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GALPROP Code for Galactic Cosmic Ray Propagation and Associated Photon Emissions

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Recent discoveries in astrophysics of cosmic rays (CR) and γ-ray astronomy demand more accurate and reliable CR propagation code. Having 21 years of development behind it, the GALPROP model has become a de-facto standard in astrophysics of CR, diffuse γ-rays, and searches of new physics. The GALPROP project is devoted to the development of a self-consistent model for CR propagation in the Galaxy and associated diffuse emissions (radio, microwave, X-rays, γ-rays). The project stimulated independent studies of the interstellar radiation field (ISRF), distribution of the interstellar gas (H_2, H I, H II), synchrotron emission and the Galactic magnetic field, and a new study of the isotopic production cross sections. These studies provide necessary and unique input datasets for the GALPROP model. The code is optimized and parallelized and accessible as a standalone executable or library that can be linked to other codes enabling many other studies, such as Markov Chain Monte Carlo, MultiNest, SuperBayeS, and DarkSUSY. The new version of the code has many updates that improve its accuracy and capabilities. As always, the latest release of the code is available through the WebRun, a service to the scientific community enabling easy use of the GALPROP code via web browsers.

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1. Introduction

A dramatic increase in the accuracy of CR measurements and γ-ray observations has lead to many spectacular discoveries in the last decade. The most remarkable are the unexpected rise in the positron fraction [1–4], breaks in the spectra of the light nuclei [5–7], puzzling difference in the spectral indices of protons and heavier nuclei [6–9], a continuous decline in the B/C ratio up to 2 TV [10–12], traces of primary ^{60}Fe at low energies [13], enormous Fermi bubbles observed in γ-rays [14, 15], possible hints at the excess emission from the Galactic center [16], and many others. Meanwhile, built with the technology of 1970s, Voyager 1, 2 spacecrafts left the heliosphere and are delivering unique data on the elemental spectra and composition at the interstellar reaches of the Solar system [17, 18]. More discoveries are in the queue as we are awaiting for the first results from CALET and DAMPE, and the long-awaited launch of ISS-CREAM.

Interpretation of the precise data available nowadays demands the equally detailed theoretical description of the processes in the interstellar medium (ISM) and in the heliosphere. The latter is impossible without fully numerical models. The first of its kind a fully numerical model called GALPROP[1] was developed about 21 years ago [19,20]. Even though it was somewhat an overshoot at that time it has become in a strong demand soon after that. The key idea behind GALPROP is that all CR-related data, including direct measurements, γ-rays, synchrotron radiation, etc., are subject to the same Galactic physics and must be modeled self-consistently [21]. Since then the GALPROP model for CR propagation is being continuously improved in order to provide a framework for studies of CR propagation in the Galaxy and interpretation of relevant observations [19,20,22–33]. The goal for GALPROP-based models is to be as realistic as possible and to make use of available astronomical information, nuclear and particle data, with a minimum of simplifying assumptions.

Surprisingly to some, accurate calculation of heliospheric propagation is equally important. Minuscular in size compared to the size of the Galaxy, the heliosphere affects the fluxes of Galactic CR species that are captured by our instruments. Even though, it affects only particles with energies below 30–50 GeV, this is the range where the most precise measurements are made. These low energy data are used to derive the parameters of interstellar propagation that are then extrapolated onto the whole Galaxy and all energies up to the multi-TeV region.

In this paper we report about latest updates of the GALPROP model, its initially auxiliary datasets that grew into important and independent studies of the Galactic structure, such as distributions of gas, dust, radiation and magnetic fields, as well as about improvements in the description of physical processes. Extremely important are the results of recent combined study of the interstellar-heliospheric propagation of light CR species [34], see also PoS(ICRC2017)278.

2. The GALPROP code

The GALPROP project [19, 20] began in late 1996[2]. The code, originally written in fortran90, was made public in 1998. A version rewritten in C++ was produced in 2001, and the forthcoming public version is v.56, which is significantly updated compared to previous v.54-v.55 [29]. The GALPROP code is available from a dedicated website[1], where a 500+ core facility for users to

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

[2]http://sciencewatch.com/dr/erf/2009/09octerf/09octerfStronET/

run the code via online forms in a web-browser, WebRun, is also provided [29]. The number of registered users is currently exceeding 1000. A complete description of the rationale and motivation is given in the review [22]. A very short summary of GALPROP is provided below; for details the reader is referred to the relevant papers [19, 20, 22–33, 35–37].

The GALPROP code solves the CR transport equation with a given source distribution and boundary conditions for all CR species [20]. This includes a galactic wind (convection), diffusive reacceleration in the (ISM), energy losses, nuclear fragmentation, radioactive decay, and production of secondary particles and isotopes. The distribution of CR sources can be specified as required [32], and the injection spectra can be chosen independently for each of the CR species. The numerical solution of the transport equation is based on a Crank-Nicholson implicit second-order scheme. The spatial boundary conditions assume free particle escape. For a given halo size the diffusion coefficient, as a function of momentum and propagation parameters, is determined from secondary/primary ratios. Non-linear wave damping [28] can be included if required.

Cross-sections are based on the extensive LANL database, nuclear codes, and parameterizations [26, 38, 39]. Less important cross-sections are computed using phenomenological approximations [40, 41] renormalized to the data where they exist. The nuclear reaction network is built using the Nuclear Data Sheets. A project aimed at an improved representation of the isotopic production cross sections (ISOPROCS project) is currently under development [35].

The GALPROP code computes a full network of primary, secondary and tertiary CR production starting from input source abundances. Starting with the heaviest primary nucleus considered (e.g. ^{64}Ni, $A = 64$) the propagation solution is used to compute the source term for its spallation products $A-1$, $A-2$ and so forth, which are then propagated in turn, and so on down to protons, secondary $e^{\pm}$, and $\bar{p}$. The inelastically scattered p and $\bar{p}$ are treated as separate components (secondary p, tertiary $\bar{p}$). GALPROP includes K-capture, electron stripping, and knock-on electrons.

Production of π^0 and secondary $e^{\pm}$ is calculated using the formalism of [19, 42, 43] with a correction [44] or parameterizations [45, 46]. The γ-ray and synchrotron emissivities are calculated using the propagated CR distributions, including a contribution from secondary $e^{\pm}$ [27, 47]. The inverse Compton scattering is treated using the formalism for an anisotropic photon field [23] with the full spatial and angular distribution of the ISRF [47, 48]. The electron bremsstrahlung calculations are described in [24]. Intensity skymaps are then generated using line-of-sight integrations where the gas-related γ-ray intensities (π^0-decay, bremsstrahlung) are normalized to the column densities of H I and H_2 for Galactocentric annuli based on recent 21-cm and CO survey data. Spectra of all species and the γ-ray and synchrotron sky maps are output in standard astronomical formats: FITS, HEALPix [49], and *Fermi*-LAT MapCube.

Also included in GALPROP are specialized routines to calculate the propagation of dark matter annihilation or decay products and associated diffuse γ-ray emission and synchrotron sky maps. Details of the linking to other codes (e.g., DarkSUSY [50], SuperBayeS [30] and so forth) can be found at the aforementioned website.

3. New functionality

The GALPROP code was significantly updated and optimized to allow for additional functionality, improved accuracy, and optimal usage of memory and CPU resources. Most important

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updates include: a separate injection spectrum for each isotope, improved handling of the components of the interstellar gas and CR composition. The system of the propagation equations has been generalized to allow for spatial variations in the diffusion coefficient. Scaling of the diffusion coefficient and the Alfvén speed with the strength of the Galactic magnetic field was used for modeling of the interstellar emissions in [51] (their model C). The current development also addresses recent advances into the previously unexplored regions, both in the energy range (keV to milti-TeV) and the accuracy. The most challenging is the AMS-02 data with its claimed accuracy of 1%-3%, but other experiments, such as Fermi-LAT, Voyager 1, 2, PAMELA, CALET, NUCLEON, ISS-CREAM and others, should also benefit from the improved accuracy of model predictions that enables them to search for subtle effects and signals. The code was optimized for speed that includes parallelization/multi-treading, elimination of unnecessary loops, and memory leakage.

New improved parameterizations of secondary particle production (γ-rays, secondary $e^{\pm}$, $\bar{p}$) in pp-, pA-, and AA-interactions were developed [36,37] that use the EPOS-LHC and QGSJET-II-04, two the most advanced Monte Carlo generators tuned to numerous accelerator data including those from the LHC. The $\bar{p}$ yields of the two MC generators agree reasonably well with each other and the available experimental data. Therefore, the results of these generators can be used to predict the γ-rays, secondary $e^{\pm}$, and $\bar{p}$ yields outside the energy range covered by fixed target accelerator data. The new secondary yield calculations is a user-selected option with GALPROP v.56.

Isotopic production cross sections are being improved. We are participating in an international collaboration formed at the meeting[3] "XSCRC2017: Cross sections for Cosmic Rays @ CERN" with a goal to improve on the accuracy of calculation of astrophysically-important reactions.

An extensive work was done on combining the GALPROP code with numerical methods employing the Bayesian approach [30,33]. We did show that optimization of propagation parameters, source isotopic abundances, and other parameters can be done using the blind accelerated multimodal Bayesian inference (BAMBI) algorithm that employs the MultiNest package to train the artificial neural network that was then used to significantly accelerate the convergence of the algorithm. The results indicate that the diffusion coefficient is non-uniform on large scales [33].

An important issue is a correct calculation of CR propagation in the heliosphere. We are working together with the HelMod team[4] to combine the HelMod and GALPROP codes that allows an easy calculation of the modulated spectra of CR at any arbitrary epoch in the past. The ultimate goal of that study is to provide the local interstellar spectra for all CR species in the whole energy range – a very desirable ingredient in many astrophysical studies. The first publications give the details of our approach and provide the derived local interstellar spectra for protons, He, and $\bar{p}$ [34], see also PoS(ICRC2017)278.

The 3-dimensional models of the components of the interstellar gas, ISRF, and magnetic field are currently under development. First results demonstrating the effects of the 3D structure of the ISM are discussed in PoS(ICRC2017)736, PoS(ICRC2017)737, PoS(ICRC2017)871.

The skymap integrator has been re-written using a variable step size integrator that is faster and more accurate. The location of the observer can now be arbitrary in (x,y,z). The integrator also allows for the absorption of γ-rays on the ISRF [52]. If this option is selected, the resulting $e^{\pm}$-pairs

[3]https://indico.cern.ch/event/563277/

[4]http://www.helmod.org/helmod/

are added to secondaries. The $e^{\pm}$ production cross section is taken from [53].

The 3D treatment of the magnetic field now includes regular and random components that can be specified differently in the disk and the halo. Temperature and polarization of radio and microwave synchrotron emission can be calculated. Synchrotron I, Q and U Stokes parameters are calculated and output as HEALPix maps. Radio absorption and free-free emission are included, more details can be found in [54–56].

4. Code updates

The improvements to GALPROP made for v.56 include significant modifications to its architecture as well as numerous technical improvements related to additional physics code. An overview of the major changes is given below, while specific examples of command line configuration/build/installation/execution are provided at the GALPROP website[1].

Starting with GALPROP v.56 there is only a single external dependency on the GALTOOLSLIB library. Because of re-use considerations – the FRaNKIE [PoS(ICRC2015)908], GALGAS (in prep.), and GaRDiAn [32] packages also developed by members of the GALPROP-team use many common elements – core functionality across all code bases is abstracted into this library. GALTOOLSLIB includes utility code for parameter parsing (e.g., reading the galdef configuration file of a GALPROP run), specifying spatial distributions (e.g., for CR source densities), libraries for the representation of results (e.g., skymaps with HEALPix), core physics routines for the nuclear reaction network and energy losses, and other commonly reused code. Its required external library dependencies are: CFitsIO and CCfits, CLHep, the Gnu Scientific Library, HEALPix, and Xerces-C. Optional external library dependences are: libastro from XEphem, WCSLIB, OpenCL, and CppUnit. WCSLIB and libastro are used both for reading and writing data in different map projections. OpenCL can be used to distribute calculations across CPUs and compute accelerators for FRaNKIE and GALGAS but is not needed for GALPROP runs. CppUnit is a framework that is used by the various packages developed by the GALPROP team for unit testing.

Supported build targets are Linux and OS X, with other Unix-like variants possible. The configuration/build/installation now uses CMake, where the minimum requirement is CMake 3.0. The base language support requires a C/C++ compiler that implements the C++11 standard, and a Fortran 77/90 compiler. Examples include gcc/g++ 4.8.5, clang/clang++ 3.3, and recent Intel compiler suites for the C++11 support. Almost any recent Fortran compiler is sufficient.

Technical and physics improvements have focussed on better memory layout and computational speed and making GALPROP more flexible as a general code for calculating CR propagation and interstellar emissions from an *arbitrary* galaxy. Many of the internal structures and loops have been reorganized. Parallelization now is taking advantage of vectorization facilities of the OpenMP 4 specification. New solvers for the transport equations, in particular, take advantage of the vectorization to dramatically increase the speed of the 3D mode.

More options are now available for the distributions of the interstellar gas and CR sources. This is done via the galstruct library included in GALTOOLSLIB, which reads XML files describing the distributions of the gas and CR sources. The galstruct library is easily extended with new modules and functionality, plus it includes many pre-defined distributions. The new framework allows easy incorporation of multiple spectral models. Each isotope can also have a separate injection spectrum.

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Relative normalization of the isotopes has also been improved and can now be specified in terms of either a single point in energy or an integrated band in energy. The latter impoves stability when modifying GALPROP parameters in maximum-likelihood fits because it reduces degeneracy of the spectral parameters of different isotopes.

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