Cosmic ray studies with GALPROP

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Cosmic-Ray Propagation and Interactions in the Galaxy

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Key Words
energetic particles, gamma rays, interstellar medium, magnetic fields, plasmas

Abstract
We survey the theory and experimental tests for the propagation of cosmic rays in the Galaxy up to energies of \(10^{15}\) eV. A guide to the previous reviews and essential literature is given, followed by an exposition of basic principles. The basic ideas of cosmic-ray propagation are described, and the physical origin of its processes is explained. The various techniques for computing the observational consequences of the theory are described and contrasted. These include analytical and numerical techniques. We present the comparison of models with data, including direct and indirect—especially \(\gamma\)-ray—observations, and indicate what we can learn about cosmic-ray propagation. Some important topics, including electron and antiparticle propagation, are chosen for discussion.
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more than ¼ century ago
' We are not alone '.

Other numerical propagation codes e.g.

- Buesching/Pohl  
  Green's function approach

**POSTER:**
- Evoli/Maccione/Gaggero/Grasso  
  DRAGON code (similar to GALPROP)

- DeMarco/ Blasi/Stanev  
  Trajectory approach, for > 1 PeV

- Hanasz etal  
  PIERNIK code: MHD, CR= fluid

and others not too numerous to mention

They emphasize other aspects than GALPROP,

They are welcome 'competition' !
Guiding principle:

- to fit a wide range of data even approximately is more important than to fit a small range of data precisely

The original motivation:

- to escape from the leaky-box into the Galaxy

but now...

precision experiments e.g. Fermi, PAMELA, AMS, ACE ........ require correspondingly detailed models to do them justice.
Leaky-box, path-length distribution models
these are numerical 0-D models

not discussed here since we both (AWS. and DM) regard them as outdated.

But it is a well-known fact that for stable nuclei without energy losses, these methods can be designed to produce the same results as propagation models,

So OK for cosmic-ray source composition studies.

For unstable nuclei, electrons, positrons, gamma rays... not realistic enough to be useful
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**Spatial Propagation models**

Advantage is the physical interpretation in terms of diffusion, convection etc. related to the real Galaxy. Intuitive understanding of meaning of terms.

Both analytical and numerical, and hybrids, all have their proponents.
versus
## Propagation models

A main advantage is the physical interpretation in terms of diffusion, convection etc. related to the real Galaxy. Intuitive understanding of meaning of terms.

1D, 2D, or 3D
Both analytical and numerical, and hybrids, all have their proponents.

<table>
<thead>
<tr>
<th>Analytical</th>
<th>Numerical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mainly 1D, some 2D</td>
<td>2D or 3D</td>
</tr>
<tr>
<td>complex (but impressive) formulae</td>
<td>simple formulae (computer does the work)</td>
</tr>
<tr>
<td>simplified energy losses</td>
<td>full energy losses</td>
</tr>
<tr>
<td>simplified gas distribution</td>
<td>gas based on HI, CO surveys in 3D</td>
</tr>
<tr>
<td>simplified magnetic field</td>
<td>any magnetic field model</td>
</tr>
<tr>
<td>gamma rays only in simple way</td>
<td>full gamma ray calculation</td>
</tr>
<tr>
<td>synchrotron only in simple way</td>
<td>full synchrotron calculation</td>
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</tbody>
</table>
GALPROP code

Built up over more than 10 years by a small (but growing) team.

*Dramatis personae:*

Igor Moskalenko (Stanford): physics processes. GALPROP website/forum

Troy Porter (UCSC): interstellar radiation field, configuration

Gulli Johannesson (Stanford): HEALPix, parallelization, gas surveys, Fermi interface

Elena Orlando (MPE): magnetic fields and synchrotron

Seth Digel (Stanford): gas surveys specialist

Andy Strong (MPE): project management, code hosting, and general coding
GALPROP

Public code

Dedicated website galprop.stanford.edu for code and forum, ~90 registrations

Used in many papers / year

New release planned later this year (to coincide with ICRC in July)

Adopted as standard model for Fermi, for both diffuse and source analysis

Need such a model to do justice to the quality of Fermi data

Other applications include contribution to Planck Galaxy model.
focus: cosmic-ray production & propagation in the Galaxy
cosmic-ray sources: p, He .. Ni, e

Secondary: $^{10}$Be, $^{11}$B ...

Secondary: $e^+$ p

cosmic-ray sources: p, He .. Ni, e

HALO

intergalactic space

reacceleration

energy loss
decay

synchrotron

bremsstrahlung
inverse Compton

$\gamma$-rays
... secondary nuclei
10Be 11B ...

primary p He ... Ni

interstellar radiation field
optical, FIR, CMB
dE/dt

B-field
dE/dt

diffusion
convection
reacceleration

secondary e+ e- p
electron

bremsstrahlung
inverse Compton
synchrotron

Direct
measurements
HEAO, ACE ...

GRO, Fermi
Radio surveys

Direct
measurements

cosmic-ray sources: SNR

Direct measurements

Primary p He ... Ni
The **goal**: use *all* types of data in a self-consistent way to test models of cosmic-ray propagation.

Observed **directly, near Sun:**
- primary spectra (p, He ... Fe; e\(^-\))
- secondary/primary (B/C etc)
- secondary e\(^+\), pbar

Observed **from whole Galaxy:**
- \(\gamma\) - rays
- synchrotron
Cosmic-ray propagation

\[ \frac{\partial \psi (r, p)}{\partial t} = q(r, p) \]

- cosmic-ray sources (primary and secondary)

\[ + \nabla \cdot (D_{xx} \nabla \psi - v \psi) \]

- diffusion
- convection

\[ + \frac{\partial}{\partial p} \left[ p^2 D_{pp} \frac{\partial}{\partial p} \psi / p^2 \right] \]

- diffusive reacceleration (diffusion in p)

\[ - \frac{\partial}{\partial p} \left[ \frac{dp}{dt} \psi - \frac{p}{3} (\nabla \cdot v) \psi \right] \]

- momentum loss
- adiabatic momentum loss

\[ - \frac{\psi}{\tau_f} \]

- nuclear fragmentation

\[ - \frac{\psi}{\tau_r} \]

- radioactive decay
How the propagation is computed:

Linear equation, easy to solve.

2D or 3D grid, resolution down to 100 pc

\[ \Delta n = \frac{dn}{dt} \Delta t \]

stabilized by Crank-Nicolson scheme

\[ \frac{dn}{dt} = \text{source terms} + \text{propagation terms} \]

\[ \Delta t = \text{eg 1000 yrs} \]

for steady-state, follow until \( \frac{dn}{dt} = 0 \)
(trick: start with large \( \Delta t \) and decrease \( \Delta t \): finds steady-state fast)

or time-dependent solution if required eg for stochastic sources.

nuclei: start from \(^{64}\text{Ni}\) and work down in \((A, Z)\)
   including secondary production
   plus secondary positrons, electrons, pbar

primary electrons: separate species
Model for cosmic-ray propagation

3D gas model based on 21-cm (atomic H), CO (tracer of H$_2$) surveys

cosmic-ray sources $f (r, E)$

interstellar radiation field $f (r, \nu)$

nuclear cross-sections database

energy-loss processes

B-field model

$\gamma$–ray, synchrotron
Gas Rings: HI
Inner & Outer Galaxy

Seth Digel '05

Gas Rings: HI
Local Galaxy
Interstellar Radiation Field
(for electron dE/dt, inverse Compton γ-rays):
new model (Troy Porter, UCSC)

New ISRF
using latest information

stellar populations, dust
radiative transfer

UV  optical  IR  FIR  CMB
GALPROP computes:

- cosmic-ray fluxes \( f(A, Z, x, y, z, E) \)
- gamma ray skymaps \((l, b, E)\)
- synchrotron skymaps \((l, b, \nu)\)

... and more
Key data: primary cosmic-ray nuclei spectra

galdef ID 49_6002029RD

$E^2 I(E), \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{MeV}$

$\Phi = 0 \text{ MV}$
$\Phi = 500 \text{ MV}$
$\Phi = 600 \text{ MV}$

$Z=1 A=1$

$Z=2 A=4$

energy, MeV

energy, MeV
Key data II: cosmic-ray secondary/primary ratios: e.g. Boron/Carbon probes cosmic-ray propagation parameters

Peak in B/C can be explained by diffusive reacceleration with Kolmogorov $D \sim \beta p^{1/3}$
For any model, first adjust parameters to fit Boron/Carbon

then predict the other cosmic-ray spectra

antiprotons

plain diffusion
diffusive reacceleration
wave damping
Having described some of what GALPROP can do (more later)

now...
Having described some of what GALPROP can do (more later)

now...

**Some things GALPROP can't do (yet)**

- spatially-varying / anisotropic diffusion (but trivial to implement)
- local effects: local bubble enhancements in / exclusion from molecular clouds.
- Trajectory-type calculations – but B-field is there, so easy
- MC instead of D.E. to allow more general models
- more realistic Galactic winds (e.g. CR-driven)
- rapid parameter scans (MCMC) but this is coming.

Development continues, some of these are foreseen
GALPROP realistic?

you gotta be kidding

the Galaxy and all its processes are much more complex than we know or can ever know

but it is a step in the right direction we believe

End of Part 1
END OF PART 1
PART 2

GALPROP APPLICATION:
Fermi GAMMA RAYS
NASA’s Fermi telescope reveals best-ever view of the gamma-ray sky

Credit: NASA/DOE/Fermi/LAT Collaboration

Press release, Feb 11
NASA’s Fermi telescope reveals best-ever view of the gamma-ray sky
First Fermi results on diffuse Galactic emission

Intermediate Galactic latitudes $10^\circ < |b| < 20^\circ$

Motivation: the gamma rays come from a 'local' region: within 1 kpc

$\rightarrow$ cosmic rays should be similar to those observed directly near the Sun

$\rightarrow$ model should be reliable

This was \textit{not} the case for EGRET -

found the notorious 'GeV excess' relative to the expected emission
Modelling diffuse Galactic $\gamma$-rays:

*Conventional* model: proton, electron spectra as measured
Wherever you looked, the EGRET GeV $\gamma$-ray excess was there!
The GeV region is lower in Fermi than EGRET

The two experiments have different instrumental backgrounds, so this comparison is not exact, but the difference is not mainly attributable to this.

Abdo et al. in preparation for the Fermi-LAT Collaboration
A 'Conventional model' based on local cosmic-ray spectra agrees with Fermi!

Small, uniform excess can be due to uncertainties in cosmic rays, gas surveys, unresolved sources, etc.

\textit{Abdo et al. in preparation for the Fermi-LAT Collaboration}
GALPROP application: models for Fermi electrons (from John Bregeon's talk)
Part 3 (according to time):
More GALPROP Applications

Radioactive nuclei
Cosmic-ray source distribution
Synchrotron
Hard X-rays
Galactic SED
Radioactive nuclei: cosmic-ray clocks set limits on size of Galactic halo.

Data:
- ACE, ISOMAX

Galprop model: $4 \text{kpc}$ halo height

$^{10}\text{Be}$ decays in $10^6$ years, $^9\text{Be}$ is stable, so ratio sensitive to cosmic-ray confinement time, halo size.

Hams et al. 2004 ApJ 611, 892
not just spectra .......... also skymaps

EGRET $\gamma$-ray data
Tracer of SNR cosmic-ray sources: Pulsar distribution

Parkes Deep Survey

Yusifov & Kücük 2004
(Lorimer 2004: almost same result)
Old mystery of cosmic-ray gradient: gradient based on $\gamma$-rays much smaller than SNR gradient.

SNR (traced by latest pulsar surveys: Lorimer 2004)
Old mystery of cosmic-ray gradient: gradient based on $\gamma$-rays much smaller than SNR gradient.

SNR (traced by latest pulsar surveys: Lorimer 2004)

\begin{align*}
\text{Clue: Galactic metallicity gradient e.g. [O/H]} \\
\text{metallicity decreases with } R, \quad X = \frac{H_2}{CO} \text{ decreases with metallicity} \\
\text{>>>>>>>> } X = \frac{H_2}{CO} \text{ increases with radius} \\
\text{$\gamma$-rays = sources(R) * X(R) * CO(R) } ( + HI, inverse Compton terms) \\
\text{Steeper sources * flatter } X = \text{ observed gamma-rays} \\
\text{Strong et al. 2004 A&A 422, L47}
\end{align*}
Stochastic cosmic-ray sources with GALPROP

ELECTRONS

130 GeV

Sampled spectra over Galaxy

3D, time-dependent, several SNR/year over Galaxy

Extreme fluctuations in space / time at high energies.
Strong and Moskalenko, ICRC 2001
PAMELA positron fraction with other experimental data and with secondary production model.

GALPROP used to calculate secondary positrons for PAMELA to show the excess attributed to DM or pulsars or ....
Gamma-rays, inner Galaxy

inverse Compton from primary electrons, secondary electrons, positrons

These processes are very relevant down to hard X-rays!

Bouchet et al power-law continuum

Porter, Moskalenko, Strong, Orlando, Bouchet ApJ 682, 400
and towards the highest energies...

Diffuse Galactic Emission
B regular
Interstellar radiation over 20 decades of energy
Outlook

Fermi operational, results coming out fast
Try to keep the models up to the data challenges

Continue to use GALPROP to exploit synergy between cosmic-rays - gammas - microwave - radio