GALPROP: principles, internal structure, recent results, and perspective

Igor V. Moskalenko & Andy W. Strong
NASA/GSFC                MPE, Germany

with
Olaf Reimer
Bochum, Germany

Topics to cover:

- GALPROP: principles, inputs/outputs, calculations
- Recent results (GeV excess & pbars, extragalactic background)
- Dark Matter
- Near future developments
Transport Equation

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

**diffusion** + \( \vec{\nabla} \cdot [ D_{xx} \vec{\nabla} \psi - \vec{V} \psi ] \)

**convection**

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

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

**convection**

**fragmentation** - \( \frac{\psi}{\tau_f} - \frac{\psi}{\tau_d} \)

**radioactive decay**

\( \psi(\vec{r}, p, t) \) – density per total momentum

CR Propagation: Milky Way Galaxy

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

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

1 kpc~3x10^{18} cm
CR Interactions in the Interstellar Medium

Sources: SNRs, Shocks, Superbubbles

- Particle acceleration
- Photon emission

X, γ, e^+, p, He, CNO

ISM

Diffusion, energy losses, reacceleration, convection, etc.

B, ISRF

gas

synchrotron, IC, bremsstrahlung

Halo, disk

escape

Solar modulation

BESS, AMS, ACE

Chandra, GLAST
GALPROP is parameter-driven (user can specify everything!)

Grids
- 2D/3D -options; symmetry options (full 3D, 1/8 -quadrants)
- Spatial, energy/momentum, latitude & longitude grids
- Ranges: energy, R, x, y, z, latitude & longitude
- Time steps

Propagation parameters
- $D_{\text{xx}}$, $V_A$, $V_C$ & injection spectra ($p$, $e$)
- X-factors (including R-dependence)

Sources
- Parameterized distributions
- Known SNRs
- Random SNRs (with given/random spectra), time dependent eq.

Other
- Source isotopic abundances, secondary particles ($p$, $e^\pm$, $\gamma$, synchro), anisotropic IC, energy losses, nuclear production cross sections...
Typical grid steps (can be arbitrary!)
Δz = 0.1 kpc, ΔΔz = 0.01 kpc (gas averaging)
ΔR = 1 kpc
ΔE = x1.2 (log-grid)
Gas Distribution

Molecular hydrogen $H_2$ is traced using $J=1-0$ transition of $^{12}CO$, concentrated mostly in the plane ($z\sim70$ pc, $R<10$ kpc)

Atomic hydrogen $H\ I$ has a wider distribution ($z\sim1$ kpc, $R\sim30$ kpc)

Ionized hydrogen $H\ II$ - small proportion, but exists even in halo ($z\sim1$ kpc)
Interstellar Radiation Field

- Stellar
- Dust
- CMB
Nuclear Reaction Network + Cross Sections

Secondary, radioactive ~1 Myr & K-capture isotopes

Plus some dozens of more complicated reactions.
But many cross sections are not well known...
Nuclear component in CR: What we can learn?

Stable secondaries: Li, Be, B, Sc, Ti, V

Radio (t_{1/2}~1 Myr): ^{10}\text{Be}, ^{26}\text{Al}, ^{36}\text{Cl}, ^{54}\text{Mn}

K-capture: ^{37}\text{Ar}, ^{49}\text{V}, ^{51}\text{Cr}, ^{55}\text{Fe}, ^{57}\text{Co}

Short t_{1/2} radio ^{14}\text{C} & heavy Z>30

Heavy Z>30: Cu, Zn, Ga, Ge, Rb

Diffuse $\gamma$-rays
Galactic, extragalactic: blazars, relic neutralino

Propagation parameters:
Diffusion coeff., halo size, Alfvén speed, convection velocity...

Energy markers:
Reacceleration, solar modulation

Local medium:
Local Bubble

Material & acceleration sites, nucleosynthesis (r- vs. s-processes)

Solar modulation

Nucleosynthesis: supernovae, early universe, Big Bang...

Dark Matter ($\bar{p}, d, e^+, \gamma$)
Fixing Propagation Parameters: Standard Way

Using secondary/primary nuclei ratio:
- Diffusion coefficient and its index
- Propagation mode and its parameters (e.g., reacceleration $V_A$, convection $V_Z$)

Radioactive isotopes:
- Galactic halo size $Z_h$
Peak in the Secondary/Primary Ratio

- **Leaky-box model:**
  fitting path-length distribution -> free function

- **Diffusion models:**
  - Diffusive reacceleration
  - Convection
  - Damping of interstellar turbulence
  - Etc.

Measuring many isotopes in CR simultaneously may help to distinguish
Heliosphere
Electron Fluctuations/SNR stochastic events

**GeV electrons**

**100 TeV electrons**

Electron energy loss timescale:
- 1 TeV: \(~300,000\) yr
- 100 TeV: \(~3,000\) yr
CR Variations in Space & Time

More frequent SN in the spiral arms

Historical variations of CR intensity over 150 000 yr (Be$^{10}$ in South Polar ice)

Electron/positron energy losses

Different “collecting” areas A vs. p
Provides literally everything:

- All nuclei and particle spectra in every grid point \((x,y,R,z,E)\) - FITS files

Separately for \(\pi^0\)-decay, IC, bremsstrahlung:

- Emissivities in every grid point \((x,y,R,z,E,\text{process})\)
- Skymaps with a given resolution \((l,b,E,\text{process})\)

“CONSUMERS:”

- AMS, Pamela - dark matter searches
- ACE, TIGER - interpretation of isotopic abundances
- HEAT - electrons, positrons
- GLAST(?) - spectrum of the diffuse emission & background model
algorithm

- primary source functions (p, He, C .... Ni)
- source abundances, spectra
- primary propagation - starting from maxA=64

- source functions (Be, B...., e⁺, e⁻, pbars)
- using primaries and gas distributions
- secondary propagation

- tertiary source functions
- tertiary propagation

- γ-rays (IC, bremsstrahlung, π⁰-decay)
- radio: synchrotron
GALPROP Calculations

Constraints

• Bin size \((x,y,z)\) depends on the computer speed, RAM; final run can be done on a very fine grid!
• No other constraints! -any required process/formalism can be implemented; vectorization!!

Calculations (\(\gamma\)-ray related)

- Vectorization options
  - Heliospheric modulation: routinely force-field, can use Potgieter model
  1. For a given propagation parameters: propagate p, e, nuclei, secondaries (currently in 2D)
  2. The propagated distributions are stored
  3. With propagated spectra: calculate the emissivities (\(\pi^0\)-decay, IC, brems) in every grid point
  4. Integrate the emissivities over the line of sight:
    • GALPROP has a full 3D grid, but currently only 2D gas maps (H2, H I, H II)
    • Using actual annular maps (column density) at the final step
    • High latitudes above \(b=40^\circ\) -using integrated H I distribution
Near Future Developments

Full 3D Galactic structure:
• 3D gas maps (from S.Digel, S.Hunter and/or smbd else)
• 3D interstellar radiation & magnetic fields (A.Strong & T.Porter)

Cross sections:
• Blattning et al. formalism for $\pi^0$-production
• Diffractive dissociation with scaling violation (T.Kamae)
• Isotopic cross sections (with S.Mashnik, LANL; try to motivate BNL, JENDL-Japan, other Nuc. Data Centers)

Energy range:
• Extend toward sub-MeV range to compare with INTEGRAL diffuse emission (continuum; 511 keV line)

Modeling the local structure:
• Local SNRs with known positions and ages
• Local Bubble -may be done at the final calculation step

Heliospheric modulation:
• Implementing a complimentary drift model by M.Potgieter

Visualization tool (started) using the classes of CERN ROOT package:
• images, profiles, and spectra from GALPROP to be directly compared with data

Improving the GALPROP module structure (for DM studies) & developing a dedicated Web-site to allow for a communication with users
Recent results
Wherever you look, the GeV $\gamma$ - ray excess is there!
Reacceleration Model: Secondary Pbars

B/C ratio

\[ \frac{B}{C} \]

\( E_k, \text{GeV/nucleon} \)

Antiproton flux

\( \phi = 450 \text{ MV} \)

\( \phi = 550 \text{ MV} \)

\( E_k, \text{GeV} \)

- Voyager
- Ulysses
- ACE
- HEAO-3
- BESS 95-97
- MASS91
- CAPRICE98

Tertiary
Positron Excess?

HEAT (Coutu et al. 1999)

- Are all the excesses connected somehow?
- A signature of a new physics (DM)?

Caveats:
- Systematic errors?
- A local source of primary positrons?
- Large E-losses -> local spectrum…

$e^+/e^-$
SUSY DM candidate has also other reasons to exist - particle physics...

**Supersymmetry** is a mathematically beautiful theory, and would give rise to a very predictive scenario, if it is not broken in an unknown way which unfortunately introduces a large number of unknown parameters...

Lars Bergström (2000)
**Supersymmetry:**
- MSSM
- Lightest neutralino $\chi^0$
- $m_\chi \approx 100$–500 GeV
- $S=\frac{1}{2}$ Majorana particles
- $\chi^0\chi^0 \rightarrow p, \bar{p}, e^+, e^-, \gamma$

- Look at the combined (pbar, e+, $\gamma$) data
- Possibility of a successful "global fit" cannot be excluded - non-trivial!
- If successful, it may provide a strong evidence for the SUSY DM
**GeV excess: Optimized model**

**Uses all sky and antiprotons & gammas to fix the nucleon and electron spectra**

- Uses antiprotons to fix the *intensity* of CR nucleons @ HE
- Uses gammas to adjust
  - the nucleon spectrum at LE
  - the *intensity* of the CR electrons
  - (uses also synchrotron index)
- Uses EGRET data up to 100 GeV

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**antiprotons**

**electrons**

**protons**
Diffuse Gammas from Secondary Positrons/Electrons

**Heliosphere**

- $e^+ \sim 0.1e^-$
- $e^+ / e^-$
- $e^+=e^-$
- Important below 200 MeV

**Interstellar**

- $\Phi = 600 \text{ MV}$
- $\text{electrons}$
- $\text{sec.} e^- = 10\%$
- $\text{positrons}$

- $E^2$ Flux, GeV m$^{-2}$ sr$^{-1}$

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GLAST meeting/SLAC 2004/09/27-30
Anisotropic Inverse Compton Scattering

- Electrons in the halo see anisotropic radiation
- Observer sees mostly head-on collisions

Important @ high latitudes!
Diffuse Gammas at Different Sky Regions

- Hunter et al. region: $l=300^\circ-60^\circ, |b|<10^\circ$
- Intermediate latitudes: $l=0^\circ-360^\circ, 10^\circ<|b|<20^\circ$
- Outer Galaxy: $l=90^\circ-270^\circ, |b|<10^\circ$
- Intermediate latitudes: $l=0^\circ-360^\circ, 20^\circ<|b|<60^\circ$
Longitude Profiles |b|<5°

50-70 MeV

0.5-1 GeV

2-4 GeV

4-10 GeV
Latitude Profiles: Inner Galaxy

50-70 MeV

0.5-1 GeV

2-4 GeV

4-10 GeV

20-50 GeV
Latitude Profiles: Outer Galaxy

- 50-70 MeV
- 0.5-1 GeV
- 2-4 GeV
- 4-10 GeV

Intensity, cm$^{-2}$ s$^{-1}$

Galactic latitude
Extragalactic Gamma-Ray Background

Predicted vs. observed

Sreekumar et al. 1998

Strong et al. 2004

Elsaesser & Mannheim, astro-ph/0405235

Blazars
Cosmological neutralinos

Predicted vs. observed
Distribution of CR Sources & Gradient in the CO/H$_2$

CR distribution from diffuse gammas (Strong & Mattox 1996)

SNR distribution (Case & Bhattacharya 1998)

Pulsar distribution (Lorimer 2004)

$X_{\text{CO}} = \frac{N(H_2)}{W_{\text{CO}}}$:
- Histo - This work, Strong et al. '04
- Sodroski et al. '95, '97
- 1.9x10$^{20}$ - Strong & Mattox '96
- $\sim Z^{-1}$ - Boselli et al. '02
- $\sim Z^{-2.5}$ - Israel '97, '00, [O/H] = 0.04, 0.07 dex/kpc
Again Diffuse Galactic Gamma Rays

Very good agreement!

More IC in the GC - better agreement!

The pulsar distribution vs. R falls too fast OR larger H$_2$/CO gradient
Accurate measurements of diffuse gamma rays, secondary antiprotons, and other CR species simultaneously may provide a new vital information for Astrophysics – in broad sense, Particle Physics, and Cosmology.

**Gamma rays:** GLAST is scheduled to launch in 2007 – diffuse gamma rays is one of its priority goals

**Dark Matter**

**CR species:** New measurements at LE & HE simultaneously are highly desirable (Pamela, S-TIGER, AMS...), sec. positrons!
Conclusions II

Antiprotons: Pamela (2005), AMS (2008) and a new BESS-polar instrument to fly a long-duration balloon mission (in 2004, 2006...), we thus will have more accurate and restrictive antiproton data.

HE electrons: Several missions are planned to target specifically HE electrons.

We must be ready!

GALPROP is a propagation model to play now.
Thank you!