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GALPROP Code for Galactic Cosmic Ray Propagation and Associated Photon Emissions

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Recent years are marked with many breakthroughs in astrophysics of cosmic rays (CRs), and more are expected in the nearest future. Their proper interpretation is impossible without a well-developed propagation code. The GALPROP project celebrates its 19th anniversary this year. Over these years the project has established itself as a standard self-consistent model for CR propagation in the Galaxy and associated diffuse emissions (radio, microwave, X-rays, γ-rays) that is widely used by the astrophysical community. The project stimulated independent studies of the interstellar radiation field, distribution of the interstellar gas (H2, 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 (MCMC), MultiNest, SuperBayeS, and DarkSUSY. We describe a new updated version of the code that has new capabilities and improved accuracy. 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

Considerable advances in astrophysics of CRs in recent years have become possible due to superior instrumentation launched into space and to the top of the atmosphere. A small Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) has delivered breakthrough results, such as the unexpected rise in the positron fraction, spectral breaks in H and He spectra, and updated fluxes of other CR species in an extended energy range. Measurements of the elemental spectra by the Cosmic Ray Energetics And Mass (CREAM), Advanced Thin Ionization Calorimeter (ATIC), and the Transition Radiation Array for Cosmic Energetic Radiation (TRACER) experiments up to the TeV energies hint at the spectral flattening in the spectra of heavier nuclei. Launched in 1977, Voyager 1, 2 spacecraft demonstrate unbelievable scientific longevity providing unique data on the elemental spectra and composition at the interstellar reaches of the solar system at 132 AU and 108 AU from the sun, correspondingly. Launched in 2011, the Alpha Magnetic Spectrometer (AMS-02) on board of the International Space Station (ISS) started to release its unmatched precise measurements of spectra of CR species in a wide energy range. Low energy CR detectors of the Advanced Composition Explorer (ACE) are continuing to provide data on isotopic composition.

Indirect CR measurements are made by multi-wavelength observatories in space and on the ground. The *Fermi* Large Area Telescope (*Fermi*-LAT) continues to map the diffuse γ-ray emission, and CRs accelerators. Yet, its superior capabilities allow the detector to be used for direct electron measurements in the energy range from GeV to $\sim$1 TeV, and measure the proton spectrum from 100 GeV to several TeV through the observations of the γ-ray emission of the Earth's limb. The International Gamma-Ray Astrophysics Laboratory (INTEGRAL), the High-Altitude Water Cherenkov Observatory (HAWC), the High Energy Stereoscopic System (HESS), Major Atmospheric Gamma-ray Imaging Cherenkov Telescopes (MAGIC), and the Very Energetic Radiation Imaging Telescope Array System (VERITAS), observe keV – TeV energy emissions produced by energetic particles in the ISM and near the CR accelerators. High-resolution data in the microwave domain are provided by the Wilkinson Microwave Anisotropy Probe (WMAP) and PLANCK.

Yet, more outstanding experiments are coming. The ISS-CREAM, and CALorimetric Electron Telescope (CALET), targeting CR nuclei and electrons in the multi-TeV domain are built and awaiting for the next opportunity to be launched to the ISS.

Therefore, there are serious hopes to resolve the hundred-years-old puzzle of the origin of CRs and to finally understand the inner workings of the Milky Way and other spiral galaxies. However, Nature's communications are always encrypted. Decoding them requires an intelligence and sophistication. The proper interpretation of the precise data delivered by many different CR experiments over several decades requires a well-developed propagation code. The most advanced numerical propagation model GALPROP celebrates its 19th anniversary this year. Over these years the project has established itself as a standard self-consistent model for CR propagation in the Galaxy and associated diffuse emissions (radio, microwave, X-rays, γ-rays) that is widely used by the astrophysical community – the experimental teams and individuals. The project stimulated independent studies of the interstellar radiation field, distribution of the interstellar gas (H2, 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. In this paper we are reporting about the latest updates.

2. The GALPROP code

The GALPROP project [1, 2] began in late 1996[1]. 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.55, which is significantly updated compared to previous v.54 [3]. The GALPROP code is available from a dedicated website (`http://galprop.stanford.edu`) where a 500+ core facility for users to run the code via online forms in a web-browser (WebRun) is also provided [3]. The number of registered users is currently approaching 1000.

The key concept underlying the GALPROP code is that various kinds of data, e.g., 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 hence have to be modeled self-consistently [4]. The goal is for GALPROP-based models to be as realistic as possible and to make use of available astronomical information, nuclear and particle data, with a minimum of simplifying assumptions. A complete description of the rationale and motivation is given in the review [5]. A very short summary of GALPROP is provided below; for details the reader is referred to the relevant papers [1]-[15].

The GALPROP code solves the CR transport equation with a given source distribution and boundary conditions for all CR species [2]. This includes a galactic wind (convection), diffusive reacceleration in the interstellar medium (ISM), energy losses, nuclear fragmentation, radioactive decay, and production of secondary particles and isotopes. The distribution of CR sources can be specified as required (see, e.g., [13]), 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 the reacceleration or convection parameters, is determined from secondary/primary ratios. If reacceleration is included, the momentum-space diffusion coefficient D_{pp} is related to the spatial coefficient D_{xx} ($= \beta D_0 \rho^\delta$) [16], where $\delta = 1/3$ for a Kolmogorov spectrum of interstellar turbulence or $\delta = 1/2$ for a Kraichnan cascade (but can also be arbitrary), $\rho \equiv pc/Ze$ is the magnetic rigidity. Non-linear wave damping [10] can also be included if required.

Cross-sections are based on the extensive LANL database, nuclear codes, and parameterizations [17]. The most important isotopic production cross-sections are calculated using our fits to major production channels [9, 18]. Other cross-sections are computed using phenomenological approximations [19] and/or [20] renormalized to the data where they exist. The nuclear reaction network is built using the Nuclear Data Sheets. An project aimed at an improved representation of the isotopic production cross sections (ISOPROCS project) is currently under development [12].

The GALPROP code computes a complete 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

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

to protons, secondary electrons and positrons, and antiprotons. The order of propagation of CR species with the same A is optimized according to the dependency graph, which allows for all types of radioactive decay to be accounted in a single loop thus significantly cutting the run time for CPU-heavy applications, such as Bayesian analysis or MCMC [11]. The inelastically scattered protons and antiprotons are treated as separate components (secondary protons, tertiary antiprotons). GALPROP includes K-capture, electron stripping, and knock-on electrons.

Production of neutral pions, secondary positrons and electrons is calculated using the formalism of [21, 22] as described in [1] with a correction [23] or using parameterizations [24, 25]. The γ-ray and synchrotron emissivities are calculated using the propagated CR distributions, including a contribution from secondary particles such as positrons and electrons from inelastic processes in the ISM that increases the γ-ray flux at MeV energies [26, 27]. The inverse Compton (IC) scattering is treated using the appropriate formalism for an anisotropic radiation field [6] with the full spatial and angular distribution of the interstellar radiation field (ISRF) [26, 28]. The electron bremsstrahlung cross section is calculated as described in [7]. 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. A 3D model of the Galactic gas components is currently under development (Jóhannesson et al., these Proceedings). Spectra of all species on the chosen grid and the γ-ray and synchrotron sky maps are output in standard astronomical formats for direct comparison with data: FITS, HEALPix [29], and *Fermi*-LAT MapCube format for use with LAT Science Tools.

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 [30], SuperBayeS [11] and so forth) can be found at the aforementioned website.

3. New features

The GALPROP code has been updated to include new features. The system of the propagation equations was 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 already used for modeling of the Galactic diffuse γ-ray emission [31] (foreground model C). However, such modification of the propagation equations makes the numerical solution with the wave damping [10] unstable. Therefore, an approximate solution, eq. (15) in [10], is used instead.

More options are now available for the distributions of the interstellar gas and CR sources. This is done by adding a new library, *galstruct*, that can read an XML file describing the distribution of the gas and CR sources. The *galstruct* library can be easily extended with new modules and functionality, see details in Jóhannesson et al. (these Proceedings).

New flexibility is added to the injection spectrum, which allows it to be set independently for each isotope. The *isotopic_abundances* are now evaluated internally at the kinetic energy per nucleon specified with *proton_norm_Ekin*, the kinetic energy at which the proton spectrum is normalized.

The skymap integrator has been re-written using a variable step size integrator that is both faster and more accurate. A location of the observer can now be arbitrary in (x, y, z). The output

IC maps were generalized to allow for an arbitrary spatial splitting, in particular, their splitting can be set to match the splitting of the gas-related emission. This allows for more flexible template fitting as used, e.g., in the analysis of the emission from the inner Galaxy (see Porter et al., these Proceedings).

Other optimizations and improvements include: the GALPROP code is now split up into several different libraries with core functionality for easier use in other projects, Healpix output is now compatible with the Aladdin code, added the CPPUnit test library that allows internal testing for many routines, memory optimization and fixes of memory leaks, new error logger, new GALDEF file parser.

4. New functionality

3D treatment of the magnetic field now includes regular and random components that can be specified differently in the disk and the plane. 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 [32, 33] and Orlando et al. (these Proceedings).

The continuous γ-ray emission is generated mainly through the decay of neutral pions and kaons produced in hadronic CR interactions with the ISM, IC scattering of CR electrons off ISRF, and bremsstrahlung. The nuclear component of CRs is dominated by protons, but heavier nuclei also provide an essential contribution to the γ-ray yield. The latter depends on the energy range and spectra of the CR species that could vary in different locations making an accurate evaluation of their contribution rather difficult. In all studies of the diffuse γ-ray emission, the effects of heavier nuclei ($A > 1$) in CRs and in the target material are usually taken into account by simply rescaling the γ-ray yield from pp-interactions to the CR-ISM γ-ray yield with a so-called nuclear enhancement factor ε_M. However, application of a single ε_M in many cases could result in significant errors. In fact, there is no a universal enhancement factor as the rescaling factor depends on the abundances of CRs and the ISM, on the individual spectral shapes of CR species, as well as on the kinematics of the processes involved, e.g., pA vs. Ap yields.

In paper [14] we use the QGSJET-II-04 and EPOS-LHC event generators, which accurately reproduce accelerator data [34], to simulate pp-, pA-, and AA-interactions. We have shown that the value of the enhancement depends strongly on the spectral shapes of CR species: not only via the respective energy dependence of the partial abundances of primary nuclei, but also via the spectrally averaged photon energy fraction. It is the latter point which was missed in previous calculations. Paper [14] provides tables that allow a calculation of ε_M for an arbitrary composition of CRs and the ISM for a reasonably wide range of power-law indices.

Antiprotons in CRs are produced in CR interactions with interstellar gas and are, therefore, called secondary. The same interactions produce charged and neutral mesons that decay to secondary $e^\pm$ and γ-rays. $\bar{p}$ data and their correct interpretation hold the key to the resolution of many astrophysical puzzles. If the rise in the positron fraction is due to weakly interacting massive particle (WIMP) annihilations, $\bar{p}$ data provide important constraints on WIMP models [35, 36], for a review, see [37]. If the rise is due to conventional astrophysics, $\bar{p}$ and B/C measurements extended to higher energies may be able to discriminate between the pulsar [38, 39, 40, 41, 42] and the supernova remnant (SNR) hypotheses [43, 44]. The latter proposes a secondary component with a hard energy spectrum that is produced in an SNR shock by accelerated protons.

A significant effort [15] (also Moskalenko et al., these Proceedings) was devoted to the analysis of $\bar{p}$ production in pp-, pA-, and AA-interactions using EPOS-LHC and QGSJET-II-04, two of the most advanced QCD Monte Carlo (MC) generators tuned to numerous accelerator data including those from the Large Hadron Collider (LHC). It was found that 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 reliably the $\bar{p}$ yield outside the energy range covered by fixed target accelerator data, $E_{\bar{p}} \approx 10-100$ GeV. In the case, when the spectra of CR species can be approximated by a power-law, the nuclear enhancement of the $\bar{p}$-yield due to contributions of nuclear species in CRs and of the helium component in the ISM were derived. In contrast to all previous calculations, our results indicate a strong rise of the nuclear enhancement for secondary antiprotons with energy, which reaches a factor of two for $E_{\bar{p}}^{\rm kin} \simeq 1$ TeV. The $\bar{p}$-yield differ by a factor of few from yields of parameterizations commonly used in astrophysics.

The GALPROP code is currently being updated to include these latest developments.

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