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GALPROP Code for Galactic Cosmic Ray Propagation and Associated Photon Emissions

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Signatures of new phenomena are abundant – thanks to the new instrumentation launched into space and built on the ground. *Modern technologies employed by those instruments provide measurements with unmatched precision, enabling searches for subtle signatures of dark matter (DM) and new physics in cosmic rays (CRs) and photon emissions.* Understanding the conventional astrophysical backgrounds is vital in moving to the new territory. The state-of-the-art CR propagation code called GalProp is designed to address exactly this challenge. Having 25 years of development behind it, the GalProp framework has become a *de-facto* standard in astrophysics of CRs, diffuse photon emissions (radio- to γ-rays), and searches of new physics. GalProp uses information from astronomy, particle, and nuclear physics to predict CRs and their associated emissions and their polarization in a self-consistent manner – it provides the modeling framework unifying the many results of individual measurements in physics and astronomy spanning in energy coverage, types of instrumentation, and the nature of detected species. The range of physical validity of the GalProp framework covers sub-keV–PeV energies for particles and from μeV–PeV for photons. Combining GalProp with HelMod, a heliospheric transport code, into a unified framework considerably extends its capabilities providing a consolidated description of CR transport from their sources to the near-Earth orbit. The framework and the datasets are public and are extensively used by many experimental collaborations, and by thousands of individual researchers worldwide for interpretation of their data and for making predictions. This paper details the latest updates to the GalProp framework, further developments of its initially auxiliary datasets that grew into independent studies of the Galactic structure – distributions of gas, dust, radiation and magnetic fields as well as further extension of its capabilities.

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1. Introduction

Signatures of new phenomena are abundant–thanks to the new instrumentation launched into space and built on the ground. *Modern technologies employed by those instruments provide measurements with unmatched precision, enabling searches for subtle signatures of DM and new physics in CR and photon data.* Among those missions are the Alpha Magnetic Spectrometer–02 (AMS-02), the *Fermi* Large Area Telescope (*Fermi*-LAT), the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA), the NUCLEON experiment, the CALorimetric Electron Telescope (CALET), the DArk Matter Particle Explorer mission (DAMPE), and the Cosmic-Ray Energetics and Mass investigation (ISS-CREAM). Outstanding results have been also delivered by mature missions, such as the Cosmic Ray Isotope Spectrometer onboard of the Advanced Composition Explorer (ACE-CRIS), and Voyager 1, 2 spacecraft, currently at 151 au/126 au from the Sun, respectively. Indirect observations of high-energy processes in the Galaxy and beyond are made by X-ray and γ-ray telescopes: the International Gamma-Ray Astrophysics Laboratory (INTEGRAL), *Fermi*-LAT, the High-Altitude Water Cherenkov γ-ray observatory (HAWC), and by atmospheric Cherenkov telescopes, the High Energy Stereoscopic System (H.E.S.S.), Major Atmospheric Gamma-ray Imaging Cherenkov Telescopes (MAGIC), the Very Energetic Radiation Imaging Telescope Array System (VERITAS). High-resolution data relevant to studies of the cosmic microwave background (CMB) are provided by the *Wilkinson* Microwave Anisotropy Probe (WMAP), and *Planck* mission. *The reached level of precision demonstrates that we are on the verge of major discoveries.*

Each of these experiments provides a unique piece of the Great Puzzle. However, to understand the internal working of the Milky Way and beyond, the whole puzzle must be assembled. The research tool we are developing is the state-of-the-art fully numerical GalProp code that does exactly that–it provides a self-consistent interpretation and combines in a single framework the results of individual measurements in physics and astronomy spanning in energy coverage, types of instrumentation, and the nature of detected species. Its range of physical validity extends from sub-keV–PeV energies for particles and from 10^{-6} eV (μeV)–PeV for photons. GalProp has 25 years of development behind it [48, 68]; over these years, it has proven to be invaluable tool in sophisticated analyses in many areas of astrophysics including numerous searches for new phenomena [1, 3–7, 9, 20, 21, 23, 38, 39, 77].

This paper details the latest updates to the GALPROP code, further developments of its initially auxiliary datasets that grew into independent studies of the Galactic structure – distributions of gas, dust, radiation and magnetic fields as well as further extension of its capabilities.

2. The GalProp framework

The GalProp framework is the state-of-the-art *public* numerical tool that describes propagation of Galactic CRs and production of the diffuse emissions in conjunction with other software packages, such as DarkSUSY, HelMod, SuperBayeS, etc. The GalProp code is available from a dedicated website[1], where a 500+ core facility for users to run the code via online forms in a web-browser, WebRun, is also provided [78]. Here we give a brief description of GalProp, for details see [19, 29, 32, 44, 48, 49, 51, 52, 56, 58, 59, 65, 68, 71, 72, 77, 78].

[1]https://galprop.stanford.edu

The GalProp code uses information from astronomy, particle, and nuclear physics to predict CRs, γ-rays, synchrotron emission and its polarization in a self-consistent manner. The key GalProp concept is that various kinds of data, e.g., direct CR measurements, $\bar{p}$, $e^\pm$, γ-rays, synchrotron radiation, and so forth, are all related to the same Galaxy and hence have to be modeled self-consistently [53, 68]. It provides the modeling framework unifying results of many individual experiments in physics and astronomy spanning in energy coverage, types of instrumentation, and the nature of detected species. The goal for the GalProp-based models is to be as realistic as possible and to make use of available information with a minimum of simplifying assumptions [70].

The GalProp code solves a system of about 90 time-dependent transport equations (partial differential equations in 3D or 4D: spatial variables plus energy) with a given source distribution and boundary conditions for all CR species: ^{1}H–^{64}Ni, $\bar{p}$, $e^\pm$ [68–70]. This includes convection, distributed reacceleration, energy losses, nuclear fragmentation, radioactive decay, and production of secondary particles and isotopes. The numerical solution is based on a Crank-Nicholson implicit second-order scheme [63]. The spatial boundary conditions assume free particle escape. For a given halo size the diffusion coefficient, as a function of rigidity and propagation parameters, is determined from secondary-to-primary nuclei ratios, typically B/C, [Sc+Ti+V]/Fe, and/or $\bar{p}/p$. If reacceleration is included, the momentum-space diffusion coefficient D_{pp} is related to the spatial coefficient $D_{xx} = \beta D_0 R^\delta$ [66], where $\beta = v/c$ is the particle velocity, R is the magnetic rigidity, $\delta = 1/3$ for a Kolmogorov spectrum of interstellar turbulence [40], or $\delta = 1/2$ for an Iroshnikov-Kraichnan cascade [30, 41], but can also be arbitrary. The non-linear damping of interstellar turbulence by CRs [65] can also be included if required. The injection spectra of CR species are parametrized by the rigidity-dependent function: $q(R) \propto (R/R_0)^{-\gamma_0} \prod_{i=0,1,2} \left[1 + (R/R_i)^{\frac{\gamma_i-\gamma_{i+1}}{s_i}}\right]^{s_i}$, where $\gamma_{i=0,1,2,3}$ are the spectral indices, $R_{i=0,1,2}$ are the break rigidities, s_i are the smoothing parameters (s_i is negative/positive for $|\gamma_i| \lessgtr |\gamma_{i+1}|$).

The GalProp code computes a complete network of primary, secondary, and tertiary isotope production starting from input CR source abundances. Since the decay branching ratios and half-lifes of fully stripped and hydrogen-like ions may differ, GalProp includes the processes of K-electron capture, electron pick-up from neutral ISM gas and formation of hydrogen-like ions as well as the inverse process of electron stripping [22, 62, 82]. It also includes knock-on electrons [2, 11] that may significantly contribute to hard X-ray—soft γ-ray diffuse emission through inverse Compton scattering and Bremsstrahlung [61].

The nuclear reaction network is built using the *sixty four* volumes of Nuclear Data Sheets (see [55] for Cumulated Index to A-Chains for $A = 1-64$ nuclei). Included are multistage chains of p, n, d, t, ^{3}He, α, $\beta^\pm$-decays, and electron K-capture, and, in several cases, more complicated reactions. This accounts for up to 4 stages of 3 decay branchings each in any of the decay channels, i.e. up to $3^4 = 81$ total daughter nuclei in the final state for *each fragment* produced in spallation of the initial target nucleus plus unlimited number of p, n, and $\beta^\pm$-decays.

The routines for the isotopic production cross sections are built using all available data extracted from Los Alamos (LANL) and EXFOR databases, as well as from an extensive literature search. To account for different measurement techniques that were introduced since 1950s, the distinction was made between the *individual, direct, decaying, charge-changing, cumulative, differential, total, and isobaric cross sections, or reactions with metastable final states, with the target* *that could be a particular isotope, a natural sample with mixed isotopic composition, or a chemical compound.* Often, experimental cross sections for the same reaction published by various groups were found to differ by a significant factor. A (tough) decision on which set to be used was based on examination of the descriptions of particular experimental setups in the original papers.

The isotopic production cross sections were ranked by their contributions to the production of a particular isotope (e.g., see [54]). The most effort was devoted to the main contributing channels. The approach to the description of each channel depended on the accuracy and availability of experimental data. If the cross section data were detailed enough, they were approximated with fitted functional dependences or provided as a table for interpolation. If only a few or no data points were available, such cross sections were approximated using the results of the Los Alamos nuclear codes [43, 45, 46, 50, 51], such as a version of the Cascade-Exciton Model (CEM2k, [43]) and the ALICE code with the Hybrid Monte Carlo Simulation model (HMS-ALICE, [12, 13]). In general, parameterizations of all isotopic production cross sections are provided from a few MeV nucleon^{-1} to several GeV nucleon^{-1}, above which it is assumed a constant.

In the case of a minor contribution channel, the best of the available semi-empirical formulae by Webber et al. (WNEWTR code with modifications made in 2003 [79]) or parametric formulae by Silberberg and Tsao (YIELDX code [67, 76]) normalized to the data when exists was used. Each of the 1000s channels was tested to ensure the best description of the available data. *A very limited database* of the measured cross section points is supplied with GalProp routines to renormalize the output of WNEWTR and YIELDX codes. The data points to include into this database were selected for the stated validity range of the semi-empirical formulae (typically >150 MeV nucleon^{-1} [79]), while the data points outside of this validity range were excluded from the auxiliary files.

The total (inelastic) fragmentation cross sections for pA- and AA-reactions are calculated using CRN6 code by Barashenkov & Polanski [10], or using optional parameterizations by Letaw et al. [42] or by Wellisch & Axen [81] (with corrections provided by the authors) and A-scaling dependencies.

Though the overall process was very laborious and often impossible to automate, it produced probably the most accurate package (nuc_package.cc and auxiliary files) for massive calculations of the production nuclear cross sections so far. Since it is the core part of GalProp, it was used in numerous studies where the GalProp code was employed. It was also used in many studies of the accuracy of the isotopic production cross sections employed in astrophysical applications (e.g., [26, 29, 75]), and in other Galactic propagation codes, such as, e.g., DRAGON [27, 28].

Production of secondary particles in GalProp is calculated taking into account pp-, pA-, Ap-, and AA-reactions. Calculations of $\bar{p}$ production and propagation are detailed in [33, 35, 51, 52], where inelastically scattered (tertiary) $\bar{p}$ and (secondary) p are treated as separate species. Production of neutral mesons (π^0, K^0, $\bar{K}^0$, etc.), and secondary $e^{\pm}$ is calculated using the formalism by [24, 25] as described in [48] or recent parameterizations [33, 34, 36, 37].

Production of γ-rays is calculated using the propagated CR distributions, including primary e^-, secondary $e^{\pm}$, and knock-on e^-, as well as inelastically scattered (secondary) protons [61, 72]. The inverse Compton scattering is treated using the formalism for an anisotropic background photon distribution [49] with full Galactic interstellar radiation field on the 2D or 3D grid [47, 60]. Electron bremsstrahlung cross section is calculated as described in [71]. Gas-related γ-ray intensities (π^0-decay, bremsstrahlung) are computed from the emissivities using the column densities of

H_2+H I+H II gas for Galactocentric annuli based on 2.6-mm carbon monoxide CO (a tracer of molecular hydrogen H_2) and 21-cm H I (atomic hydrogen) survey data. The synchrotron emission[2] and its polarization are computed [56] using published models of the Galactic magnetic field for regular, random, and striated components [31, 64, 73, 74]. The line-of-sight integration of the corresponding emissivities with the distributions of gas, interstellar radiation and magnetic fields yields γ-ray and synchrotron sky maps. Spectra of CR species and the γ-ray and synchrotron sky maps are output in standard astronomical formats.

DM: Similarly to ordinary CR species and their diffuse emissions, GalProp *has well-developed options to propagate particles produced in exotic sources and processes*, such as annihilation or decay of DM particles, and calculate the associated emissions (DM γ-ray and synchrotron skymaps). It can be used alone or run in conjunction with dedicated packages, such as DarkSUSY; the appropriate interface is also provided.

The latest GalProp code v.56 [32, 44, 58] allows arbitrarily small, even sub-parsec, grid sizes and finely sampled energy/time spans provided that it is running on a machine that has enough computing resources. Given that, the actual employed grid sizing is physically motivated and consistent with the baseline assumptions used to derive transport equations. Meanwhile, many optimizations and updates are made to enable as much realistic calculations as possible on moderately sized single-memory spaced systems with limited resources. Besides that the latest version allows for the spatially variable diffusion coefficient, a separate injection spectrum for each isotope, scaling of the propagation parameters with the strength of the Galactic magnetic field and many other improvements including treatment of production of secondary particles and isotopes.

Heliospheric propagation of CRs is treated using the Parker equation [57], where the numerical solutions are provided by the HelMod code [14–18]. HelMod is a Monte Carlo code developed to describe the transport of Galactic CRs through the heliosphere from the local interstellar space to the Earth. HelMod was proved to reproduce spectra of CR protons, nuclei, and electrons observed during solar cycles 23–24 by several detectors, such as PAMELA, BESS, ACE-CRIS, and AMS-02. In particular, the unprecedented accuracy of AMS-02 observations allowed the formalism implemented in HelMod to be fine tuned. HelMod is also capable of reproducing the fluxes observed by the Voyager probes in the inner and outer regions of heliosphere up to its boundary. Combining GalProp with HelMod into a unified framework considerably extends capabilities of individual codes providing a consolidated description of CR transport from their sources to the near-Earth orbit.

Time-dependent solutions: Essential enhancements to the GalProp code have been implemented to enable more efficient time-dependent CR propagation and interstellar emissions modeling. The "discrete sampler" is a new facility that produces a spatial and temporal discretized list of CR source regions from a user-supplied smooth CR spatial density distribution and time interval. This enables direct comparison of CR energy densities and interstellar emission intensity maps resulting from a steady-state and equivalent time-dependent realization from the same CR source density model. The discrete sampler uses an acceptance/rejection method with pseudo-random number generator, which allows full reproducibility of the discretization of the smooth density model

[2]GalProp calculations of the foreground synchrotron emission were used by the *Planck* Collaboration [6, 7] to study anisotropies in Cosmic Microwave Background (CMB) with many important implications for the DM studies.

for different luminosity evolutionary scenarios for the CR sources in the time-dependent case. This new facility has been used for recent work to investigate the effect of time/space discretized CR sources on predictions for the non-thermal interstellar emissions [59].

Gas: Other improvements include the updated models of the spatial density distribution of the components of the interstellar gas (H I, H_2) [32]. The spatial density distribution of the interstellar gas is a vital element in many astrophysical studies, but its determination is difficult because of the position of the observer in one location in the Galactic plane. Until recently models have employed the 2D Galactocentric azimuthally symmetric geometry approximation, but their accuracy is well behind the accuracy of available data. New 3D spatial density models for the neutral and molecular hydrogen are constructed based on empirical model fitting to gas line-survey data. The developed density models incorporate spiral arms and account for the warping of the disk, and the increasing gas scale height with radial distance from the Galactic center.

The models for the interstellar radiation field [58] are developed based on stellar and dust spatial density distributions taken from the literature that reproduce local near- to far-infrared observations. The interstellar emission models that include arms and bulges for the CR source and interstellar radiation densities provide plausible physical interpretations for features found in the residual maps from high-energy γ-ray data analysis. The 3D models for CR and interstellar radiation densities provide a more realistic basis that can be used for the interpretation of the non-thermal interstellar emissions from the Galaxy.

3. Recent Studies

Finally, a couple of recent illustrative examples of GalProp capabilities. Using the GalProp–HelMod framework and available data from a number of instruments we derived a self-consistent set of the local interstellar spectra (LIS) for CR nuclei H–Ni, and e^- and $\bar{p}$ for the first time [16, 18, 19]. The LIS energy range covers 7 orders of magnitude in energy from ~10 MeV nucleon^{-1} to ~100 TeV nucleon^{-1}. We also provide a set of propagation parameters and the injection spectra and relative abundances for each isotope $^1_1$H–$^{64}_{28}$Ni. This is a significant step forward that allows the propagation in the Galaxy and in the heliosphere to be disentangled, while each future measurement can be analyzed within a self-consistent framework.

One of the latest long awaited surprises is the spectrum of $_{26}$Fe just published by AMS-02 [8]. Because of the large fragmentation cross section and large ionization energy losses, most of CR iron at low energies is local, and may harbor some features associated with relatively recent supernova activity in the solar neighborhood. Our analysis [20] of the new AMS-02 results together with Voyager 1 and ACE-CRIS data reveals an unexpected bump in the iron spectrum and in the Fe/He, Fe/O, and Fe/Si ratios at 1–2 GV, while a similar feature in the spectra of He, O, Si, and in their ratios is absent, hinting at a local source of low-energy CRs. The found excess extends the recent discoveries of radioactive ^{60}Fe deposits in terrestrial and lunar samples, and in CRs.

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