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# The GALPROP cosmic ray and non-thermal photon emissions framework: v57 release

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We are reporting about the latest release of state-of-the-art cosmic ray (CR) propagation code called GalProp. 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 $\gamma$-rays), and searches for new physics. GalProp uses information from astronomy, particle, and nuclear physics to predict CRs and their associated emissions self-consistently, providing 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 its physical validity covers sub-keV–PeV energies for particles and from $\mu$eV–PeV for photons. 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.

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## 1. GALPROP

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, $\gamma$-rays, sychrotron radiation, etc., are subject to the same physics and must therefore be modelled self-consistently [1]. 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* [2]. For a detailed description of the latest release, see [3].

The latest v57 includes substantial new features with emphasis to making realistic time-dependent 3D modelling of CR propagation through the ISM and the production of the associated diffuse emissions computationally tractable. These developments are of particular relevance for modelling and interpretation of the new data into the very high energy ($\gtrsim$100 GeV) range coming from different instruments both space- (e.g., CALET, DAMPE) and ground-based (e.g., HAWC, LHASSO). The releases of the GalProp framework and supporting data products are available at the dedicated website, which also provides the facility to run GalProp via a web browser interface, the WebRun. The website also contains links to all GalProp–team publications together with information on the astrophysics related to the CR propagation and non-thermal diffuse emissions.

## 2. Features of the New Release

The main new features in the v57 release of GalProp are the following:

- A new installer to ease the configuration and compilation of the required support libraries and GalProp code.
- New run modes to enable robust completion for the time-dependent runs. Restarting is now possible, if the calculation is interrupted, for the CR propagation/non-thermal emissions production. The latter can also be post-processed for both steady-state and time-dependent runs using the calculated CR distributions.
- New solvers for the propagation equation with revised differencing scheme to make treatment of edge cases more robust, and to support the non-uniform spatial grids.
- Non-uniform grids are now supported for improved resolution where it is most needed.
- New source distributions, including a sampler for producing spatial distributions of time-dependent discrete CR sources.
- New routines for production cross sections for isotopes of hydrogen, $^2$H and $^3$H, and helium, $^3$He, in $p + A$ and He $+ A$ reactions, as well as $^2$H production in the $pp$-reaction. Improved parameterisations for calculations of the total inelastic cross sections for $p + A$ and He $+ A$ reactions have also been made.

## 3. Example Applications

New with the v57 release are a collection of physical modelling applications that show usage of the GalProp framework features. The `examples` directory that contains them is accessible at the top level of the installation after the archive is extracted. All applications are non-trivial, showing the uses of GalProp for 2D and 3D geometries for steady-state and time-dependent scenarios, they can be used as templates and easily extended. For simplicity the heliospheric modulation is done using the force-field approximation [4]. However, substitution with a modern specialised code, such as HelMod [5] can be done for more realistic modelling of the heliospheric CR propagation.

The usual "observables" that are the output of a GalProp run are the spatial distributions for the CR spectral intensities (FITS data cube) and intensity skymaps for different processes (HEALPix or Mapcube FITS files). Standard methods for reading from these file formats can be used to extract results from the GalProp run outputs. For each example there is a documented usage and run sequence in the sub-directory. All configuration files necessary for reproducing the runs are provided in the individual example sub-directories.

### 3.1 Propagation Model Parameter Optimisation

Determination of model parameters using, e.g., secondary-to-primary ratios is a staple of CR propagation studies for the MW. The v57 release includes an example of applying GalProp for determining optimised propagation model parameters using a limited set of CR nuclei measurements. We have coupled the GalProp library with an external driver routine (a "fitter") to make the tuning procedure as automatic as possible. This example should yield results relatively quickly.

For minimal memory image and fast execution, we assume a 2D cylindrically symmetric geometry where the IAU recommended $R_S = 8.5$ kpc [6] is used for the distance from the Sun to the Galactic centre (GC). The maximum radial size of the CR propagation region is $R_{\rm max} = 20$ kpc and the halo size is set to $Z_{\rm max} = 6$ kpc, consistent with that obtained in [7]. The spatial grid spacing uses the tangent grid function with $\Delta_R = 1.1$ kpc and $\Delta_Z = 0.1$ kpc at the solar system reference location. The kinetic energy grid is logarithmic from 3 MeV to 10 TeV with 48 planes. The operator splitting solver with the Crank-Nicholson updating scheme is selected for this problem.

For the the CR source density models we use the SNR [8] and the pulsar [9] distributions. The former peaks around $R{\sim}4$ kpc while the latter is peaked at $R{\sim}1$–2 kpc. For both source densities the functional dependence perpendicular to the plane has a $sech^2$ profile with scale height of 200 pc. The primary CR source spectra are modelled as broken power laws in rigidity where the location of the break and the two indices are common but the normalisation for each species is independent.

For the ISM, we use the 2D neutral gas (H I and $H_2$) distribution model with 90% H and 10% He by number, and the H II gas distribution described by the hybrid model included in the GalProp code that is based on the NE2001 model [10] and [11] (assuming a 7500 K electron temperature). For the $H_2$ gas, the $^{12}$CO distribution is converted to $H_2$ via the $X_{\rm CO}$=$N$H$_2$/I$_{\rm CO}$ conversion factor [12]. The two distributions for $X_{\rm CO}$ (units $10^{20}$ cm$^{-2}$ [K km s$^{-1}$]$^{-1}$), constant value of 1.9 everywhere, and a Galactocentric radial variation $10^{-0.4+0.066R}$ for $R<15$ kpc with constant outside, give two models for the gas density distribution.

For each configuration we tune the CR intensities, together with the spatial diffusion coefficient and its rigidity dependence, using a limited set of B/C data from Voyager I and AMS-02. The driver routine first reads in the relevant FITS data products, the CR data to be optimised against, the base GalProp configuration (geometry, etc.), sets parameters to be fit along with their initial values, and initialises GalProp. It then iteratively calls GalProp to obtain the CR intensities for the current parameter configuration and evaluates the quality of the fit with the data using a $\chi^2$ goodness-of-fit estimator, until the convergence criterion is met. From the procedure we obtain the optimised parameters for each of the input configurations along with fitter-estimated uncertainties. The fitter also provides estimates of parameter correlations. The strongest correlations are between the diffusion coefficient $D_{0,xx}$ and Alfvén velocity $v_A$, and the strongest anti-correlations are between the modulation potential and injection index $\gamma_1$. Extension to more sophisticated Bayesian sampling frameworks as employed by [13] and [7] can be readily accomplished.

### 3.2 Steady-State Interstellar Emission Models

The GalProp framework has an extensive history for modelling the non-thermal interstellar emissions from the MW across the electromagnetic spectrum [e.g., 14–18]. The standard approach employs a CR source spatial density described as a smoothly varying function of position that does not evolve with time, and solves for the steady-state CR distribution throughout the MW. For the CR nuclei, the slow energy losses coupled with the long residence times for these particles are thought to provide sufficient mixing to effectively erase individual contributions of the CR sources, leading to a "sea" of CR particles through the ISM. For lower energies, the steady-state assumption is less valid due to the fast ionisation losses and fragmentation. For CR electrons/positrons, their much more rapid energy losses mean that the approximation may be physically inaccurate for $\gtrsim$100 GeV energies. But, the steady-state approach remains widely used because of its modelling simplicity and that the majority of data is covered by its applicable energy range.

We include with this release an example for steady-state interstellar emission models that enables straightforward intercomparison between predicted observables, e.g., non-thermal intensity skymaps, over a grid of CR source models. The `steady_state` sub-directory gives a set of 3D modelling configurations differing only by their CR source spatial density distributions, which are consistently normalised at the solar system location. The normalisation/optimisation method used for this example enables the models to be used to make predictions for broadband non-thermal emissions from radio to the $\gtrsim$100 TeV $\gamma$-rays.

The calculations use a 3D right-handed spatial grid (tangent grid function) with the solar system on the positive $X$-axis and $Z = 0$ kpc defining the Galactic plane. The parameters for the grid transformation function are chosen so that the $X/Y$ resolution nearby the solar system is ~50 pc, increasing to ~0.5 kpc at the boundary of the Galactic disc, which is at 20 kpc from the GC. In the $Z$-direction the resolution is 25 pc in the plane, increasing to 0.5 kpc at the boundary of the grid at $|Z_{\rm halo}| = 6$ kpc [7]. The kinetic energy grid is logarithmic from 10 MeV to 1 PeV with 32 planes.

The tuning procedure follows that of [19] and [20]. We employ the same set of CR data as [21] (see their Table 1). For each of the SA0, SA50, and SA100 source density models [19], we make an initial optimisation for the individual propagation model parameters by fitting to the observed spectra of CR nuclei: Be, B, C, O, Mg, Ne, and Si. These are kept fixed and the injection spectra for electrons, protons, and He nuclei are then fitted together to the data. The procedure is then iterated until convergence. Solar modulation is accounted for in this first step by using the force-field approximation with one modulation potential value for each observation period.



PoS(ICRC2023)041

After the initial optimisation we determine the best-fit model using $\chi^2$ and use it for extrapolation outside of the range covered by the data. The solution for the SA100 density distribution gives the best-fit model, and its predicted local spectra are used as "data" giving coverage for the full CR kinetic energy range (10 MeV to 1 PeV). We then re-optimise the parameters for the SA0 and SA50 solutions to the SA100 interstellar spectra, as for the first step of the procedure described above. This ensures that the three models give the same local CR spectra, reducing inconsistencies caused by limited data statistics and coverage over the modelled energy range.

### 3.3 Discretised Source Ensemble Interstellar Emission Model

The steady-state formalism ignores the reality that the CRs are produced by discrete sources, e.g., SNRs that have finite lifetimes. When the source birth rate and active injection lifetime are comparable to timescales for energy losses and diffusion, spatial fluctuations in the CR intensities occur and the assumption that the ISM is prevaded by a temporally invariant CR sea is less clear. Discretised CR source descriptions have been explored for a long time for modelling the local CR fluxes [e.g., 22–30]. The fluctuations in the CR intensities also affect the non-thermal emissions [31, 32]. Because the other ISM components change over much longer time scales, at the highest energies the diffuse emissions encode the current snapshot of the CR source activity on top of the cumulative emissions from the residual particle clouds produced by sources active in the past. At lower energies they blend into the large-scale diffuse emissions that are from the pervasive CR sea.

We have included an example that shows how the new release of GalProp can be employed to model space/time discretised CR source ensembles and investigate the energy dependent fluctuations in the associated diffuse emissions.

### 3.4 Inhomogeneous Diffusion

Observations of the extended TeV emission around Geminga and PSR B0656+14 PWN by the HAWC experiment [33] show evidence for inhomogeneous diffusion properties nearby the individual sources, extending out to ~50 pc scales. Similar inhomogeneous CR diffusion has been observed in the LMC around the 30 Doradus star-forming region, where an analysis of combined $\gamma$-ray and radio observations yielded a diffusion coefficient, averaged over a region with radius 200–300 pc, an order of magnitude smaller than the typical value in the MW [34].

To model such scenarios a two-zone approach with so-called "slow diffusion zones" (SDZs) about the sources with a transition to ISM conditions has been suggested [e.g., 35–37]. We include with the v57 release an example that shows how treating the inhomogeneous diffusive properties in the space surrounding the "true" CR sources. The example simulates the time-dependent evolution of the CR electron/positron "cloud" injected by the Geminga PWN, accounting for the effects of the slower diffusion as well as its proper motion. It is based on the "Scenario C" from the work of [21], who considered a collection of scenarios for the diffusive properties about Geminga and its intrinsic source characteristics.

## 4. Conclusion

Building a comprehensive model for the diffuse Galactic multi-wavelength and multi-messenger (CRs, $\gamma$-ray, neutrinos) emission for the $\mu$eV–TeV energy range is an ambitious goal. Such a model can only be built self-consistently because of interdependencies between the components of the ISM, i.e., gas, Galactic magnetic and radiation fields, and the diffuse Galactic multi-wavelength emission. The Galactic distribution of all secondary species, such as $\pi^{0,\pm}$, $e^{\pm}$, $\bar{p}$, Li, Be, B, Sc, V, is very non-uniform and depends of the distribution of gas (CR target), ionisation and bremsstrahlung energy losses, and the value of the diffusion coefficient. Besides, the flux of secondary $e^{\pm}$, produced in CR interactions with gas, is comparable to the flux of primary $e^{-}$ below ~1–2 GeV and thus affects the predictions for synchrotron, bremsstrahlung, and IC emission. Accounting also for the the effects that the limited sources lifetime has on the major components of the diffuse emission, including the sources in the vicinity of the solar system, is also essential. Constructing such a model is the major objective since the inception of the GalProp project.

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PoS(ICRC2023)041

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