
</tr>
</thead>
<tbody>
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<td>50 MeV</td>
<td><img src="1" alt="Image" /></td>
<td><img src="2" alt="Image" /></td>
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<tr>
<td>35 GeV</td>
<td><img src="3" alt="Image" /></td>
<td><img src="4" alt="Image" /></td>
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</tbody>
</table>
Ratio Bulge $\times 10$/Standard (10 kpc halo)

<table>
<thead>
<tr>
<th>anisotropic skymap</th>
<th>aniso sum</th>
<th>iso sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 MeV</td>
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<td><img src="image5" alt="35 GeV aniso sum" /></td>
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</table>
Milky Way from far far far away...
Multi-wavelength luminosity of the Milky Way

- “Proximity” of the MW plus direct measurements allow us to construct its detailed “microscopic” model (GALPROP)

- Integral properties of the MW – a useful template for studies of the normal galaxies

Milky Way as electron calorimeter

- Calculations for $Z_{\text{halo}} = 4 \text{kpc}$
- Leptons lose $\sim 60\%$ of their energy
- $\gamma$-rays: 50-50 by nucleons and by leptons

Cosmic rays $7.90 \times 10^{40} \text{erg/s}$

Primary nucleons $98.6\%$

Ionization losses $1\%$

Secondary leptons $e^+: 0.33\%$
$e^-: 0.10\%$

Neutral pions $0.85\%$

Synchrotron $0.35\%$

Bremsstrahlung $0.15\%$

Inverse Compton $0.58\%$

Total gamma rays $1.6\%$

* The percentages in brackets show the values relative to the luminosity of their respective lepton populations
Constrains on CR propagation models from global scans
**Methodology**

- Bayesian approach \((\Theta - \text{vector of parameters}, D - \text{available observations})\):

\[
P(\Theta | D) = \frac{P(D | \Theta)P(\Theta)}{P(D)}
\]

- \(P(\Theta|D)\) – posterior distribution of parameters
- \(P(D|\Theta)\) – likelihood function (for fixed \(D\))
- \(P(\Theta)\) – prior distribution
- \(P(D)\) – Bayesian evidence

- Bayesian approach allows for a more sophisticated treatment of systematics
- Nested sampling algorithm by John Skilling’04,06 and MultiNest by Feroz&Hobson’08 (SuperBayeS code by Ruiz de Austri+’06, Trotta+’08)
- Total \(1.4 \times 10^5\) samples, \(\sim 13\) CPU years
- The posterior distribution is in excellent agreement with one from MCMC
- Representative data from ACE, ISOMAX, HEAO-3, ATIC-2, CREAM
- Fit a total of 17 parameters, best fit chi-squared/dof \(\sim 1\)
- More details in the paper (to be submitted in a few days)
Posterior probability distributions

Normalization of the diffusion coeff. and its index

- the best fit
vertical line – posterior mean
color bar – 68%, 95% error ranges

Reacceleration model

Parameters are very close to those derived by the eye-fitting method
2D posterior probability distributions

- Contours enclose 68% and 95% probability regions
- best fit
- posterior mean
Examples of the fits: B/C and Be ratios

B/C ratio

Be$^{10}$/Be$^{9}$ ratio
Examples: Carbon and pbars

Carbon

pbars (not fitted!)
GALPROP WebRun

galprop.stanford.edu

Igor Moskalenko

for the GALPROP development team
GALPROP WebRun

- GALPROP WebRun is a service that allows to run GALPROP via the WWW

- No local installation of the code or related libraries is necessary, only a web browser is required

- Available at http://galprop.stanford.edu/webrun

- Calculations can be performed on a new cluster at Stanford University, using the most recent GALPROP v54, older versions are also available

- The service is free and open to the community. Registration is required

- Acknowledge by citing the web-page and the introduction paper http://arxiv.org/abs/1008.3642 (submitted to Computer Physics Communications)
Configuring GALPROP via WebRun

- Interactive interface for parameter entry
- Parameters are validated to avoid misconfigured runs
Running calculations

- Multiple simultaneous runs are allowed
- Sharing resources fairly between users
Evaluating and obtaining results

- Archive with FITS files (output) available to the owner
- URL to the archive may be shared with anyone
- Quick peek possible with built-in plot templates
Computing cluster (galprop.stanford.edu)

**Head node:**
- web server
- data storage (12TB RAID0)

**Infiniband link** (10 Gbit/s)

**Compute nodes. On each node:**
- 4 x 12-core processors (6174 AMD Opteron)
- 128 GB shared memory
- small fast hard drives.

Total: 196 cores.

Easily extendable.
Thank you!