GALPROP CODE FOR GALACTIC COSMIC RAY PROPAGATION
AND ASSOCIATED PHOTON EMISSIONS

IGOR V MOSKALENKO - STANFORD

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Decade of discoveries in astrophysics of CRs

✧ High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-500 GeV
✧ Electron and Positron Fluxes in Primary Cosmic Rays
✧ Precision Measurement of the \((e^+e^-)\) Flux in Primary Cosmic Rays from 0.5 GeV to 1 TeV and above
✧ Discovery of breaks in spectra of p and He and their precision measurements up to 3 TV
✧ Antiproton Flux, Antiproton-to-Proton Flux Ratio, and Properties of Elementary Particle Fluxes in Primary Cosmic Rays
✧ Precision Measurement of the Boron to Carbon Flux Ratio in Cosmic Rays from 1.9 GV to 3 TV
✧ Observation of the Identical Rigidity Dependence of He, C, and O Cosmic Rays at High Rigidities
✧ Observation of New Properties of Secondary Cosmic Rays Lithium, Beryllium, and Boron
✧ Measurements of spectra of CR species in the interstellar medium (Voyager 1)
✧ Observation of \(^{60}\)Fe in CRs
✧ Observation of Fermi Bubbles
✧ Observation of gamma-ray emission from normal starforming galaxies
CRs in the interstellar medium

GALPROP

GALPROP

HESS

HESS

Chandra

Fermi

WIMP annihil.

SNR RX J1713-3946

42 sigma (2003+2004 data)

HESS

PSF

IC

PSF

IC

HESS

B

GALPROP

gas

gas

B

ISRF

ISRF

Gamma rays:

- Trace whole Galaxy
- Line of sight integration
- Only major species (p, He, e)

CR measurements:

- Detailed information on all species
- Only one location
- Solar modulation

Modeling is a must!

Heliosphere

AMS-02

PAMELA

BESS

ACE

GALPROP

GALPROP
Original motivation

✧ Pre-GALPROP (before ~1997)
  ✧ Leaky-box type models: simple, but not physical
  ✧ Many different simplifying assumptions – hard to compare
  ✧ Many models, each with a purpose to reproduce data of a single instrument
  ✧ No or few attempts to make a self-consistent model

✧ Two key concepts are forming the basis of GALPROP

I. One Galaxy – a self-consistent modeling:
   Various kinds of data, such as direct CR measurements including primary and secondary nuclei, electrons and positrons, γ-rays, synchrotron radiation, and so forth, are all related to the same astrophysical components of the Galaxy and, therefore, have to be modeled self-consistently

II. As realistic as possible:
   The goal for GALPROP-based models is to be as realistic as possible and to make use of all available astronomical and astrophysical information, nuclear and particle data, with a minimum of simplifying assumptions
Components of GALPROP

✧ Numerically solves time-dependent transport equations for all cosmic ray species (stable + long-lived isotopes + pbars + leptons ~90) in 2D or 3D

✧ Propagation, diffusive acceleration, convection, energy losses…

✧ Derives the propagation parameters corresponding to the assumed transport phenomenology and source distribution

✧ Detailed gas distribution from HI and CO gas surveys (energy losses from ionization, bremsstrahlung; secondary production; γ-rays from π⁰-decay, bremsstrahlung)

✧ Interstellar radiation field (inverse Compton losses/γ-rays for eˡˡ)

✧ B-field models

✧ Nuclear & particle production cross sections + the reaction network (cross section database + LANL nuclear codes + phenomenological codes)
GALPROP development team

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And many others who contributed over many years of development;
Special thanks to: Stepan Mashnik (cross sections), Seth Digel (initial gas maps),
Roberto Trotta…

Our former colleagues:

Andrew W Strong (retired)
Max-Planck-Institut
für extraterrestrische Physik

Andrey Vladimirov
Colfax International

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Stanford University
Computing cluster: http://galprop.stanford.edu

Provides the latest version of GALPROP and WebRun service (online version)

Now: 500+ cores (Xeon & Opteron)

Upgrade will nearly double the capacity

- Intel Xeon 4 × 32 cores
  - 384 GB shared memory each
- Intel Xeon Phi coprocessor 4 × 2 cards
- AMD Opteron 3 × 64 cores
  - 256 GB shared memory each
- 6174 AMD Opteron 4 × 48 cores
  - 128 GB shared memory each
- Web server
- Data storage (12 TB RAID0)
- Infiniband link (10 Gbit/s)
New GALPROP features (v.56)

- Options for 2D/3D gas distributions (Jóhannesson et al., 2018)
- Options for 2D/3D interstellar radiation field (Porter et al., 2017)
- Options for 2D/3D source density distributions
- Allows spatial variations in the diffusion coefficient and Alfvèn speed
- Wave damping: to speed up, an approximate solution is now used
- The observer can now be anywhere in \((x, y, z)\); gamma-ray skymaps!
- Injection spectrum allows it to be set independently for each isotope
- A new skymap integrator with a variable step size
- Can be used for arbitrary galaxy
- Single external dependency on the GALTOOLSLIB library
- Numerous generalizations, improvements, and optimizations
- Other large and small upgrades
3D gas: H I & H$_2$

- Forward folding model fitting technique
- Max-likelihood fit to H I LAB and the DHT CO surveys
- Re-binned to HEALPix order 7 (H I) and 8 (CO), degraded to 2 km/s v-bins
-Built iteratively, starting with 2D disk, adding warping, central bulge/bar, flaring (outer Galaxy), and spiral arms

- The location and shape of the spiral arms are identical between the H I and CO models, but the radial and vertical profiles differ
- Each spiral arm also has a free normalization
Effect of 3D gas on gamma-ray skymaps

- Ratio of the total gamma-ray skymaps at 1 GeV for 3D/2D models
- The 3D/2D ratio demonstrates features similar to the Fermi-LAT residual map
Secondary $e^+$ and B/C ratio in models with CR sources in spiral arms

Energy density of secondary positrons in the mid-plane of the MW

B/C ratio @ 10 GeV/n
Spatial variations of the B/C ratio and positron spectrum in the Galaxy in 2D/3D models

The B/C ratio and positron spectrum at $R_\odot$ but in different environments

**B/C ratio**

**$e^+$ spectrum**
3D interstellar radiation field

- Monte Carlo radiation transfer code FRaNKIE
- Two models for the stellar and dust distributions are chosen from the literature:
  - \(R12 = \text{Robitaille}^{+2012}\)
  - \(F98 = \text{Freudenreich}^{1998}\)
- The simulation volume for the radiation transfer: a box \(X,Y=\pm 15 \text{ kpc}, Z=\pm 3 \text{ kpc}\)
- \(\lambda\)-grid = 0.0912–10000 \(\mu\text{m}\)

\[\text{Longitudinal profile averaged over } |b|<5^\circ\]

\[\text{Energy density for distances } X=0,4,8,12,16 \text{ kpc}\]
Energy density of interstellar radiation field

✧ Integrated ISRF energy densities in the Galactic plane
✧ The ISRF structure will translate into the structure in the inverse Compton
✧ A comparison with the Fermi-LAT data is not made yet
✧ Affects spectra of electrons/positrons at HE and diffuse emission
Nuclear & particle production cross sections

✦ Bottle neck for further advances in Astrophysics of CRs
✦ To improve:
  ✦ Use advanced Monte Carlo event generators tuned to accelerator data (e.g., QGSJET-II-04 & EPOS-LHC)
  ✦ New measurements of astrophysically important cross sections
✦ Examples:
  ✦ Kachelriess, IM, Ostapchenko, 2014 “Nuclear enhancement of the photon yield in cosmic ray interactions”
  ✦ Kachelriess, IM, Ostapchenko, 2015 “New calculation of antiproton production by cosmic ray protons and nuclei”
✦ New international collaboration to measure/improve on the astrophysically important cross sections was formed at XSCRC2017: Cross sections for cosmic rays @ CERN (March 29-31, 2017)
GALPROP package for calculation of the Xsections

✧ nuc_package.cc
✧ Includes an extensive nuclear reaction network built using the Nuclear Data Sheets
✧ Takes into account all intermediate unstable nuclei and follows the decay chains down to 5 generations of the decay products
✧ Based on a careful inspection of the quality and systematics of various datasets and semi-empirical formulae
✧ Uses the best of parametric formulae (normalized to the data when exists) and results of nuclear codes: SEM, HMS-ALICE, LAQGSM
✧ Sometimes – a direct fit to the data for particular reactions
✧ Can handle H-like ions, electron pick-up from the interstellar gas, and electron stripping – important for isotopes decaying through electron capture (EC)
Current status and desired accuracy of the isotopic production cross sections relevant to astrophysics of cosmic rays I. Li, Be, B, C, N

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(Dated: March 14, 2018)

✧ Provides a motivation for a proposal to make new measurements of isotopic production cross sections using secondary ion beams, isotopes of Li, Be, B, C, N, O. Nuclear fragments from CERN SPS, Pb beam on primary target with momentum 13A GeV/c at different A/Z settings.

✧ Got time at the NA61/SHINE facility at the end of 2018!
Examples of Xsections $^{12}$C+H

- $^{12}$C → $^{6}$Li
- Flux impact: Li 13.57%

- $^{12}$C → $^{7}$Li
- Flux impact: Li 11.87%

- $^{12}$C → $^{7}$Be
- Flux impact: Li 0.41%
- Be 15.88%

- $^{12}$C → $^{9}$Be
- Flux impact: Li 0.13%
- Be 9.27%

- $^{12}$C → $^{10}$Be
- Flux impact: Li 0.16%
- Be 2.16%
- B 1.48%

- $^{12}$C → $^{10}$B
- Flux impact: Li 0.64%
- Be 0.64%
- B 7.41%

- $^{12}$C → $^{11}$B
- Flux impact: Li 1.38%
- Be 1.43%
- B 18.07%

- $^{12}$C → $^{11}$C
- Flux impact: Li 0.16%
- Be 0.15%
- B 1.87%

GP12 = GALPROP, option 12
WKS98, W03 = Webber et al.
Error impact on calculations of CR Li, Be, B fluxes

✧ The bands are shown for 15%-25% errors on all cross sections
✧ “Current” – indicates current uncertainty
✧ Most impact is due to reactions with $^{12}$C, $^{16}$O on $^1$H target (shown assuming 0% error)
HelMod Forecasting of the Intensities of Ion Cosmic Rays

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GALPROP/HelMod

- Goal #1: reliable local interstellar spectra of all CR species (>100 MeV/n)
- Goal #2: reliable heliospheric modulation for an arbitrary epoch in the past
- Time dependent Parker (1965) equation
- 2D Monte Carlo, backward in time
- Convection, energy loss, full description of the diffusion tensor (charge sign effect)
- http://www.helmod.org
Time and Spatial Variation of Cosmic Rays

The Ulysses Probes explore the tridimensional view of the inner heliosphere.

Ulysses allow to probe the interplanetary space up to 5 AU and +/- 80 degree of Solar Latitude: Outside ecliptic Plane

Electrons 1.18 GeV

Protons 1.75 GeV

Periods which need further investigations
Using derived LIS HeLMod is also able to simulate solar modulation for Ions.

ACE Data: http://www.srl.caltech.edu/ACE/ASC/

Time and Spatial variation of Cosmic Rays
Low level of solar activity ($A \leq 0$)

- **GALPROP/HelMod calcs** for the low level of solar activity and both polarities of the solar magnetic field
Antiprotons were not fitted!

GALPROP/HeIMod calcs for high activity periods vs. AMS-02 data

Active Sun: 2011-15

- Accuracy of AMS-02 data is a few per cent
- Fitting such data with a physical model is a challenge
- But we managed!
Heliospheric propagation of electrons uses parameters derived from propagation of protons.
He, C, O fluxes

Excellent agreement of calculated spectra with precise measurements by AMS-02

Same models/parameters were used for Galactic and heliospheric propagation
Why the Local Interstellar spectra are important

The derived local interstellar spectra of CR species can be used to facilitate significantly studies of CR propagation in the Galaxy and in the heliosphere by disentangling these two massive tasks and will lead to further progress in understanding of both processes.

The follow up paper on secondary nuclei (Li, Be, B) is in progress.
GALPROP remains the leading tool for interpretation of the observational data in astrophysics of cosmic rays and gamma-ray astronomy.

- It becomes a self-consistent 3D model of all components of the interstellar medium (gas, sources, radiation field).
- It becomes even better each year as more precise data in many areas of astrophysics becomes available.