

GALPROP framework for propagation of Galactic cosmic rays and associated diffuse emissions

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We are reporting about recent updates to the GALPROP framework for propagation of Galactic cosmic rays (CRs) and associated diffuse emissions. GALPROP is a comprehensive interpretation package, combining 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 (μ eV)–PeV for photons. GALPROP has 27+ years of development behind it, it is continually updated to keep up with ever increasing amount and precision of experimental data. GALPROP development is supported by NASA grants and is free for the community. It is an open source code, which is extensively used by many high-profile collaborations, such as *Planck*, *Fermi-LAT*, AMS-02, HAWC, Voyager 1, 2, ACE-CRIS, and by 1000s of other researchers for interpretation of their data and for making predictions. The new features of version 57.2, to be released in the fall of 2025, include: (i) the AAfrag 2.01 interpolation package [1] for Monte Carlo results on secondary production in hadronic interactions is now incorporated into GALPROP and can be called upon appropriate selection of input parameters. It includes new options for calculation of secondary $e^{\pm}$, $\bar{p}$, p , γ -rays, and ν . The spectra and sky maps for different neutrino flavors can be calculated individually or combined. AAfrag 2.01 provides the results for $A=H, He, C, Al, Fe$ targets with p -projectile, as well as for $He+p$ and $He+He$ reactions. Meanwhile, GALPROP includes interpolation/extrapolation for other nuclei species. The beam+target combinations for production of secondary species now include $p + A$, $A + p$, and $He+He$, where $A=H-Ni$. (ii) Functionality to use inhomogeneous gas and dust distributions [2] for the cosmic ray spallation and secondary production. Calculation of secondary emissions (γ -rays and ν) have options to use these models. (iii) New options for 3D Galactic magnetic field models by Unger-Farrar [3] and Korochkin-Semikoz-Tinyakov [4]. (iv) The GALPROP self-installer now requires a minimum of system tools (only compilers, cmake, and autotools). It has been updated for compatibility with latest releases of RockyLinux and OSX.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland



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1. GALPROP framework

GALPROP has about 27 years of development behind it [5–7]. The latest release of GALPROP, version 57.1, became available for public in 2022 [8]. For more details see [9–14].

The GALPROP package¹ is a state-of-the-art comprehensive framework for analysis and interpretation of the measurements of Galactic CRs and their emissions. Theoretical understanding of CR propagation in the interstellar medium (ISM) is the framework that the GALPROP code is built around. The key idea is that all CR-related data, including direct measurements, γ -rays, synchrotron radiation, etc., are subject to the same physics and must therefore be modeled self-consistently [15]. GALPROP can combine 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 (μ eV)–PeV for photons. The goal for the GALPROP-based models is to be as realistic as possible and to make use of all available astrophysical information, nuclear and particle data, with a minimum of simplifying assumptions [7].

GALPROP solves a system of 90+ time-dependent (partial differential) transport equations in 3D or 4D (spatial variables + rigidity) with a given source distribution and boundary conditions for all CR species (^1H – ^{64}Ni , $\bar{p}$, $e^\pm$) [6–8, 16]. This includes convection, reacceleration, energy losses, nuclear fragmentation, radioactive decay, and production of secondary species. For a given propagation model the diffusion coefficient $D_{xx}(R)$, as a function of rigidity R , 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 $D_{xx} = \beta D_0 R^\delta$, where $\beta = v/c$, and $\delta = 1/3$ for a Kolmogorov spectrum of interstellar turbulence or $\delta = 1/2$ for an Iroshnikov-Kraichnan cascade. The current version allows an improved spatial resolution and spatially variable diffusion coefficient [10, 11, 17, 18].

GALPROP computes a complete network of secondary and tertiary isotope production starting from primary CR source abundances and includes the processes of electron capture (EC), e^- pick-up from neutral ISM gas and formation of H-like ions, and e^- stripping. Also included are knock-on e^- s that produce hard X-rays through inverse Compton scattering (ICS) and bremsstrahlung [19, 20]. The nuclear reaction network is built using Nuclear Data Sheets. Included are multistage chains of p^- , n^- , d^- , t^- , $^3\text{He}^-$, α^- , $\beta^\pm$ -decays, EC, and other reactions [12]. Isotopic production cross section routines are built using LANL nuclear codes [21], databases (LANL, EXFOR), an extensive literature search [12], and parameterizations. We distinguish the *individual*, *direct*, *decaying*, *charge-changing*, *cumulative*, *differential*, and *total cross sections*, with the target made from a *particular isotope*, a *natural sample*, or a *chemical compound*. The developed routines are used in many studies and in CR codes.

Production of neutral mesons (π^0 , K^0 , $\bar{K}^0$...) and “hadronic” γ -rays, secondary $\bar{p}$ and $e^\pm$ (from $\pi^\pm$ -decays) is calculated for pp^- , pA^- , Ap^- , and AA -reactions using published formalisms. The inelastically scattered “tertiary” $\bar{p}$ and “secondary” p are treated as separate species. Electron bremsstrahlung cross section is calculated as described in [22]. The ICS is treated using the formalism for an anisotropic interstellar radiation field (ISRF) [9] with full 2D or 3D ISRF [23, 24].

¹<https://galprop.stanford.edu>

Production of γ -rays is calculated using the propagated CR distributions. Gas-related γ -ray intensities (π^0 -decay, bremsstrahlung) are computed from the emissivities using the column densities of $\text{H}_2 + \text{H I}$ (+ H II) gas for Galactocentric annuli based on 2.6-mm carbon monoxide CO (a tracer of H_2) and 21-cm H I survey data. The synchrotron emission and its polarization are computed [25] using published GMF models for regular, random, and striated components. The line-of-sight integration of the corresponding emissivities with ISM distributions of gas, ISRF, and GMF yields multi-wavelength skymaps (radio to γ -rays).

Heliospheric transport is treated using the Parker equation that includes diffusion, adiabatic energy changes, convection, and drifts. Solutions are provided by the state-of-the-art HELMOD code [26]. We use the GALPROP–HELMOD framework (e.g., [12]) for realistic modeling of local interstellar spectra (LIS) for all CR species and their heliospheric transport.

2. Updates of the Production Cross Sections in GALPROP

An extensive work was carried out to update the `nuc_package` routines and data files using measurements that became available over the last two decades. The most progress was achieved in measurements of radioactive daughter nuclei with half-lives in the range of tens of minutes to several years using the nuclear de-excitation lines techniques (e.g., [27, 28]). An important factor is also availability of such cross section measurements in the EXFOR data base. Meanwhile, there are still a number of reaction channels where there is no data or just a few points exist, or there are abundant measurements, which, however, are quite contradictory. In such cases, decisions were made based on the extensive studies of the original publications, existing semi-empirical systematics, and results of the nuclear codes, and/or subjective knowledge and experience.

Table 1 summarizes the most significant reevaluations and updates. The columns list the parent nuclei (targets), the isotopic products, and the isotope(s) of interest. The projectiles are protons. The products column shows the final products along with intermediate (radioactive) isotopes, which production contributes to the final products and was used in the cross checks and evaluations.

In many cases, only measurements involving natural elemental samples were available. In the absence of the measurements with pure isotopic targets, such measurements were used as a substitute for reactions with large change in the mass number ΔA . We tried to avoid this for small ΔA , where the production cross sections for different isotopes of the same element can differ significantly.

3. AAfrag 2.01 interpolation package

The Monte Carlo generators QGSJET-II and QGSJET-III for hadronic interactions are standard tools for data analysis in high energy physics and CR astrophysics. The AAfrag 2.01 package [1] is based on the results of QGSJET-II-04m, which validity was extended toward low energies. The package provides interpolation tables for calculations of the production of secondary species (γ , ν , $e^\pm$, $\bar{p}$), and covers a wide range of energies of the beam particles in pA -, Ap -, and AA -reactions. It is now incorporated into GALPROP and can be called upon appropriate selection of input parameters. The spectra and skymaps for different neutrino flavors can be calculated individually or combined. AAfrag 2.01 provides the results for $A=\text{H, He, C, Al, Fe}$ targets with p -projectile, as well as for $\text{He}+p$ and $\text{He}+\text{He}$ reactions. Meanwhile, GALPROP includes interpolation/extrapolation for other

Table 1: Most significant reevaluated and updated production cross sections

Targets ($p + A$)	→	Reaction Products	Isotopes of Interest
${}^7\text{Li}, {}^{7,9}\text{Be}, {}^{10,11}\text{B}, {}^{12,13}\text{C}, {}^{14,15}\text{N}, {}^{16}\text{O}, {}^{56}\text{Fe}$	→	${}^{6,7}\text{Li}, {}^7\text{Be}$	${}^{6,7}\text{Li}$
${}^9\text{Be}, {}^{10,11}\text{B}, \text{nat}, {}^{12,13}\text{C}, \text{nat}, {}^{14,15}\text{N}, \text{nat}, {}^{16}\text{O}, \text{nat}, {}^{24}\text{Mg}, \text{nat}, {}^{28}\text{Si}, \text{nat}, {}^{32}\text{S}, \text{nat}, {}^{56}\text{Fe}$	→	${}^{7,9,10}\text{Be}, {}^{10}\text{B}, {}^{10}\text{C}$	${}^{7,9,10}\text{Be}$
${}^{11}\text{B}, \text{nat}, {}^{12,13}\text{C}, \text{nat}, {}^{14,15}\text{N}, \text{nat}, {}^{16}\text{O}, {}^{20,22}\text{Ne}, \text{nat}, {}^{24}\text{Mg}, \text{nat}, {}^{28}\text{Si}, \text{nat}, {}^{56}\text{Fe}$	→	${}^{10}\text{Be}, {}^{10,11}\text{B}, {}^{10}\text{C}$	${}^{10,11}\text{B}$
$\text{nat}, {}^{14,15}\text{N}, \text{nat}, {}^{16}\text{O}, {}^{20,22}\text{Ne}, \text{nat}, {}^{24}\text{Mg}, \text{nat}, {}^{28}\text{Si}, \text{nat}, {}^{56}\text{Fe}$	→	${}^{13}\text{C}, {}^{13}\text{N}$	${}^{13}\text{C}$
$\text{nat}, {}^{16}\text{O}, {}^{20,22}\text{Ne}, \text{nat}, {}^{24}\text{Mg}, \text{nat}, {}^{28}\text{Si}, \text{nat}, {}^{32}\text{S}, \text{nat}, {}^{56}\text{Fe}$	→	${}^{15}\text{N}, {}^{15}\text{O}$	${}^{15}\text{N}$
${}^{19}\text{F}, {}^{20,22}\text{Ne}, {}^{23}\text{Na}, \text{nat}, {}^{24}\text{Mg}, {}^{27}\text{Al}, \text{nat}, {}^{28}\text{Si}, \text{nat}, {}^{32}\text{S}, \text{nat}, {}^{56}\text{Fe}$	→	${}^{17}\text{C}, {}^{17}\text{N}, {}^{17,18}\text{O}, {}^{17,18}\text{F}, {}^{17,18}\text{Ne}$	${}^{17,18}\text{O}$
${}^{20,22}\text{Ne}, {}^{23}\text{Na}, \text{nat}, {}^{24}\text{Mg}, \text{nat}, {}^{28}\text{Si}, \text{nat}, {}^{32}\text{S}, \text{nat}, {}^{56}\text{Fe}$	→	${}^{19}\text{F}, {}^{19}\text{Ne}$	${}^{19}\text{F}$
$\text{nat}, {}^{24}\text{Mg}, {}^{27}\text{Al}, \text{nat}, {}^{28}\text{Si}, \text{nat}, {}^{56}\text{Fe}$	→	${}^{21,22}\text{Ne}, {}^{21,22}\text{Na}$	${}^{21,22}\text{Ne}$
$\text{nat}, {}^{48,49}\text{Ti}, \text{nat}, {}^{52}\text{Cr}, \text{nat}, {}^{56}\text{Fe}$	→	${}^{45}\text{Ca}, {}^{45}\text{Sc}, {}^{45}\text{Ti}$	${}^{45}\text{Sc}$
$\text{nat}, {}^{52}\text{Cr}, {}^{55}\text{Mn}, \text{nat}, {}^{56}\text{Fe}$	→	${}^{47}\text{Ca}, {}^{46,47,48,49,50}\text{Sc}, {}^{44,46,47,48,49,50,51}\text{Ti}, {}^{46,47,48,49,50,51}\text{V}, {}^{48,49,51}\text{Cr}, {}^{49,51,54}\text{Mn}$	${}^{44,46,47,48,49,50}\text{Ti}, {}^{50,51}\text{V}$

nuclei species. The beam+target combinations for production of secondary species now include $p + A$, $A + p$, and $\text{He}+\text{He}$, where $A=\text{H-Ni}$.

4. Inhomogeneous gas and dust distributions

ISM gas consists of 90.8% of H and 9.1% of He by number (uniformly mixed), and 0.1% of other elements [29]. The atomic gas (H I) is the most massive component (60% of the mass) while molecular (H_2) and ionized (H II) gas comprise about 25% and 15%, respectively. The H II gas has a broad distribution with a scale height of a few 100 pc and low density, while the H_2 gas is very clumpy and contained mostly in high density clouds. Cold H_2 does not emit, but is traced through 2.6 mm CO emission line; the emission brightness is related to H_2 column density through a conversion factor X_{CO} [30]. 2D Galactocentric axisymmetric models were produced in [31], and fully 3D models for the H I and ${}^{12}\text{CO}$ distributions were developed by us [11] using a maximum-likelihood forward-folding optimization with the GALGAS code applied to the LAB-H I [32] and CfA composite CO [33, 34] data. The 3D models have added degrees of freedom (spiral arms, bar) and capture the features observed in the line-emission surveys (Fig. 2 in [11]).

Recently, new models for H I and H_2 gas have been developed based on an inversion of the same data employed for our models [11], but using a different statistical methodology [2]. In particular, the latter reconstruction is based on deprojecting gas line surveys by the HI4PI Collaboration [35] as well as CO surveys [33, 36] with a variable Galactic velocity field and emission line widths. The underlying model is based on Gaussian processes with a fixed, isotropic, and homogeneous correlation structure and includes the effects of absorption under the assumption of constant excitation temperatures for H I and CO. This solution is not smooth like in [11], and is notably more clumpy in its distribution of low- and high-density regions. The two models are equivalent descriptions that can be used for calculating effects of the gas density distribution on CR propagation and diffuse emission.

For the ISM dust, we have smooth distributions already available from the 3D ISRF modeling [10]. The ISRF models R12 and F98, that correspond to the stellar/dust distributions from [37, 38], respectively, similarly reproduce data from DIRBE and IRAS (Figs. 4, 7 in [10]). The R12 model

provides better correspondence toward the spiral arm tangents, but does not display the asymmetry associated with the bar, and the stellar disk scale length is incompatible with the near-IR profiles. The F98 model has the disk scale-length in better agreement with the near-IR data, incorporates the bulge/bar asymmetry, but has none of the structure associated with the spiral arms. The dust models employed for the R12 and F98 models are variants of warped exponential disks with “holes” in the distribution within a few kpc of the GC.

Recently, inversions of stellar extinction data have yielded distributions within ~ 4 kpc of the Solar system of the ISM dust down to very fine (sub-10 pc) scales. There are now studies based on Gaia-EDR3 and 2MASS data and centered on the Solar system, which provide a $6 \times 6 \times 0.8$ kpc³ cube for the dust extinction at 5 pc resolution [39], a $740 \times 740 \times 540$ pc³ cube at 1 pc resolution [40], and a spherical de-projection probing from 1 pc out to ~ 7 pc at ~ 1 kpc [41]. The latter [39, 41] are now incorporated into GALPROP [42] replacing the R12 and F98 dust distributions within the covered region about the Solar system, while smoothly joining to them at larger scales. This enables us to predict at equivalent spatial and angular resolutions to the gas maps the CR-induced emissions from the ISM dust.

5. 3D Galactic magnetic field models

The GMF consists of the large-scale regular and small-scale random components that are about equal in intensity. The random fields are mostly produced by the SNe and other outflows, which result in randomly oriented fields with a typical spatial scale of 100 pc or less. However, despite extensive literature and many models exist, the morphology of the large-scale GMF is still not well-understood [43, 44].

New models of the Galactic magnetic field have been developed recently [3, 4], which used the latest full-sky Faraday rotation measures (RMs) of extragalactic sources and polarized synchrotron intensity (PI) maps from the WMAP and *Planck*. In particular, a set of improved models [3] of the coherent magnetic field of the Milky Way feature better functional descriptions of the disk and poloidal fields of the Galaxy. Compared to previous analyses, it uses more variants of auxiliary models for the thermal and CR electron densities. The parameters of these new models are constrained with the latest RM and PI data. The models [4] combine several phenomenological components of the GMF – the spiral arms, the toroidal halo, the X-shaped field, and the field of the Local Bubble – to construct a new model of the regular GMF outside the thin disk. It was built on the previously existing models; but apart from using the most recent data, it has several novel features as compared to previous works, such as the contribution of the magnetic field in the wall of the Local Bubble. Both models use the same data, but their approach is different making these models complementary; they can be used for bracketing systematic uncertainties.

GALPROP includes multiple large-scale GMF models.

Acknowledgments

IVM and TAP acknowledge support from NASA Grants No. 80NSSC23K0169, 80NSSC22K0718, and 80NSSC22K0477.

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