GALPROP Explanatory Supplement

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Abstract
This document provides a description of the GALPROP cosmic ray propagation code.

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1 Introduction

The origin of cosmic rays have been intriguing scientists since 1912 when V. Hess carried out his famous balloon flight to measure the ionisation rate in the upper atmosphere. The cosmic rays are energetic particles, which come to us from outer space, and are measured either through satellites, balloons, or Earth based experiments. The spectrum of cosmic rays can be approximately described by a single power law with index $\sim 3$ from $\sim 10$ GeV to the highest energies ever observed $\sim 10^{20}$ eV. The only feature observed below $10^{18}$ eV is a knee around $10^{15}$ eV. Because of this featureless spectrum, it is believed that cosmic-ray production and propagation is governed by the same mechanism over decades of energy, the same mechanism at least works below the knee and the same or another one works above the knee. Meanwhile the origin of the cosmic rays spectrum is not still understood.

Galactic cosmic rays are important part of the interstellar medium. The energy density of relativistic particles is about 1 eV cm$^{-3}$ and is comparable to the energy density of interstellar radiation field, magnetic field, and turbulent motions of the interstellar gas. This makes cosmic rays one of the essential factors determining the dynamics and processes in the interstellar medium.

The sources of cosmic rays are believed to be supernovae and supernova remnants, pulsars, compact objects in close binary systems, and stellar winds. Observations of X-ray and $\gamma$-ray emission from these objects reveal the presence of energetic particles thus testifying to efficient acceleration processes near these objects. Particles accelerated near the sources propagate tens of millions years in the interstellar medium where they lose or gain energy, their initial spectra and composition change, they produce secondary particles and $\gamma$-rays. The distruaction of primary nuclei via spallation gives rise to secondary nuclei and isotopes which are rare in nature, antiprotons, and charged pions that decay producing secondary positrons and electrons.

The variety of isotopes in cosmic rays allows one to study different aspects of their acceleration and propagation in the interstellar medium as well as the source composition. Stable secondary nuclei tell us about the diffusion coefficient and Galactic winds (convection) and/or re-acceleration in the interstellar medium (2nd order Fermi acceleration mechanism). Long-lived radioactive secondaries allow one to constrain global Galactic properties such as Galactic halo size. Abundances of K-capture isotopes, which being stopped in the interstellar gas would decay via electron K-capture, allow one to probe the gas density and acceleration time scale. All these together allow us in principle to build a model of particle acceleration and propagation in the Galaxy.

Such a model is however incomplete. The whole of our knowledge is based on measurements done only at one point on the outskirts of the Galaxy, the solar system, and the assumption that particle spectra and composition are (almost) the same at every point of the Galaxy. The latter may not necessarily be correct. $\gamma$-rays are able to deliver the information directly from distant regions thus complementing that obtained from cosmic-ray measurements. Some part of the diffuse $\gamma$-rays is produced in energetic nucleons interactions with gas via neutral pion production, another is produced by electrons via inverse Compton scattering and bremsstrahlung. These processes are dominant in different parts of the spectra of $\gamma$-rays, therefore, if deciphered the $\gamma$-ray spectrum can provide information about the large-scale spectra of nucleonic and leptonic components of cosmic rays.

To extract information which is contained in cosmic ray abundances and $\gamma$-ray fluxes one needs to develop a model of particle production and propagation in the Galaxy. Though the basic features of particle diffusion in the Galaxy seem to be well-established, the continuous flow of new more and more accurate data from space, balloon and ground based experiments motivates further development of models. Analytical and semi-analytical models are able to interpret one or only a few features and often fail when they try to deal with the whole variety of data. Therefore more realistic and consistent models are required which would be able to incorporate many processes and astrophysical data of many different kinds simultaneously: nuclear reaction networks and nuclear cross sections, production of antiprotons, positrons, $\gamma$-rays and synchrotron emission, realistic gas distribution, radiation field distribution and spectrum, energy losses, convection, diffusive re-acceleration etc.

In several years new missions planned for cosmic ray experiments will tremendously increase the quality and accuracy of cosmic-ray data making new progress impossible without highly developed models. Data will continue to flow from the high resolution detectors on Ulysses, Advanced Composition Explorer and Voyager space missions. During the next few years there will be several flights of balloon-borne high resolution spectrometers that will extend our knowledge of antiproton, positron and electron spectra in cosmic rays. Several more high resolution space experiments are planned to be launched in the next 2–3 years, e.g., PAMELA to measure antiprotons, positrons, electrons, and isotopes H through C over the energy range of 0.1 to 200 GeV, the Alpha
Magnetic Spectrometer will measure particle and nuclear spectra to TeV energies. The previous γ-ray mission EGRET, one of the four detectors on board of the Compton Gamma-Ray Observatory, gave a detailed map of the Galactic diffuse emission in the range 30 MeV – 10 GeV which traces the cosmic ray distribution in the Galaxy and possibly the acceleration sites of cosmic rays. The current Fermi-LAT mission capability covers the range 30 MeV – 1 TeV with a sensitivity two orders of magnitude better.

Clearly, a detailed model of cosmic ray propagation in the Galaxy should supplement the high quality data obtained by the spacecraft and balloon-borne missions, providing support for the necessary interpretation and analysis.

Recent developments of galprop with corresponding results can be found in Strong et al. (47, 48, 49). A review of subject and the context and philosophy of galprop can be found in Strong et al. (50). A short paper summarizing this release v54 is in Strong et al. (51). A description of the enhancements and Web interface is in Vladimirov et al. (56).

### 1.1 Versions of GALPROP and its Explanatory Supplement

In this manual we describe galprop version 54, first released in September 2010, and which succeeds version 50p. It replaces the previous manuals which were called galprop,v50.pdf, galprop,v54.pdf, galprop,v55.pdf.

It also describes subsequent developments, now labelled galprop version 55.

GALPROP is maintained under subversion (svn), and revisions (‘rnnnn’=revision mnnn) refer to this repository.

The public version (54) started as a copy of trunk r508. Public version r984 is available from the GALPROP website, and further developments are made available regularly at http://sourceforge.net/projects/galprop.

This manual is still being updated, and is not completely up-to-date. All input parameters are described, but the code documentation and description of some features is still incomplete. New versions will be issued as available. Up-to-date details on compiling and running GALPROP are given in the README file from the GALPROP distribution.

Comments, questions, errors found, and suggestions are welcome and should be addressed to the authors.

## 2 General Principles

### 2.1 Transport equation

GALPROP solves the transport equation with a given source distribution and boundary conditions for all cosmic-ray species. This includes Galactic wind (convection), diffusive reacceleration in the interstellar medium, energy losses, nuclear fragmentation, and decay. The numerical solution of the transport equation is based on an implicit second-order scheme (33). The spatial boundary conditions assume either zero CR density at the boundaries or, more physically plausible, free particle escape at the boundaries. Since we have a 3-dimensional (R, z, p) or 4-dimensional (x, y, z, p) problem (spatial variables plus momentum) we use “operator splitting” to handle the implicit solution.

The propagation equation is written in the form:

\[
\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{V} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[ \frac{\hat{p} \psi - p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \dot{\psi},
\]

where \( \psi = \psi(\vec{r}, p, t) \) is the density per unit of total particle momentum, \( \psi(p)dp = 4\pi p^2 f(p) \) in terms of phase-space density \( f(p) \), \( q(\vec{r}, p) \) is the source term, \( D_{xx} \) is the spatial diffusion coefficient, \( \vec{V} \) is the convection velocity, reacceleration is described as diffusion in momentum space and is determined by the coefficient \( D_{pp} \), \( \dot{p} \equiv dp/dt \) is the momentum loss rate, \( \tau_f \) is the time scale for fragmentation, and \( \tau_r \) is the time scale for the radioactive decay. The details of the numerical scheme is described in §3.

For a given halo size the diffusion coefficient as a function of momentum and the reacceleration or convection parameters is determined by boron-to-carbon ratio data. The spatial diffusion coefficient is taken as \( D_{xx} = \beta D_0(p/p_0)^\delta \) if necessary with a break (\( \delta = \delta_{1.2} \) below/above rigidity \( p_0 \), where the factor \( \beta (= v/c) \) is a consequence of a random-walk process. For the case of reacceleration the momentum-space diffusion coefficient \( D_{pp} \) is related to the spatial coefficient \( D_{xx} \) as (47), where \( \delta = 1/3 \) for a Kolmogorov spectrum of interstellar turbulences. The convection velocity (in z-direction only) \( V(z) \) is assumed to increase linearly with distance.
from the plane \((dV/dz > 0 \text{ for all } z)\); this implies a constant adiabatic energy loss. The linear form for \(V(z)\) is consistent with cosmic-ray driven MHD wind models \(59\). Since the wind cannot blow in both directions at \(z = 0\) this formulation requires a zero velocity there. A more general case where the wind starts at \(z = \pm z_0\) and is zero for \(|z| < z_0\) has therefore been implemented; in this case \(dV/dz = 0\) will give a constant wind velocity equal to the value at \(z_0\).

The distribution of cosmic-ray sources \(41\) is chosen to reproduce the cosmic-ray distribution determined by analysis of EGRET \(\gamma\)-ray data \(40\). The injection spectrum of nucleons is assumed to be a power law,
\[dq(p)/dp \propto p^{-\gamma}.\]
Energy losses \(41\) for nucleons by ionization and Coulomb interactions are included, and for electrons by ionization, Coulomb interactions, bremsstrahlung, inverse Compton, and synchrotron. The total magnetic field distribution is adjusted to match the 408 MHz synchrotron longitude and latitude distributions. This is in agreement with interstellar field estimates \(3\) and other magnetic field models (e.g., \(16; 55\)).

### 2.1.1 Interstellar hydrogen distribution

The interstellar hydrogen distribution uses \(\text{H}_1\) and CO surveys and information on the ionized component \(30\); the helium fraction of the gas is taken as 0.11 by number. The \(\text{H}_2\) gas number density is defined in the form of table \(4\), which is interpolated linearly, and the conversion factor is taken as \(X = n_{\text{H}_2}/n_{\text{CO}} = 1.9 \times 10^{20}\) mols. cm\(^{-2}\)/(K km s\(^{-1}\)) \(40\). The \(\text{H}_1\) gas number density in the Galactic plane is defined by a table \(14\) which is renormalized to agree with the total integral perpendicular to the plane by Dickey & Lockman \(9\). The \(z\)-dependence is calculated using the approximation by Dickey & Lockman \(9\) for \(R < 8\) kpc, using the approximation by Cox et al. \(6\) for \(R > 10\) kpc, and interpolated in between. The ionized component \(\text{H}_i\) (atom cm\(^{-3}\)) is calculated using a cylindrically symmetrical model \(5\).

### 2.1.2 Interstellar radiation field (ISRF)

For calculation of the spectrum of \(\gamma\)-rays arising from inverse Compton scattering and electron energy losses, the full ISRF as function of \((R, z, \nu)\) is required, which was previously not available in the literature. Our ISRF calculation uses emissivities based on stellar populations and dust emission. The infrared emissivities per atom of \(\text{H}_1\) and \(\text{H}_2\) are based on COBE/DIRBE data from Sodrowski et al. \(37\), combined with the distribution of \(\text{H}_1\) and \(\text{H}_2\). The spectral shape is based on the silicate, graphite and PAH synthetic spectrum using COBE data from Dwek et al. \(10\). For the distribution of the old stellar disk component we use the model of Freudensch (12) based on the COBE/DIRBE few micron survey. The stellar luminosity function is taken from Wainscosat et al. \(57\). For each stellar class the local density and absolute magnitude in standard optical and near-infrared bands is given, and these are used to compute the local stellar emissivity by interpolation in wavelength. The \(z\)-scaleheight for each class and the spatial functions (disk, halo, rings, arms) given by Wainscosat et al. \(57\) then give the volume emissivity as a function of position and wavelength. All their main-sequence and AGB types were explicitly included.

A new model of the ISRF is now available, see Porter & Strong \(32\); Moskalenko et al. \(31\).

### 2.1.3 Gamma rays

Gas-related \(\gamma\)-ray intensities are computed from the emissivities as a function of \((R, z, E_\gamma)\) using the column densities of \(\text{H}_1\) and \(\text{H}_2\) for Galactocentric annuli based on 21-cm and CO surveys. Neutral pion production is calculated using a formalism by Dermer \(7, 8\) as described in Moskalenko & Strong \(24\); bremsstrahlung is calculated using a formalism by Koch & Motz \(18\) as described in Strong et al. \(44\). The inverse Compton scattering is treated using the formalism for an isotropic or anisotropic radiation field developed by Moskalenko & Strong \(26\), and this uses the interstellar radiation field calculations as described above.

**NB in v54 the anisotropic calculation is not yet implemented.**

### 2.1.4 Nuclei H to Ni

In the new version, the code is updated to include the cross-section measurements and energy dependent fitting functions \(43\). The nuclear reaction network is built using the Nuclear Data Sheets. Currently, the isotopic cross section database consists of more than 2000 points collected from sources published in 1969–1999. This includes...
a critical re-evaluation of some data and cross checks. The isotopic cross sections are calculated using the author’s fits to major beryllium and boron production cross sections. Other cross sections are calculated using phenomenological approximations by Webber et al. [55] (code WNEWTR.FOR version of 1993) and/or Silberberg and Tsao (code YIELDX011000.FOR version of 2000) renormalized to the data where it exists. The cross sections on the He target are calculated using a parametrization by Ferrando et al. [11]. For \(pp\) and \(pA\) inelastic cross sections we adapted parametrizations by Tan & Ng [52] and Letaw et al. [21]. The reaction network is solved starting at the heaviest nuclei (i.e., \(^{64}\text{Ni}\)). The propagation equation is solved, computing all the resulting secondary source functions, and then proceeds to the nuclei with \(A - 1\). The procedure is repeated down to \(A = 1\). Our preliminary results for all cosmic ray species \(Z \leq 28\) are given in Strong & Moskalenko [43] and re-evaluation of the radioactive isotopes of Be, Al, Cl, Mn is given in Moskalenko et al. [28].

### 2.1.5 Secondary antiprotons

The code calculates production and propagation of secondary antiprotons as described in Moskalenko et al. [29] and Moskalenko et al. [30]. Antiproton production in \(pp\)-collisions has been calculated using the parametrization of the invariant \(\bar{p}\)-production cross section given by Tan & Ng [53]. The antiproton production by nuclei with \(Z \geq 2\) is calculated using effective nuclear factors; the latter computed using the Monte Carlo event generator DTUNUC [34; 36] or scaling factors similar to Gaisser & Schafer [13]. For the inelastic proton cross sections we adapted parametrizations by Tan & Ng [52] and Letaw et al. [21]. The total \(\bar{p}p\) inelastic cross section has been calculated using a fit from Tan & Ng [52] and parametrization by Groom et al. [15]. The antiproton absorption cross section on nuclear targets is calculated following Moiseev & Ormes [23]. Inelastically scattered antiprotons are treated as a separate “tertiary” component.

### 2.1.6 Secondary positrons and electrons

Secondary positrons and electrons in cosmic rays are the final product of decay of charged pions and kaons which in turn created in collisions of cosmic-ray particles with gas. Pion production in \(pp\)-collisions is considered following a method developed by Dermer [7, 8], which combines isobaric [38] and scaling [1; 39] models of the reaction. Secondary positron and electron production is computed as described in Moskalenko & Strong [24], that includes a critical reevaluation of the charged pion and kaon decay calculations. Primary electrons are computed in the same propagation model.

### 2.2 Working quantities

The nuclei are aligned on the same kinetic energy per nucleon \(E_{kin}\) since this simplifies the secondary-to-primary computation, where primaries produce secondaries of the same \(E_{kin}\). However the basic CR density used has units of density per total momentum \(p\) since this is natural for propagation. The actual units used internally are \(\frac{dn}{dp}\), where \(n(p) = \frac{dn}{dp}\) in units of \(\text{cm}^{-3} \text{MeV}^{-1}\).

When the flux \(I(E_{kin})\) in \(\text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1} (\text{MeV/nucleon})^{-1}\) is necessary, it can be simply obtained from

\[
I(E_{kin}) = \frac{\beta c}{4\pi} \frac{dn}{dp} \frac{dp}{dE_{kin}} = \frac{c}{4\pi} n(p)A, \tag{2}
\]

where \(A\) is the nucleus mass number. This follows from \(dp = \frac{4}{\beta} dE_{kin}\). The combined requirements of transport and fragmentation are thus elegantly met. The normal units for presentation of CR data are \(\text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1} (\text{MeV/nucleon})^{-1}\), and with this scheme the conversion is trivial. The nucleus energy scales are logarithmic in \(E_{kin}\).

The output nuclei spectra are fluxes as defined above, multiplied by \(E_{kin}^2\). The spectra are at \(z = 0\) as a function of \(R\) in kpc. The flux spectra are directly comparable with experimental data at \(R = R_0\).

### 2.3 Abundances and normalization

All calculations are done treating \(n(p)\) as the basic quantity; the final step is to normalize to the absolute proton or electron fluxes given in the galdef file. All other primary and secondary nuclei follow the same normalization.

---

1 Note this differs from the old f90 version which outputted \(\frac{c}{4\pi} p^2 n(p)\).
factor as for protons since source abundances relative to protons are specified in the galdef file. The global normalization to the absolute proton flux is applied at the end of the entire propagation, in nuclei_normalize. Only for output is the flux computed for all nuclei, in routine store_gcr. The $T^1$-decay emissivities depend on $p$, He and the bremsstrahlung and IC emissivities depend on electrons. The nuclei and electron normalizations are therefore done before computing gammas and synchrotron.

2.4 Secondary production

For computation of gamma-ray emissivities and source functions for secondary positrons, electrons and antiprotons, the integral over nucleon energies is required.

For computation of gamma-ray emissivities and source functions for secondary positrons, electrons and antiprotons, the integral over nucleon energies is required. The nucleus energy scales are uniform in $\log E_{kin}$. It is easy therefore to replace integration over kinematic variable with summation over $\Delta(\log E_{kin})$. In case of secondary source function for, e.g., antiprotons it can be calculated as following

$$q(p) = \beta c n_H \int dp \frac{d\sigma(p, p')}{dp} n(p'),$$

where $n_H$ is the gas density (in this case pure Hydrogen), $d\sigma(p, p')/dp$ is the production cross section, $n(p')$ is the CR proton density, and $p'$ is the total momentum of a nucleus. Substitution of $dp'$ with $d(\log E_{kin})$ gives:

$$q(p) = c n_H A \int d(\log E_{kin}) E_{kin} n(E_{kin}) \frac{d\sigma(p, E_{kin})}{dp}$$

$$= c n_H A \Delta(\log E_{kin}) \sum_{E_{kin}} E_{kin} n(E_{kin}) \frac{d\sigma(p, E_{kin})}{dp},$$

where we used $dp' = 1/AE_{kin}d(\log E_{kin})$.

2.5 Coordinate Systems

**galprop** works either in 2D $(R, z)$ or 3D $(x, y, z)$ coordinates; these are consistently defined, with $R = \sqrt{x^2 + y^2}$. The system is chosen for simplicity and after reviewing the literature. Here put a diagram!

In *galprop* we adopt a system with the Galactic centre at $(0,0,0)$ and the Solar position on the +ve x axis at $z = R_o$. The system is right-handed, i.e. $Z = X \times Y$, so that $z = R_o - s \cos(b) \cos(l), y = -s \cos(b) \sin(l), z = s \sin(b)$, where $s$ is the distance from the Sun. In the RH system, looking down from the +Z axis, $x$ is to the right and $y$ is up.

NB at present the B-field sometimes uses a LH system ($Z = -X \times Y$) for consistency with some recent usages (to be clarified). In the LH system, looking down from the +Z axis, $x$ is to the right and $y$ is down, $y = s \cos(b) \sin(l)$. The parity only has importance at present for the B-field, but would be relevant when e.g. spiral structure is also included in the cosmic-ray source function. The Sun et al. 2008 model uses a RH system like *galprop*, but with the solar position on the -ve x-axis unlike *galprop* (+ve x-axis).

The 3D structure of the gas for making gamma-ray maps is implemented via observed column-density maps in (l,b), so is independent of these definitions. A more detailed description including pitch angles for spirals is given in the section on B-fields and synchrotron (to be written).

An arbitrary camera location is now possible in *galprop*. The camera location is given as an (x,y,z) triple and the skymap outputs are such that 1,b = 0,0 always points along the negative x-axis, 1,b = 90° points along the negative y-axis, and 1,b = 0,90° points in the positive z-axis. This may change in the future with an option to rotate the field of view.

---

2 There appears to be no accepted standard convention (even from the IAU) for the orientation and parity of the 3D system, and the convention adopted is just one of those in common use. Some use the Sun on the +ve x-axis (e.g. Drimmel and Spergel 2001, LH system), on the -ve x-axis (e.g. Sun et al 2009, Jansson et al 2009, RH system), others on the +ve y-axis (e.g. Taylor and Cordes 1983, NE2001 electron density model of Cordes and Lazio http://arxiv.org/abs/astro-ph/0007156), RH system. Han and Qiao 1994 do not explicitly use x,y but their system is equivalent to Sun on +x, LH system, since the azimuth angle $\theta$ increases clockwise.
3 The galprop Code

galprop is the main program which calls the routines to read the galdef file, read the nuclear data arrays, fill in the gas and radiation field distributions in the Galaxy, create cosmic rays, propagate particles, and finally store the output arrays.

The code consists of C++ source, with a few (for historical reasons) FORTRAN 77 files. The code distribution is a gzipped tar file. The executable galprop is built automatically using the autotools package. Data files for cross-sections are also part of the package.

It requires several public-domain external packages: cfitsio, CCfits, HEALPix, GSL, CLHEP. Details of how to build galprop are given in the README file.

Astronomical data required by galprop (HI, CO surveys, interstellar radiation field) are provided as separate datasets in a separate distribution.

Below are listed the routines’ names with a short description.

### 3.1 C++ files

This is not complete for v54: to be updated.

#### 3.1.1 Headers

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#### 3.1.2 Routines

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<td>Galdef.cc</td>
<td>mHII.cc</td>
</tr>
<tr>
<td>He_to_H_CS.cc</td>
<td>nuc_package.cc</td>
</tr>
<tr>
<td>IC_anisotropy_factor.cc</td>
<td>nuclei_normalize.cc</td>
</tr>
<tr>
<td>IC_cross_section.cc</td>
<td>print_BC.cc</td>
</tr>
<tr>
<td>Particle.cc</td>
<td>propagate_particles.cc</td>
</tr>
<tr>
<td>create_SNR.cc</td>
<td>propel.cc</td>
</tr>
<tr>
<td>create_galaxy.cc</td>
<td>propel_diagnostics.cc</td>
</tr>
<tr>
<td>create_gcr.cc</td>
<td>read_isrf.cc</td>
</tr>
<tr>
<td>create_transport_arrays.cc</td>
<td>sigma_boron_dec_heinbach_simon.cc</td>
</tr>
<tr>
<td>decayed_cross_sections.cc</td>
<td>source_SNR_event.cc</td>
</tr>
<tr>
<td>e_KN_loss.cc</td>
<td>source_distribution.cc</td>
</tr>
<tr>
<td>electrons_normalize.cc</td>
<td>store_IC_skymap.cc</td>
</tr>
<tr>
<td>energy_losses.cc</td>
<td>store_IC_skymap_comp.cc</td>
</tr>
<tr>
<td>fort_interface1.cc</td>
<td>store_bremss_emiss.cc</td>
</tr>
<tr>
<td>fort_interface2.cc</td>
<td>store_bremss_ionized_skymap.cc</td>
</tr>
<tr>
<td>galprop.cc</td>
<td>store_gcr.cc</td>
</tr>
<tr>
<td>gen_IC_emiss.cc</td>
<td>store_gcr_full.cc</td>
</tr>
<tr>
<td>gen_IC_skymap.cc</td>
<td>store_ionization_rate.cc</td>
</tr>
<tr>
<td>gen_bremss_emiss.cc</td>
<td>store_pi0_decay_emiss.cc</td>
</tr>
<tr>
<td>gen_bremss_ionized_skymap.cc</td>
<td>store_synch_skymap.cc</td>
</tr>
<tr>
<td>gen_ionization_rate.cc</td>
<td>test_Distribution.cc</td>
</tr>
<tr>
<td>gen_isrf_energy_density.cc</td>
<td>test_Particle.cc</td>
</tr>
<tr>
<td>gen_pi0_decay_emiss.cc</td>
<td>test_float_accuracy.cc</td>
</tr>
</tbody>
</table>
3.2 FORTRAN files

WNEWTR_FUNC_aws.f  bremss_spec.f  inter.f  synchrotron.f
YIELDX_011000_imos.f  cfactor.f  nucleon_cs.f
antiproton.f  e_loss_compton.f  pp_meson.f

3.3 Input data files:

Nuclear physics:
WNEWTR_082693.CDR  isotope_cs.dat  nucdata.dat  p_cs.fits.dat
barpol.dat  eval_iso_cs.dat

Galactic structure:
rbands_hi7.fits.gz:
.... HI surveys in 9 Galactocentric rings
rbands_co4.fits.gz:
.... CO surveys in 9 Galactocentric rings
MilkyWay_DR0.5_DZ0.1_DPHI10_RMAX20_ZMAX5_galprop_format.fits
.... ISRF interstellar radiation field as function of (R,z,λ)

3.4 Output data files

All data output is entirely in the form of FITS files. The names are appended with the ID of the galdef file used to generate them, in this example
galdef_50_600203a
was used so they are appended with
50_600203a

This allows unique identification of the version and parameters used to produce the results. The tag, in our example 600203a, can be any (no blanks) string up to 10 characters long. (Our publications include the ID on the tables/plots for easy reference and we encourage this practice.)
nuclei_50_600203a
nuclei_full_50_600203a
Spectrum of all nuclei, electrons and positrons, as function of kinetic energy.

Units: \((\text{MeV/nucleon})^2 \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} (\text{MeV/nucleon})^{-1}\).

First form has spectra at \(z=0\) only, for 2D as function of \((R, E, \text{species})\), for 3D as function of \((x, y, z, E, \text{species})\). Second form is full spatial 2D (function of \(R, z, E, \text{species}\)) or spatial 3D (function of \(x, y, z, E, \text{species}\)) and used e.g. for a warm start as described for the corresponding parameter in Section 4. Header contains keywords identifying the particles and the (logarithmic) energy scale. The particles are ordered by \(Z, A, K\) (\(K=K\) electron). In the ambiguous case of \(Z = -1, A = 0\) which can be primary or secondary electrons, the secondaries are stored first in case both are present.

Example of nuclei 2D file FITS header:

```plaintext
SIMPLE = T / file does conform to FITS standard
BITPIX = -32 / number of bits per data pixel
NAXIS = 4 / number of data axes
NAXIS1 = 21 / length of data axis 1
NAXIS2 = 1 / length of data axis 2
NAXIS3 = 11 / length of data axis 3
NAXIS4 = 21 / length of data axis 4
EXTEND = T / FITS dataset may contain extensions
COMMENT FITS (Flexible Image Transport System) format is defined in 'Astronomy
and Astrophysics', volume 376, page 359; bibcode: 2001A&A...376..359H
CRVAL1 = 0. / Start of axis 1 R (kpc) = CRVAL1 + i * CDELT1
CRVAL2 = 0. / Start of axis 2 not used
CRVAL3 = 3. / Start of axis 3 log10(E/MeV) = CRVAL3 + k * CDELT3
CRVAL4 = 1. / Start of axis 4 sequential species number
CDELT1 = 1. / Increment of axis 1
CDELT2 = 0.1 / Increment of axis 2
CDELT3 = 0.301029995663981 / Increment of axis 3
CDELT4 = 1. / Increment of axis 4
NUCZ001 = 1 / Z of nucleus 1 secondary positrons
NUCA001 = 0 / A of nucleus 1
NUCK001 = 0 / K-electrons of nucleus 1
NUCZ002 = -1 / Z of nucleus 2 secondary electrons
NUCA002 = 0 / A of nucleus 2
NUCK002 = 0 / K-electrons of nucleus 2
NUCZ003 = -1 / Z of nucleus 3 primary electrons
NUCA003 = 0 / A of nucleus 3
NUCK003 = 0 / K-electrons of nucleus 3
NUCZ004 = 1 / Z of nucleus 4 protons
NUCA004 = 1 / A of nucleus 4
NUCK004 = 0 / K-electrons of nucleus 4
NUCZ005 = 1 / Z of nucleus 5 deuterium
NUCA005 = 2 / A of nucleus 5
NUCK005 = 0 / K-electrons of nucleus 5
NUCZ006 = 2 / Z of nucleus 6 3He
NUCA006 = 3 / A of nucleus 6
NUCK006 = 0 / K-electrons of nucleus 6
NUCZ007 = 2 / Z of nucleus 7 4He
NUCA007 = 4 / A of nucleus 7
NUCK007 = 0 / K-electrons of nucleus 7

The nuclei 3D file (nuclei.full) has additional keywords

---

3 To be checked for 3D!
4 In future primary positrons will be included, in which case the same principle holds: the secondaries are stored first.
ELENORM = 3.77123467891234E-34 / Electron norm factor
NUCNORM = 1.85123456718234E-25 / Proton norm factor

These are used when a warm start is made, since the file is read in and needs to be rescaled to the internal GALPROP units before normalization to the GALDEF normalization values. They are also useful when the user would like to compare fluxes independent of the normalization, for example to investigate the effect of reacceleration on the absolute spectrum for the same source input. They are defined so that normalized flux = internal flux \times ELENORM or NUCNORM. Hence to get unnormalized fluxes, divide the flux in the file by ELENORM or NUCNORM.

Bremsstrahlung emissivities ($R, z, E_\gamma$) and skymaps ($l, b, E_\gamma$) as function of $\gamma$-ray energy. First skymap is integrated over full line-of-sight. HIR, H2R signify separated contributions from HI and $H_2$, each with Galactocentric rings. ionized indicated contribution from HII gas.

Units: emissivity: $\text{MeV}^2 (H\text{ atom})^{-1} \text{sr}^{-1} s^{-1} \text{MeV}^{-1}$, skymaps: $\text{MeV}^2 \text{cm}^{-2} \text{sr}^{-1} s^{-1} \text{MeV}^{-1}$

Pion-decay emissivities ($R, z, E_\gamma$) and skymaps ($l, b, E_\gamma$) as function of $\gamma$-ray energy. First skymap is integrated over full line-of-sight. HIR, H2R signify separated contributions from HI and $H_2$, each with Galactocentric rings.

Units: emissivity: $\text{MeV}^2 (H\text{ atom})^{-1} \text{sr}^{-1} s^{-1} \text{MeV}^{-1}$, skymaps: $\text{MeV}^2 \text{cm}^{-2} \text{sr}^{-1} s^{-1} \text{MeV}^{-1}$

Inverse-Compton skymaps ($l, b, E_\nu$) as function of $\nu$. First map is sum over all components, second ('comp') has optical, FIR and CMB scattering components separated.

Units: skymaps: $\text{MeV}^2 \text{cm}^{-2} \text{sr}^{-1} s^{-1} \text{Hz}^{-1}$

Synchrotron skymaps ($l, b, \nu$) as function of frequency. Stokes I, Q, U, P. Units: $\text{erg cm}^{-2} \text{sr}^{-1} s^{-1} \text{Hz}^{-1}$

Synchrotron emissivity ($R, z, \nu$) or ($x, y, z, \nu$). Stokes I, Q, U. Units: $\text{erg cm}^{-3} \text{sr}^{-1} s^{-1} \text{Hz}^{-1}$

Synchrotron polarization angle ($\frac{1}{2} \arctan(U/Q)$) skymaps ($l, b, \nu$). Units: degrees.

Synchrotron polarized fraction ($P/I$) skymaps ($l, b, \nu$). Units: dimensionless.
free_free_skymap_54_600203a

Free-free skymaps \((l, b, \nu)\) as function of frequency. Units: \(\text{erg cm}^{-2} \text{sr}^{-1} s^{-1} \text{Hz}^{-1}\)

For skymap output format option skymap_format=3 (HEALPix) the files have instead names like

\texttt{pi0\_decay\_ring\_8\_healpix\_skymap\_54\_600203a}

for the standard Galactocentric rings 1-17. Units: \(\text{cm}^{-2} \text{sr}^{-1} s^{-1} \text{MeV}^{-1}\). **NB unlike \((l,b)\) skymaps, for HEALpix the gamma-ray intensity is not multiplied by \(E_{\gamma}^{2}\).** For HEALPix skymaps, the energy grid is in the second FITS table extension called ENERGIES.

From r2397, the HEALPix skymaps have one \textit{column} of pixels per energy gridpoint, instead of the previous \textit{vector} of energies per pixel. This is more standard and can be viewed with the Aladin software from CDS Strasbourg, and handled more easily by \texttt{fv} etc. Both formats can be read by GALPLOT. If the vector format is still required, it can be obtained as described in the README file.

\texttt{primary\_protons\_source\_function\_54\_600203a}

etc

CR source functions, for protons, Helium, primary and secondary electrons and positrons.

Units: \(\text{cm}^{-2} \text{sr}^{-1} s^{-2} \text{MeV}^{-1}\)

\texttt{ionization\_rate\_50\_600203a}

Ionization rate by nuclei and electrons as a function of position in the Galaxy. Units: \(s^{-1}\)

3.5 Running galprop

(This is currently described in the online README file, whose content should be transferred here.)

cd\ to the directory where is has been built.

Create directory \texttt{../FITS} and copy the input data (see above) there.

Create directory \texttt{../GALDEF} and put the galdef file you want to process there e.g.

\texttt{galdef\_54\_600203a}

To run \texttt{galprop}, cd to the directory where is has been built and type

\texttt{./galprop -r 600203a}

Note that the version number is contained in the executable and \texttt{galprop} looks automatically or the corresponding galdef file with the right prefix, here ‘54’. If the galdef file does not exist, the program issues an error message and stops.

For a first attempt run the provided test case (e.g. test01) which will run fast, and compare the output with that provided in the distribution.

When it has finished, look at the output e.g.

\texttt{ls ../FITS/*\_54\_600203a}

\texttt{fv ../FITS/pion\_decay\_skymap\_54\_600203a}

or plot it with \texttt{galplot}.

To make another run with the same galdef file (maybe with changed parameters) just run again as above, the output will be overwritten (when the run has finished, not before !). To make another run with a new galdef file, run as above with the new galdef ID.

Parallel runs are possible by running in the background, but pipe the screen output to avoid confusion:

\texttt{./galprop -r 600203a > log600203a &}

\texttt{./galprop -r 600203b > log600203b &}

\texttt{./galprop -r 600203c > log600203c &}

Of course the memory limits must be respected in parallel runs.
3.6 Screen output

The progress of *galprop* is logged on the standard output, which can conveniently be redirected to a log file. The output is mostly self-explanatory. The parameter `verbose=0` gives the minimum output, increasing to 1, 2 etc. will give much more. In addition, `verbose < 0` gives debug output for many routines, which is selectable by the `verbose` value. To find the available debugs, type:

```bash
grep verbose *.cc
```

and a list of the available values and their routines will appear, e.g.

```c
propagate_particles.cc: if(galdef.verbose==10) particle.secondary_source_function.print();
gen_pi0_decay_emiss.cc: if(galdef.verbose=-478)
    cout<<" cs_p_HI, cs_p_He, cs_He_HI, cs_He_He ="<<cs_p_HI<<" "<<cs_p_He<<" "<<cs_He_HI<<" "<<cs_He_He<<end
```

3.7 Test cases

A number of test cases are provided, for each of which the galdef file and the reference output data are available. Also plots to illustrate the results are provided. The test cases can be used to verify the correct running of the code on any platform; they can also be used as a starting point for the cases the user wants to run, by adjusting a few parameters at a time. The propagation parameters of these test cases are based on the optimized model of Strong et al. \(^{(18)}\) with the CR source distribution and gas distribution of Strong et al. \(^{(19)}\).

- **galdef** 50 test01 : basic test of all functions: p, He, Be, B, C, electrons, positrons, antiprotons, \(\gamma\) -rays. 2D
- **galdef** 50 test02 : all nuclei \(Z = 1 – 26\), no \(\gamma\) -rays. 2D
- **galdef** 50 test03 : p, He, electrons, positrons, \(\gamma\) -rays. 2D

4 galdef file parameter explanations

Some parameters default if not specified, but then a warning is issued and the user should provide explicit values. Some parameters are obsolete but left in this description for information when upgrading the galprop version. All parameters are written to the standard output at the start of the program.

The format of a galdef parameter line is

```
<parameter name> = <parameter value> <anything else for information, documentation etc>
```

The parameter value starts at or after column 23 after the `=`, Anything after the parameter is ignored and is useful to comment on the value. Strings as parameters (e.g. file names) must not contain blanks. Vectors of values must be comma separated without blanks (e.g. 1,2,3,4,5). Values can be ignored (e.g. to keep for reference) just by changing the parameter name.

New in trunk. The parameter `=` value is always split on the `=` sign and comments can be added manually with the `#` character. Vectors can be separated with any combination of `,` and ` ` (e.g. 1, 2, 3, 4, 5). Depending on context, anything after the parameter value may or may not be ignored. In number context (integer, floats) it is ignored, but in string and vector context it isn’t.

```
paramter_1 = 1.2 value kept for information
parameter_1 = 1.3 value I want to use here
```

Generally any text can be entered on a line which will be ignored if it does on follow the format. This is useful to document a run.

**General**

```
Title = Zh = 4 kpc cs=W i=rigidity^-2.43 D=6.10 0.33 dvdz=0 Va=30// pbar test
```
Descriptive title used to identify the run. With commands like “grep Title galdef*” you can get a summary of all runs. Otherwise ignored by the program.

**Grid options for Galaxy and spectra**

\[ n_{\text{spatial\_dimensions}} = 2 \]

Specifies whether 2 or 3 spatial dimensions. 2D is cylindrically symmetric \((R, z)\), 3D is \((x, y, z)\) and may be fully asymmetric or with symmetry in \(x, y, z\) as specified by the parameter \text{use\_symmetry}.

\[ r_{\text{min}} = 00.0 \quad \text{min } r \]

Minimum galactocentric radius \((R)\) for 2D case, in kpc. Normally 0. Ignored for 3D.

\[ r_{\text{max}} = 30.00 \quad \text{max } r \]

Maximum galactocentric radius \((R)\) for 2D case, in kpc.

\[ \text{dr} = 1.0 \quad \text{delta } r \]

Cell size in galactocentric radius \((R)\) for 2D case, in kpc.

\[ z_{\text{min}} = -04.0 \quad \text{min } z \]

Minimum height for 2D and 3D case, in kpc. In 3D case with \text{use\_symmetry} = 1 it must be 0, since in this case only \(z > 0\) is explicitly computed.

\[ z_{\text{max}} = +04.0 \quad \text{max } z \]

Maximum height for 2D and 3D case, in kpc.

\[ \text{dz} = 0.1 \quad \text{delta } z \]

Cell size in \(z\) for 2D and 3D case, in kpc.

\[ x_{\text{min}} = 00.0 \quad \text{min } x \]

Minimum \(x\) for 3D case, in kpc. In 3D case with \text{use\_symmetry} = 1 it must be 0, since in this case only \(x > 0\) is explicitly computed. Ignored for 2D.

\[ x_{\text{max}} = +20.0 \quad \text{max } x \]

Maximum \(x\) for 3D case, in kpc. Ignored for 2D.

\[ \text{dx} = 0.2 \quad \text{delta } x \]

Cell size in \(x\) for 3D case, in kpc. Ignored for 2D.

\[ y_{\text{min}} = 00.0 \quad \text{min } y \]

See \(x_{\text{min}}\), but now for \(y\)-axis.

\[ y_{\text{max}} = +20.0 \quad \text{max } y \]

See \(x_{\text{max}}\), but now for \(y\)-axis.

\[ \text{dy} = 0.2 \quad \text{delta } y \]

See \(\text{dx}\), but now for \(y\)-axis.
p_min = 1000 min momentum (MV)

Minimum particle momentum in megavolts (MV), case $p_{Ekin_{grid}} = p$. NB do not use except for testing.

p_max = 4000 max momentum

Maximum particle momentum in megavolts (MV), case $p_{Ekin_{grid}} = p$. NB do not use except for testing.

p_factor = 1.20 momentum factor

The ratio between successive momentum grid points, case $p_{Ekin_{grid}} = p$. The momentum grid is on a logarithmic scale, so that $p[i] = p_{\min} \times p_{factor}^i; p[0] = p_{\min}$. The number of grid points is chosen to give a maximum value close to $p_{\max}$. NB do not use except for testing.

Ekin_min = 1.0e1 min kinetic energy per nucleon (MeV)

Minimum particle kinetic energy per nucleon in MeV, case $p_{Ekin_{grid}} = Ekin$.

Ekin_max = 1.0e7 max kinetic energy per nucleon

Maximum particle kinetic energy per nucleon in MeV, case $p_{Ekin_{grid}} = Ekin$.

Ekin_factor = 1.20 kinetic energy per nucleon factor

The ratio between successive kinetic energy per nucleon grid points, case $p_{Ekin_{grid}} = Ekin$. The momentum grid is on a logarithmic scale, so that $E_{kin}[i] = E_{kin_{\min}} \times E_{kin_{factor}}^i; E_{kin[0]} = E_{kin_{\min}}$. The number of grid points is chosen to give a maximum value close to $E_{kin_{\max}}$.

$p_{Ekin_{grid}} = Ekin$ $p || Ekin$ alignment

The grid points are arranged so all particles are aligned the same $Ekin$ scale; this is very convenient when computing secondary/primary ratios which are always presented in this form. For details see the explanation elsewhere in this document. [The actually propagation calculation is done in terms of momentum since this is physically more natural, but the user does not have to worry about this.] NB only the case $p_{Ekin_{grid}}$ is useful for nuclei, $p$-alignment may however be interesting in some cases, hence this option is kept.

$E_{\gamma_{min}} = 0.1$ min gamma-ray energy (MeV)

Minimum gamma-ray energy (MeV) for diffuse gamma-ray maps.

$E_{\gamma_{max}} = 1.e6$ max gamma-ray energy (MeV)

Maximum gamma-ray energy (MeV) for diffuse gamma-ray maps.

$E_{\gamma_{factor}} = 10.$ gamma-ray energy factor

The ratio between successive gamma-ray energy grid points. The energy grid is on a logarithmic scale, so that $E_{\gamma}[i] = E_{\gamma_{\min}} \times E_{\gamma_{factor}}^i; E_{\gamma[0]} = E_{\gamma_{\min}}$. The number of grid points is chosen to give a maximum value close to $E_{\gamma_{max}}$.

nu_synch_min = 1.0e6 min synchrotron frequency (Hz)

Minimum frequency (Hz) for synchrotron maps.

nu_synch_max = 1.0e10 max synchrotron frequency (Hz)

Maximum frequency (Hz) for synchrotron maps.

nu_synch_factor = 2.0 synchrotron frequency factor
The ratio between successive synchrotron frequency grid points. The frequency grid is on a logarithmic scale, so that $\nu_{\text{synch}}^i = \nu_{\text{synch min}} \times \nu_{\text{synch factor}}^i; \nu_{\text{synch}}[0] = \nu_{\text{synch min}}$. The number of grid points is chosen to give a maximum value close to $\nu_{\text{synch max}}$.

- **long\_min** = 0.5 gamma-ray intensity skymap longitude minimum (deg)
  
  Minimum longitude for gamma-ray intensity skymaps (degrees). NB Bin centres as in FITS convention.

- **long\_max** = 359.5 gamma-ray intensity skymap longitude maximum (deg)
  
  Maximum longitude for gamma-ray intensity skymaps (degrees). NB Bin centres as in FITS convention.

- **lat\_min** = -89.5 gamma-ray intensity skymap latitude minimum (deg)
  
  Minimum latitude for gamma-ray intensity skymaps (degrees). NB Bin centres as in FITS convention.

- **lat\_max** = 89.5 gamma-ray intensity skymap latitude maximum (deg)
  
  Maximum latitude for gamma-ray intensity skymaps (degrees). NB Bin centres as in FITS convention.

- **d\_long** = 10. gamma-ray intensity skymap longitude binsize (deg)
  
  Binsize in longitude for gamma-ray intensity skymaps (degrees).

- **d\_lat** = 10. gamma-ray intensity skymap latitude binsize (deg)
  
  Binsize in latitude for gamma-ray intensity skymaps (degrees).

- **healpix\_order** = 7 order for healpix skymaps. 7 gives ~0.5 deg and it changes by an order
  
  For gamma-ray and synchrotron skymaps. *New in v54.*

- **lat\_substep\_number** = 1 latitude bin splitting (0,1=no split, 2=split in 2...)
  
  Controls gamma-ray skymap computation accuracy. *New in v54.*

- **LoS\_step** = 0.01 kpc, Line of Sight (LoS) integration step
  
  Controls gamma-ray skymap computation accuracy. from r586: Controls also synchrotron skymaps. *New in v54.*

- **LoS\_substep\_number** = 1 number of substeps per LoS integration step (0,1=no substeps)
  
  Controls gamma-ray skymap computation accuracy. *New in v54.*

- **los\_integration\_mode** = 1 Selects los integration, 1 gives new method, anything else gives old
  
  Controls the selected los integration mode. Useful for debugging purposes, new method should always produce more accurate results. *New in trunk*

- **cameraLocation** = 8.5,0,0 #Location of camera for skymap integration (x,y,z)
  
  Specifies the location of the camera for skymap integration. Only works properly for **los\_integration\_mode** = 1. *New in trunk*

---

**Cosmic-ray propagation parameters**
Diffusion_aniso = 0 0= isotropic diffusion, 1=anisotropic diffusion
From r2201. If isotropic, uses $D_{0_{xx}}$ only, if anisotropic uses $D_{0_{xx}}$ and $D_{0_{zz}}$.

$D_{0_{xx}} = 6.10 \times 10^{-28}$ diffusion coefficient in $x,y$ (and $z$ if isotropic diffusion) at reference

The spatial diffusion coefficient divided by $\beta (= v/c)$ at rigidity $D_{rigid_br}$.

$D_{rigid_br} = 4.0 \times 10^{-3}$ reference rigidity for diffusion coefficient in MV

$D_{g_1} = 0.33$ diffusion coefficient index below reference rigidity

$D_{g_2} = 0.33$ diffusion coefficient index above reference rigidity

$D_{0_{zz}} = 6.10 \times 10^{-27}$ diffusion coefficient in $z$ if anisotropic diffusion, at reference rigidity

Damping_p0 = 1.e6 MV -some rigidity (where CR density is low)

Damping_const_G = 0.02 a const derived from fitting B/C

Damping_max_path_L = 3.e21 Lmax~1 kpc, max free path

These parameters refer to the self-consistent MHD wave damping model described in Ptuskin et al. (2006), ApJ.642, astro-ph/0510335. Use of these parameters and the choice of turbulence spectrum is controlled by parameter diff_reacc.

convection = 0 :no convection 1,2,3 : include convection according to various model

Flag to indicate whether convection is to be included in propagation (0=no, ≥1=yes). Also controls inclusion of wave-damping: 11=Kolmogorov turbulence, 12=Kraichnan turbulence (see damping parameters below).

$\v_Alfven = 30.$ Alfven speed in km s$^{-1}$

Alfvén speed for computation of diffusive reacceleration momentum diffusion coefficient (see explanation elsewhere in document). This parameter is in fact $v_A/\sqrt{w}$ where $w$ is the ratio of MHD wave energy density to magnetic field energy density, see Strong & Moskalenko (11).

diff_reacc =1 1=include diffusive reacceleration

Flag to indicate whether diffuse reacceleration is to be included in propagation (0=no, ≥1=yes). Also controls inclusion of wave-damping: 11=Kolmogorov turbulence, 12=Kraichnan turbulence (see damping parameters below).

$\v_{Alfven} = 30.$ Alfven speed in km s$^{-1}$

$\v_{Alfven}$ speed for computation of diffusive reacceleration momentum diffusion coefficient (see explanation elsewhere in document). This parameter is in fact Alfven speed/$\sqrt{w}$ where $w$ is the ratio of MHD wave energy density to magnetic field energy density, see Strong & Moskalenko (11).

damping_p0 = 1.66 MV -some rigidity (where CR density is low)

damping_const_G = 0.02 a const derived from fitting B/C

damping_max_path_L = 3.e21 Lmax~1 kpc, max free path

These parameters refer to the self-consistent MHD wave damping model described in Ptuskin et al. (2006), ApJ.642, astro-ph/0510335. Use of these parameters and the choice of turbulence spectrum is controlled by parameter diff_reacc.

Flag to indicate whether convection is to be included in propagation, and to specify the model for convection.

1: original formulation : $v = v_{0_{conv}} + dv/dz_{conv} \times z$

2: new at r1799: $v = \text{sign}(z) \times (v_{0_{conv}} + dv/dz_{conv}(|z| - z_{0_{conv}}))$, $|z| \geq z_{0_{conv}}$; $v = 0$, $|z| < z_{0_{conv}}$.

3: new at r1955: $v = \text{sign}(z) \times v_{0_{conv}} \times 0.5 [1 + \tanh(4(z_{0_{conv}} - |z|))].$

This is a smooth function, very close to 0 at $z = 0$, tending to $\pm v_{0_{conv}}$ at large $\pm z$, and with $v(\pm z_{0_{conv}}) = \pm v_{0_{conv}}/2$. It avoids the discontinuity in $v$ which occurs for convection = 2.

The corresponding velocity gradient is $dv/dz = v_{0_{conv}} \times 0.5 \times \frac{4}{4z_{0_{conv}}} \sech^2(4|z|/4z_{0_{conv}} - 4)$. This formula gives $dv/dz \geq 0$ everywhere as required, with peaks at $z = \pm z_{0_{conv}}$. (Parameter $dv/dz_{conv}$ is not used in this case).

(Hint: running GALPROP with galdef parameter verbose=-504 will print $v$ and $dv/dz$ as a function of the coordinates for visual inspection.)
v0_conv = 0. starting convection velocity in km s^{-1}

convection = 1: Convection velocity at z = 0 (km s^{-1}). In practice only a value 0 is physical, from symmetry.

convection = 2: Convection velocity at z = z_0_{conv} (km s^{-1}).

convection = 3: Convection velocity at large z. v(\pm z_{0_{conv}}) = \pm v_{0_{conv}}/2 (km s^{-1}).

dvdz_conv = 7. \frac{dV}{dz} = \text{grad } V \text{ in km s}^{-1} \text{ kpc}^{-1}

Gradient of convection velocity, assumed linear, in km s^{-1} kpc^{-1}. Only used for convection = 1, 2.

z0_conv = 1.0 \text{ start } |z| \text{ or } z\text{-scale for wind, kpc}

Used when convection = 2, 3; see description above. new at r1799.

nuc_rigid_br = 1.0e4 reference rigidity for primary nucleus injection index in MV

In the case that the primary nucleus injection spectra have a break, this defines the rigidity of the break in MV. This is the default value for all nuclei.

nuc_g_1 = 2.23 nucleus injection index below reference rigidity

Injection index below nuc_{rigid_{br}}.

nuc_g_2 = 2.43 nucleus injection index index above reference rigidity

Injection index above nuc_{rigid_{br}}.

nuc_rigid_br0 = 1.0e3 rigidity for double broken spectrum.

The lower break rigidity for double broken power law.

nuc_g_0 = 2.1 nucleus injection index below rigid_{br0}.

The index below nuc_{rigid_{br0}} for double broken power law.

nuc_rigid_br2 = 1.0e5 rigidity for triple broken spectrum.

The upper break rigidity for triple broken power law. From r2330. Defaults to very large value if absent.

nuc_g_3 = 3.0 nucleus injection index above rigid_{br2}.

The index above nuc_{rigid_{br2}} for triple broken power law. From r2330.

inj_spectrum_type = rigidity | beta_rig | Etot | dirac nucleon injection spectrum type

The primary nucleus injection spectrum may be defined to be a power law in rigidity, \beta \times \text{rigidity} or total energy. Normally rigidity is used since it corresponds to a power-law in momentum favoured by SNR shock acceleration models. r603: new type: dirac A delta-function injection spectrum at energy controlled by nuc_{rigidity_{break}} (KE/nucleon) for nuclei and electron_{rigidity_{br}} (KE) for electrons. Use together with electron_{norm_type} = 2 or 3 to normalize to injection luminosity. Ditto for proton_{norm_type} = 2 or 3 but this is normalization is not yet implemented.

nuc_rigid_br0_{01_001} = 1e4 rigid_{br0} for Hydrogen
nuc_g_{001_01_01} = 1e6 rigid_{br} for Hydrogen
nuc_g_{0_01_001} = 1.9 g_{0} for Hydrogen
nuc_g_{1_01_001} = 2.4 g_{1} for Hydrogen
nuc_g_{2_01_001} = 2.3 g_{2} for Hydrogen
nuc_rigid_br0_{02_004} = 1e4 rigid_{br0} for Helium
nuc_rigid_br0_{02_004} = 1e6 rigid_{br} for Helium
nuc_g_{02_004} = 1.8 g_{0} for Helium
nuc_g_{12_004} = 2.3 g_{1} for Helium
nuc_g_{22_004} = 2.2 g_{2} for Helium
With such parameters is possible to set the injection spectra individually for each nuclei species. Uses the same syntax of `ZZ AAA` as `iso_abundance ZZ AAA`. If some or all of the parameters are not given they inherit the default values described above. The isotopic abundance is normalized at `nuc_rigid_br` for each species. This option is at present only in v5.5, not v5.4.

`electron_rigid_br = 1.0e4`  reference rigidity for primary electron injection index in MV

In the case that the primary electron injection spectrum has a break, this defines the rigidity of the break in MV.

`electron_g_1 = 2.30`  primary electron injection index below reference rigidity

Injection index below `electron_rigid_br`.

`electron_g_2 = 2.50`  primary electron injection index index above reference rigidity

Injection index above `electron_rigid_br`.

`electron_rigid_br0 = 1.0e3`  primary electron rigidity for double broken spectrum.

The lower break rigidity for double broken power law.

`electron_g_0 = 2.1`  primary electron injection index below rigid_br0.

The index below `nuc_rigid_br0` for double broken power law.

`electron_rigid_br2 = 1.0e6`  break rigidity for triple broken spectrum.

The upper break rigidity for triple broken power law. From r2330. Defaults to very large value if absent.

`electron_g_3 = 3.5`  electron injection index above electron_rigid_br2.

The index above `electron_rigid_br2` for triple broken power law. From r2330.

`positron_rigid_br = 1.0e3`  reference rigidity for positron injection index in MV

In the case that the primary positron injection spectrum has a break, this defines the rigidity of the break in MV.

`positron_g_1 = 2.30`  positron injection index below reference rigidity

Injection index below `positron_rigid_br`.

`positron_g_2 = 2.50`  positron injection index index above reference rigidity

Injection index above `electron_rigid_br`.

`positron_rigid_br0 = 1.0e2`  positron rigidity for double broken spectrum.

The lower break rigidity for double broken power law.

`positron_g_0 = 2.1`  positron injection index below rigid_br0.

The index below `nuc_rigid_br0` for double broken power law.

`positron_rigid_br2 = 1.0e6`  break rigidity for triple broken spectrum.

The upper break rigidity for triple broken power law. From r2330. Defaults to very large value if absent.

`positron_g_3 = 4.0`  positron injection index above positron_rigid_br2.
The index above `positron_rigid_br2` for triple broken power law. From r2330.
NB primary positrons were introduced at r2242.

**Parameters controlling interstellar medium.**

He\textsubscript{H\_ratio} = 0.11  
He/H of ISM, by number

Interstellar gas ratio of Helium to Hydrogen. Used for fragmentation, secondary production, energy loss, gamma-ray production. Values 0.08–0.11 are possible, see discussion in Strong & Moskalenko [41].

\( n_{X\_CO} = 10 \)  
an option to select functional dependence of \( X\_CO=X\_CO(R) \)  
0=constant as below, 9=standard variation as in A&A 2004 paper 10=an exponential

Controls choice of \( X\_CO \) variation. *new in v54*.

\( X\_CO = 0.4E20, 0.4E20, 0.6E20, 0.8E20, 1.5E20, 10.0E20, 10.0E20, 10.0E20 \)  
for CO rings 0.0 - 1.5 - 3.5 - 5.5 - 7.5 - 9.5 - 11.5 - 13.5 - 15.5 - 50 kpc

Radial dependence of \( X\_CO = N(H_2)/W_{CO} \). See Strong et al. [49] for details. There are 9 values corresponing to the Galactocentric rings indicated. In the case of 9-ring HI,CO data they are all used. In the case of 8-ring data the second and subsequent values are used. *New in v50*.

\( n_{HI\_model} = 1 \)  
selection of HI gas density model (not yet implemented)

\( n_{H2\_model} = 1 \)  
selection of H2 gas density model (not yet implemented)

\( n_{HII\_model} = 3 \)  
selection of HII gas density model 1=Cordes et al 1991 2=NE2001 3 = Gaensler etal

Ionized hydrogen contributes to CR secondary production, energy losses and gamma rays. NE2001 is implemented in a simplified fashion as described in 5.3.1. Option 3 is NE2001 with increased WIM scaleheight and appropriate density according to Gaensler et al 2008, see 5.3.1 (not yet).

\( HII\_Te = 7000 \)  
free electron temperature (K) for free-free absorption

\( HII\_clumping\_factor = 60 \)  
free electron clumping factor for free-free absorption

Ionized hydrogen (WIM: warm interstellar medium) parameters. Used for radio absorption (synchrotron and free-free) and for free-free radio emission. \( HII\_Te \) is the electron temperature (K) used in formulae for absorption and emission (default = 7000). \( HII\_clumping\_factor \) is the factor to multiply the absorption coefficient and free-free emissivity relative to the case of a smooth medium. Related to ‘filling factor’: in the simplest case of equal clouds, \( HII\_clumping\_factor = 1/filling\_factor \). Default = 1. Controlled by parameter free_free_absorption.

COR\_filename = rbands_co10mm_2001_qdeg.fits.gz  
File for CO surveys. *new in v54*.

HIR\_filename = rbands_hi12_qdeg_zmax1.fits.gz  
File for HI surveys. *new in v54*.

ISRF\_file = ISRF_RMax20_ZMax5_DR0.5_DZ0.1_MW_BB_24092007.fits (new) input ISRF file

ISRF\_filetype = 1  
Input file for ISRF, and format type. *new in v54*.

ISRF\_healpixOrder = 3 for output of ISRF skymaps  
Internal size of ISRF healpix skymaps. Used for anisotropic IC calculations. Values greater than or equal to 2 recommended for better accuracy. *new in v54*. 
ISRF_factors = 1.0,1.0,1.0 ISRF factors for IC calculation: optical, FIR, CMB

Scaling factors for inverse Compton from separate components: optical, FIR and CMB. Normally should be 1.0, but other values can be used to experiment. **New in v50.**

B_field_name = Pshirkov_ASS 3D B-field model name

Applies if synchrotron = 2 or 3. A set of B-field models is implemented. The meanings of the parameters depend on the model. For details see routine B_field_3D_model.cc.

- B_field_name = galprop_original: exponential model as in original 'bbbrrrzzz', but using B_field_parameters: Bo (Gauss), rscale (kpc), zscale (kpc).

The JF12 models implementations are still under test.

For description of some of the models and example of their use see Orlando and Strong, MNRAS 436, 2127 (2013)

From r592: this model is also used for synchrotron energy losses if synchrotron = 2 or 3, which was not the case before

n_B_field_parameters = 10 number of B-field parameters OBSOLETE

B_field_parameters = 5.0e-6,10.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0 parameters for 3D models, meaning

Parameters of models specified by name. For the list of models and details of their parameters, see B_field_3D_model.cc.

The number of parameters is deduced from the input string; current models need up to 10, but more will be required in future. (r885: no longer restricted to exactly 10 parameters). The example above is for exponential model galprop_original, Bo=5\mu G, rscale = 10 kpc, zscale = 2 kpc. The models will be documented in this Explanatory Supplement in the future; for now look at the code, it is reasonably self-explanatory.

B_field_model = 050100020 bbbrrrzzz bbb=10*B(0) rrr=10*rscale zzz=10*zscale OBSOLETE

Only for synchrotron = 0, 1: Specifies the random magnetic field according to the law \(B = (\text{bbb}/10) \times e^{-(R-R_0)/(\text{rrr}/10)-|z|/\text{zzz}/10})\) microgauss, where \(R_0 = 8.5 \text{kpc}\), e.g., this example has \(B = 5\mu G e^{-(R-R_0)/10 \text{kpc}-|z|/2 \text{kpc}}\) microgauss. This parameter is deprecated and can be omitted, but description is kept to decipher earlier GALDEF files. Note that synchrotron = 1 uses old routines for synchrotron, which are deprecated. This option is slated for removal in a forthcoming revision. For these reasons please only use instead synchrotron = 2 or 3 and the specification above, with B_field_name = galprop_original.

Note that synchrotron = 0 uses this B-field for synchrotron energy losses even though no synchrotron skymap is requested! Hence use synchrotron = 2 or 3 always even if a skymap is not desired. In future the B-field specification should be independent of the request for a skymap.

---

**Parameters controlling propagation calculation.**

fragmentation = 1 i=include fragmentation

Flag to indicate whether nuclei fragmentation to be included. Useful for testing effect of fragmentation.

---

\(^5R_0\) was omitted from the formula in this document although always present in the code. Corrected on 7 Feb 2012
4 GALDEF FILE PARAMETER EXPLANATIONS

momentum_losses = 1
Flag to indicate whether momentum losses to be included. Useful for testing effect of losses.

radioactive_decay = 1
Flag to indicate whether radioactive decay to be included. Useful for testing effect of decay.

start_timestep = 1.0e7 (years)
The solution of the propagation equation proceeds starting with a large timestep, repeated typically 20 times (defined by timestep_repeat) and reduces the timestep successively. The theory of this accelerated solution is given in Strong & Moskalenko (41). This parameter is the starting timestep, typically $10^7$ years corresponding to the longest timescales in cosmic-ray propagation ($20 \times 10^7$ years, sufficient for 4 kpc halo).

dend_timestep = 1.0e1 (years)
Final timestep, corresponding to the shortest timescales, dominated by energy-losses; for the highest energy electrons (and positrons) this should be $<100$ years for safety, for nuclei-only runs it can be $10^4$ years.

timestep_factor = 0.50
Factor by which timestep is reduced after timestep_repeat iterations.

timestep_repeat = 20 number of repeats per timestep in timestep_mode=1
Number of iterations of the timestep for each timestep_factor. Typically 20. Criterion is that a stable solution is obtained before proceeding to the next smaller timestep, which can be checked by turning on control_diagnostics (not normally necessary). NB must be integer format: 10000 not 1e4.

Important note: It is highly recommended to make a test run with start_timestep = end_timestep = a small value like $10^4$ years for nuclei, $100$ years for electrons/positrons, and a correspondingly large value for timestep_repeat, like $10^5, 10^7$, and timestep_factor=0.9 (the latter is just to terminate the run appropriately), to get the properly converged solution for a total time of $10^9$ years. This is because the accelerated solution is not always reliable while the small timestep solution is. If the results agree, then parameter scans can be confidently done in the rapid scheme. See Section ‘Tests of GALPROP’.

timestep_repeat2 = 10000 number of timesteps in timestep\_mode=2
At the end of the series of reduced timesteps the propagation can be continued with the smallest timestep. This parameter specifies how many timesteps are to be performed in this mode. This is mainly useful in the 3D mode with stochastic SNR sources, where the large timestep technique is not appropriate since we have a time-dependent problem. If required, the rapid method can be used to get the ‘background’ solution, while the reduced timesteps follow the subsequent time-dependence at high time resolution. It is also useful to obtain accurate solutions especially with solution_method = 2 (see below). This option was only implemented in the 3D case; in 2D this parameter has no effect. r722: now implemented for 2D also.

NB must be integer format: 10000 not 1e4.

timestep_print = 200 number of timesteps between printings
The full cosmic-ray density array can be printed at intervals using this parameter. NB must be integer format: 10000 not 1e4.

timestep_diagnostics = 10000 number of timesteps between diagnostics
Diagnostics to evaluate the quality of the propagation solution can be generated, normally only occasionally as specified by the number of timesteps between diagnostics. NB must be integer format: 10000 not 1e4. For sample output see Section ‘Tests of GALPROP’. Since diagnostics use significant CPU, this parameter should be large for productions runs (100-10000 or more) but can be set to 1 for testing and evaluating the progress of a run in detail.
control_diagnostics =0  control detail of diagnostics

Controls the amount of detail in diagnostics. Larger \rightarrow more detail.

solution_convergence = 1  use convergence diagnostic

Uses the convergence state return by propel_diagnostics to end a timestep loop and pass to the next smaller timestep (timestep mode 1) or end the propagation loop (timestep mode 2). 1 = do this, 0= don’t do this. The criterion is ‘no change (to machine accuracy) in the CR flux since the last call of propel_diagnostics’, so that further iterations have no effect on the solution with this timestep. Most useful in timestep mode 2, where the number of steps can be set very large and the convergence check automatically ends the propagation at the appropriate number of steps, ensuring an accurate solution without having to experiment manually with the diagnostics.

solution_method = 2  1=method 1:Crank-Nicolson, 2,21 = method 2:fully explicit in time

Controls the method to solve the propagation equation, in timestep mode 2 only. New at r705. Standard method is 1=Crank-Nicolson which is also the default if this parameter is absent (upwards compatible). Method 2 is fully explicit in time, see description of routine propel.cc. It gives more accurate solutions, which tend to exact according to the alpha-based diagnostics, but are not unconditionally stable (while Crank-Nicolson is). For this reason only use for short timesteps (typically 100-1000 years). Since no solution of matrix equations is required, method 2 is faster than 1 for the same timesteps, and this compensates for the need for smaller steps. Specifying 21 invokes a ‘turbo’ version of method 2, which uses linear arrays instead of 2D or 3D arrays in the propagation code. This leads to significant speed-up even in non-parallel compilations, and is much better adapted to parallelization e.g. via OpenMP. It is available both in 2D and 3D (from r805).

For timestep mode 1, where typically large timesteps are used at the start, the method is fixed at Crank-Nicolson to ensure stability.

network_iterations =1  number of iterations of protons  (default 1 if absent)

The nuclei fragmentation network is sorted and secondary particles are not calculated until their primary contributions have been calculated. This ensures that all species are calculated correctly in one pass. network_iter_compl=1 should therefore be enough for all calculations. Calculating self-consistent damping requires many iterations using protons only. Note that if network_iterations < network_iter_compl, network_iterations is increased to be equal to network_iter_compl.

prop_r = 1  1=propagate in r (2D)

Flag to indicate whether to propagate in radial direction (2D only). This and x,y,z,p flags are useful for testing the code, e.g., by allowing propagation in one direction only.

prop_x = 1  1=propagate in x (2D)

Flag to indicate whether to propagate in x-direction (3D only).

prop_y = 1  1=propagate in y (3D)

Flag to indicate whether to propagate in y-direction (3D only).

prop_z = 1  1=propagate in z (2D, 3D)

Flag to indicate whether to propagate in z-direction (2D,3D).

prop_p = 1  1=propagate in momentum

Flag to indicate whether to propagate in momentum (2D,3D).
spatial_bound_conds = 1  spatial boundary conditions. 1= zero, 2=free escape at boundaries
From r2254. Defaults to 1, the original case. Free escape is more physically plausible. See description of method, routine propel.cc, for explanation.

use_symmetry = 0 0=no symmetry, 1=optimized symmetry, 2=xyz symmetry by copying(3D)
This is only relevant for 3D. The code will solve the 3D case in general, but this leads to large computer resource requirements, in particular large memory. Often symmetry can be assumed without reducing the usefulness of the results since even with stochastic sources the fact that the sources are symmetrically distributed has no effect on the conclusions about, for example, fluctuations. Hence use_symmetry=1 is generally recommended and the code has been specially optimized to take advantage of this. The memory requirements are reduced by a factor 8 relative to the general case. Note added 22 Oct 2010, AWS: in the current version use_symmetry = 1 does not work correctly, so use_symmetry = 0 is recommended. Now that computer resources have grown since GALPROP began, the symmetry options are less relevant.

vectorized = 0 0=unvectorized code, 1=vectorized code
Flag to indicate use of vectorized portions of code. Only advantageous on vector processor machines, in 3D. Only applies to timestep_mode=2. Obsolete now that OpenMP has been implemented for multiple cores.

source_specification = 0 2D::1:r,z=0 2:z=0 3D::1:x,y,z=0 2:z=0 3:x=0 4:y=0
This parameter is for testing only, leave at 0.

source_model = 1 CR source model for nuclei 0=zero 1=parameterized 2=Case&B 3=pulsars 4= S&Mattox 5=S&Mattox
Various CR source distributions. source_model=1 uses parameters 0-5, in the formula \( R^\alpha e^{-\beta R} \frac{|z|}{zscale} \), with cutoff at \( R = r_{\text{max}} \), constant for \( r_{\text{const}} < R < r_{\text{max}} \) at value at \( r_{\text{const}} \). \( R \) is replaced by \( R + roff \) to obtain a non-zero value at \( R=0 \), default \( roff = 0 \).

For more details, more source models and their parameters see routine source_distribution.cc.

source_parameters_0 = 0.2  model 1:zscale, kpc
Defaults to 0.2 kpc, recommended to set it explicitly. In v54, valid from r2309.

source_parameters_1 = 0.5  model 1:alpha

source_parameters_2 = 1.0  model 1:beta

source_parameters_3 = 15.0  model 1:rmax

source_parameters_4 = 10.0  model 1:rconst. For \( r_{\text{const}} < r < r_{\text{max}} \), set to value at \( r_{\text{const}} \)

source_parameters_5 = 0.0  model 1:roff replace \( r \) with \( x=r+roff \) and \( r0 \) with \( x0=r0+roff \) in the equations

source_model_elec = 1  CR source model for electrons, definitions as for nuclei
source_pars_elec_1 etc : parameters of CR source model for electrons
If source_model_elec is absent it will default to source_model. If source_pars_elec_1 etc are absent they will default to source_parameters_1 etc.

n_cr_sources = 0  number of pointlike cosmic-ray sources  3D only!
This allows individual CR sources to be inserted in 3D. Useful for testing the response to a delta function, otherwise has not been used much.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cr_source_x_01</td>
<td>x position of cosmic-ray source 1 (kpc)</td>
</tr>
<tr>
<td>cr_source_y_01</td>
<td>y position of cosmic-ray source 1</td>
</tr>
<tr>
<td>cr_source_z_01</td>
<td>z position of cosmic-ray source 1</td>
</tr>
<tr>
<td>cr_source_w_01</td>
<td>sigma width of cosmic-ray source 1</td>
</tr>
<tr>
<td>cr_source_x_02</td>
<td>x position of cosmic-ray source 2</td>
</tr>
<tr>
<td>cr_source_y_02</td>
<td>y position of cosmic-ray source 2</td>
</tr>
<tr>
<td>cr_source_z_02</td>
<td>z position of cosmic-ray source 2</td>
</tr>
<tr>
<td>cr_source_w_02</td>
<td>sigma width of cosmic-ray source 2</td>
</tr>
<tr>
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<td>luminosity of cosmic-ray source 1</td>
</tr>
<tr>
<td>cr_source_L_02</td>
<td>luminosity of cosmic-ray source 2</td>
</tr>
<tr>
<td>SNR_events</td>
<td>handle stochastic SNR events</td>
</tr>
<tr>
<td>SNR_interval</td>
<td>time interval in years between SNR in 1 kpc^-3 volume</td>
</tr>
<tr>
<td>SNR_livetime</td>
<td>CR-producing live-time in years of an SNR</td>
</tr>
<tr>
<td>SNR_electron_sdg</td>
<td>delta electron source index Gaussian sigma</td>
</tr>
<tr>
<td>SNR_nuc_sdg</td>
<td>delta nucleus source index Gaussian sigma</td>
</tr>
<tr>
<td>SNR_electron_dgpivot</td>
<td>delta electron source index pivot rigidity (MeV)</td>
</tr>
<tr>
<td>SNR_nuc_dgpivot</td>
<td>delta nucleus source index pivot rigidity (MeV)</td>
</tr>
<tr>
<td>HI_survey</td>
<td>HI survey 8=orig 8 rings 9=new 9 rings</td>
</tr>
<tr>
<td>CO_survey</td>
<td>CO survey 8=orig 8 rings 9=new 9 rings</td>
</tr>
<tr>
<td>proton_norm_Ekin</td>
<td>proton kinetic energy for normalization (MeV)</td>
</tr>
<tr>
<td>proton_norm_flux</td>
<td>flux of protons at normalization energy (cm^-2 sr^-1 s^-1 MeV^-1)</td>
</tr>
</tbody>
</table>

Flag to indicate whether to generate CR sources in the form of SNR, random in space and time. Only in 3D and only for timestep_mode=2. The spatial distribution of SNR follows source specification, the time dependence is determined by the following 2 parameters.

Determined the rate of SNR, according to method described elsewhere in this document. The total SNR rate corresponding to a given value of SNR_interval can be obtained by running galprop and noting the value printed on output. Roughly 1.0 years corresponds to 3 SNR/century.

The time in years for which an SNR remains a “live” source of CR.

Allows for dispersion in the electrons source spectral index. This parameter gives the Gaussian sigma of the index around the values specified in electron_g1,2. A value 0.00 produces no dispersion.

Allows for dispersion in the nuclei source spectral index. This parameter gives the Gaussian sigma of the index around the value specified in nuc_g1,2. A value 0.00 produces no dispersion.

In the case of dispersion in the electron source index, this parameter defines the rigidity about which the spectrum pivots.

In the case of dispersion in the nucleon source index, this parameter defines the rigidity about which the spectrum pivots.

Choice of HI, CO surveys. v42.2 had 8 rings, v50 includes also improved surveys with 9 rings. New in v50. not used in v54, replace by input files.

Kinetic energy for normalization of proton flux in MeV.
proton flux at \( R = R_\odot = 8.5 \text{ kpc}, z = 0 \), at proton\(_{\text{norm}}\)Ekin in \( \text{cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} \text{ MeV}^{-1} \).

Unless proton\(_{\text{norm}}\)type \( \neq 1 \), see below.

**proton\(_{\text{norm}}\)type = 1** type of primary protons and nuclei normalization

*new parameter in r603, not yet implemented in v54 or v55.* 1 = normalize at solar position as usual in GALPROP. This is the default if this parameter is absent. 0 = no normalization at all (uses arbitrary units for primary source function), 2 = normalize to total proton injection luminosity in particles s\(^{-1}\), 3 = normalize to total proton injection luminosity in erg s\(^{-1}\). The luminosity is evaluated over the whole Galaxy volume. The value of the injection luminosity is specified via proton\(_{\text{norm}}\)flux; typical values \( 10^{44} \) particles s\(^{-1}\), \( 10^{41} \) erg s\(^{-1}\). Although not yet implemented in v54, it is straightforward to obtain the required results since the total luminosity of each species is output to the screen during the GALPROP run. An example (using parameter file galdef\(_{54}\)reltest01):

```
=====================================================
CR proton luminosity=3.06412e+41 erg s^-1
=====================================================
.....
=====================================================
CR primary electron luminosity=1.38217e+39 erg s^-1
=====================================================```

This can be used to re-normalize the CR to any required global luminosity. The calculation is done in the routine cr\_luminosity.cc by integration of the CR source function over the Galaxy and energy.

**electron\(_{\text{norm}}\)Ekin = 3.45e4** electron kinetic energy for normalization (MeV)

kinetic energy for normalization of electron flux, in MeV.

**electron\(_{\text{norm}}\)flux = 4.0e-10** flux of electrons at normalization energy (cm\(^{-2}\) sr\(^{-1}\) s\(^{-1}\) MeV\(^{-1}\))

electron flux at \( R = R_\odot = 8.5 \text{ kpc}, z = 0 \), at electron\(_{\text{norm}}\)Ekin, in cm\(^{-2}\) sr\(^{-1}\) s\(^{-1}\) MeV\(^{-1}\).

Unless electron\(_{\text{norm}}\)type \( \neq 1 \), see below.

**electron\(_{\text{norm}}\)Ekin = 3.45e4** positron kinetic energy for normalization (MeV)

kinetic energy for normalization of positron flux, in MeV.

**electron\(_{\text{norm}}\)flux = 4.0e-10** flux of positrons at normalization energy (cm\(^{-2}\) sr\(^{-1}\) s\(^{-1}\) MeV\(^{-1}\))

positron flux at \( R = R_\odot = 8.5 \text{ kpc}, z = 0 \), at positron\(_{\text{norm}}\)Ekin, in cm\(^{-2}\) sr\(^{-1}\) s\(^{-1}\) MeV\(^{-1}\).

Unless positron\(_{\text{norm}}\)type \( \neq 1 \), see below.

**electron\(_{\text{norm}}\)type = 1** type of primary electrons normalization

*new parameter in r603, implemented and used in v55, not in v54.* 1 = normalize at solar position as usual in GALPROP. This is the default if this parameter is absent. 0 = no normalization at all (uses arbitrary units for primary source function), 2 = normalize to total electron injection luminosity in particles s\(^{-1}\), 3 = normalize to total electron injection luminosity in erg s\(^{-1}\). The luminosity is evaluated over the whole Galaxy volume. The value of the injection luminosity is specified via electron\(_{\text{norm}}\)flux; typical values \( 10^{42} \) particles s\(^{-1}\), \( 10^{39} \) erg s\(^{-1}\).

NB See proton\(_{\text{norm}}\)type for more information on using total luminosity.

**positron\(_{\text{norm}}\)type = 1** type of primary positrons normalization
Same principle as for primary electrons above. (NB not used in v54).

Normally, the flux of CRs is normalized post-propagation to be equal to proton\_norm\_flux and electron\_norm\_flux at the energy proton\_norm\_Ekin and electron\_norm\_Ekin for nuclei and electrons, respectively. In special cases it may be desired to have absolute normalization of the CR source function. This can be achieved by setting proton\_norm\_flux and electron\_norm\_flux to 0 and using source\_norm and electron\_source\_norm instead for protons and electrons, respectively (otherwise these two parameters are not used). The exact units of these variables depend on the chosen source distribution. The value of these parameters for a given proton\_norm\_flux and electron\_norm\_flux are given in the full nuclei output from GALPROP. The abundances of other nuclei scale relative to protons via the source abundances as usual.

\texttt{source\_norm} = 1.0e-10 \hspace{1cm} \text{absolute normalization for proton CR source function} \\
\hspace{1cm} \text{(only if proton\_norm\_flux = 0)}

\texttt{electron\_source\_norm} = 1.0e-10 \hspace{1cm} \text{absolute normalization for electron CR source function} \\
\hspace{1cm} \text{(only if electron\_norm\_flux = 0)}

\texttt{positron\_source\_norm} = 1.0e-10 \hspace{1cm} \text{absolute normalization for positron CR source function} \\
\hspace{1cm} \text{(only if positron\_norm\_flux = 0)}

\texttt{max\_Z} = 28 \hspace{1cm} \text{maximum number of nuclei Z listed}

Specifies how many parameters use\_Z\_\dots follow.

\texttt{use\_Z\_1} = 1

Flag to specify that nuclei with \(Z = 1\) are to be processed.

\texttt{use\_Z\_2} = 1

Flag to specify that nuclei with \(Z = 2\) are to be processed, and so on:

\texttt{use\_Z\_3} = 1
\texttt{use\_Z\_4} = 1
\texttt{use\_Z\_5} = 1
\texttt{use\_Z\_6} = 1
\texttt{use\_Z\_7} = 1
\texttt{use\_Z\_8} = 1
\texttt{use\_Z\_9} = 1
\texttt{use\_Z\_10} = 1
\texttt{use\_Z\_11} = 1
\texttt{use\_Z\_12} = 1
\texttt{use\_Z\_13} = 1
\texttt{use\_Z\_14} = 1
\texttt{use\_Z\_15} = 1
\texttt{use\_Z\_16} = 1
\texttt{use\_Z\_17} = 1
\texttt{use\_Z\_18} = 1
\texttt{use\_Z\_19} = 1
\texttt{use\_Z\_20} = 1
\texttt{use\_Z\_21} = 1
\texttt{use\_Z\_22} = 1
\texttt{use\_Z\_23} = 1
\texttt{use\_Z\_24} = 1
\texttt{use\_Z\_25} = 1
\texttt{use\_Z\_26} = 1
\texttt{use\_Z\_27} = 1
use_Z_28 = 1
use_Z_29 = 0
use_Z_30 = 0

The following parameters give the primary source isotopic abundances. The values are relative, the final CR fluxes are normalized so that the proton flux is as specified by $\text{proton norm flux}$. Hence the user is free to use abundances relative to any species. The abundances are assumed to be valid at a kinetic energy per nucleon equal to $\text{proton norm Ekin}$. The example abundances give here have been described in SM2001 (COSPAR 2001).

iso_abundance_01_001 = 1.430e6 $^1\text{H}$ Source ELEM.abund.: Meyer,Drury,Ellison 1998, SSRv 86,179 abundance of $Z = 1 A = 1$.

iso_abundance_02_004 = 1.350e5 $^4\text{He}$ was 0.069e6 // Solar system relative isotope abund.: abundance of $Z = 2 A = 4$, and so on:

iso_abundance_03_006 = 0. $^3\text{Li}$
iso_abundance_04_009 = 0. $^7\text{Be}$
iso_abundance_05_010 = 0. $^8\text{B}$
iso_abundance_06_012 = 2548. (2573) $^12\text{C} = 3000$ 12–0.955
iso_abundance_06_013 = 25. $^13\text{N} = 137$.
iso_abundance_07_014 = 175. $^14\text{O} = 3673.$
iso_abundance_08_016 = 0. $^16\text{F}$
iso_abundance_09_019 = 0. $^17\text{F}$
iso_abundance_10_020 = 310. (403) $^20\text{Ne} = ??$ 20–0.88
iso_abundance_10_022 = 22/20 =0.3 in source (DuVernois et al 1996) 22–0.12
iso_abundance_11_023 = 21. $^22\text{Na}$
iso_abundance_12_024 = 626. $^24\text{Mg} = 734$ *1.1 24–0.78
iso_abundance_12_025 = 80.7 $^25\text{Mg}$
iso_abundance_12_026 = 100.5 $^26\text{Fe}$
iso_abundance_13_027 = 45. $^26\text{Al}$
iso_abundance_14_028 = 680. (760) $^28\text{Si} = 707$ Source ab.: Hesse et a. 1996 28/28–1.00
iso_abundance_14_029 = 60. $^29\text{Si}$
iso_abundance_14_030 = 20. $^30\text{Si}$
iso_abundance_15_031 = 8. $^31\text{P} = 4.92$
iso_abundance_16_032 = 97.0 (105) $^32\text{S} = 92.4$ Source ab.: Thayer 1997 32/32–1.00
iso_abundance_16_033 = 2.1 $^33\text{Ar}$
iso_abundance_16_034 = 6.3 $^34\text{Ar}$
iso_abundance_17_035 = 0. $^35\text{Cl}$
iso_abundance_17_037 = 3.2 $^36\text{Ar}$
iso_abundance_18_036 = 20.0 $^38\text{Ar} = 15.2$
iso_abundance_18_038 = 4.0 -introduced by imos
iso_abundance_19_039 = 0. $^40\text{K} -\text{introduced by imos}$
iso_abundance_20_040 = 39.0 $^40\text{Ca} = 42$.
iso_abundance_20_041 = 0.8 $^40\text{Ca}$
iso_abundance_21_045 = 0. $^41\text{Sc}$
iso_abundance_22_046 = 0. $^41\text{Ti} -\text{introduced by imos}$
iso_abundance_22_047 = 1.9 $^42\text{Ti}$
iso_abundance_22_048 = 7.3 $^44\text{Ti}$
iso_abundance_22_049 = 0. $^46\text{Ti}$
iso_abundance_22_050 = 1.4 $^48\text{Ti}$
iso_abundance_23_051 = 0. $^50\text{Ti}$
iso_abundance_24_050 = 1.4 $^50\text{Cr} -\text{introduced by imos}$
iso_abundance_24_051 = 0. $^52\text{Cr}$
iso_abundance_24_052 = 7.7
iso_abundance_24_053 = 3.4
iso_abundance_24_054 = 1.0
iso_abundance_25_053 = 2.2 Mn -introduced by imos
iso_abundance_26_054 = 72.1 (882) Fe =713 Source abund.: Connell & Simpson 1997 54/56= 9.3%
iso_abundance_26_055 = 6.8 55/56= 1.6%
iso_abundance_26_056 = 12.1 56/56= 100%
iso_abundance_26_057 = 28.8 57/56= 3.7%
iso_abundance_26_058 = 1.41 58/56= 0.18%
iso_abundance_27_059 = 0.4 Co =1.28
iso_abundance_28_058 = 30.61 (44.3) Ni =40.2 Source ab.: Connell & Simpson 1997 58/58= 100%
iso_abundance_28_059 = 0.81 59/58= 2.6% =0.69
iso_abundance_28_060 = 13.17 60/58=43.2%
iso_abundance_28_061 = 0.35 61/58 <1.2%
iso_abundance_28_062 = 1.62 62.58= 5.4%
total_cross_section = 2 =0 -Letaw83; =1 -WA96 Z>5 & BP01 Z<6; =2 -BP01 (2-best)

Options for determining total fragmentation cross sections. BP= code from V.S.Barashenkov,A.Polanski and
this is the preferred option.
cross_section_option = 012 100*i+j i=1: use Heinbach-Simon C,0->B j=kopt j=11=Webber, 21=ST

Options for determining cross sections. Details on kopt from nuc_package.cc:

//3 kopt 0 - uses best algorith described in comments belo w (not recommended);
//3 =1 - forces to use Webber'93 code (no renormalization etc.);
//3 =2 - forces to use TS00 code (no renormalization etc.);
//3 =3 - forces to use a const cross section fitted to the data.
//3 =10- forces to use Webber'93 code (renormalized if data exists);
//3 =11- forces to use cross section fit if exists (otherwise equiv. 10);
//3 =12- forces to use a numerical table if exists (otherwise equiv. 11);
//3 =20- forces to use TS00 code (renormalized if data exists).
//3 =21- forces to use cross section fit if exists (otherwise equiv. 20).
//3 =22- forces to use a numerical table if exists (otherwise equiv. 21);
//3 The best values recommended are kopt = 12, 22 (12 is preferrable).
//3 uses file_no[1] and file_no[3] as indicators of the data array and fit params.

Example: For kopt=22, the code will first try to find the cross section of a given channel in the tables in
eval_iso_cs.dat. If it fails, it will fall back to kopt=21 and look for a fit in p_cs_fits.dat. If no fit is found,
kopt=20 will be used, and the cross section will be calculated using the TS00 formula, re-normalized to fit the
data in isotope_cs.dat.

The file eval_iso_cs.dat contains calculated and measured cross sections as data tables suitable for inter-
polation; p_cs_fits.dat contains parameters of fits to measured cross sections and isotope_cs.dat contains
individual experimental data points. References to data sources are included in the comments within these data
files.

primary_electrons = 0
Flag to indicate whether to propagate primary electrons.

primary_positrons = 0
Flag to indicate whether to propagate primary positrons. From r2242.

secondary_positrons = 0
Flag to indicate whether to propagate secondary positrons.

```plaintext
secondary_electrons = 0
```

Flag to indicate whether to propagate secondary positrons.

```plaintext
secondary_antiproton = 2 1=uses nuclear scaling; 2=uses nuclear factors by Simon et al 1998
```

Flag to indicate whether to propagate secondary antiprotons, with 2 options.

```plaintext
tertiary_antiproton = 1
```

Flag to indicate whether to propagate tertiary antiprotons.

```plaintext
secondary_protons = 1
```

Flag to indicate whether to propagate secondary protons.

```plaintext
gamma_rays = 0 1=compute gamma rays 2=also for HI,CO rings
```

Flag to indicate whether to compute diffuse Galactic gamma-ray skymaps and emissivities. Requires computation of protons, Helium and electrons. If option 1 is chosen, only the line-of-sight integrated skymaps are produced, for each component bremsstrahlung, pion-decay and inverse Compton.

```
With option 2 (New in v50) the skymaps of bremsstrahlung and pion-decay for each HI, CO ring are output in addition. This produces 4 extra output datasets: brems+HI,bremss+H2,pion+HI,pion+H2. This is useful for studies of CR distribution and Xco.
```

```plaintext
pi0_decay = 3 1= old formalism 2=Blattnig et al. 3=Kamae et al. 4=Huang etal. etc
```

Options for formalism used to compute pion-decay gamma rays, secondary positrons and electrons. For option 3, Kamae (2006) is only used for gamma rays, and only for p-p interactions, otherwise old method is still used.

From r1265: 4 = use Huang et al. 2007 (Astroparticle Physics, 27, 429) matrices. These use ISM composition so the ISM He fraction (parameter He/H ratio) is not used in this case, but the composition is consistent (He/H 10% by number). For reference, but not recommended.

From r2271: other models available. To see the current available models, type

```plaintext
grep hadronic source/gen_pi0_decay_emiss.cc
giving e.g.
```

```plaintext
gen_pi0_decay_emiss.cc: if(galdef.pi0_decay== 4) hadronic_model= "Huang";
gen_pi0_decay_emiss.cc: if(galdef.pi0_decay== 5) hadronic_model= "Dermer";
gen_pi0_decay_emiss.cc: if(galdef.pi0_decay== 6) hadronic_model= "Kamae";
gen_pi0_decay_emiss.cc: if(galdef.pi0_decay== 7) hadronic_model= "Kachelriess";
gen_pi0_decay_emiss.cc: if(galdef.pi0_decay== 8) hadronic_model= "Dermer_Kachelriess";
gen_pi0_decay_emiss.cc: if(galdef.pi0_decay== 9) hadronic_model= "Kamae_Kachelriess";
gen_pi0_decay_emiss.cc: if(galdef.pi0_decay==10) hadronic_model= "Kachelriess2013";
gen_pi0_decay_emiss.cc: if(galdef.pi0_decay==11) hadronic_model= "Dermer_Kachelriess2013";
gen_pi0_decay_emiss.cc: if(galdef.pi0_decay==12) hadronic_model= "Dermer_Kachelriess2013_heavy"
```

The Dermer model is from [(8)]. Kachelriess, Kachelriess2013 are the QGSJET models from [(17)] and subsequent developments. Combinations of names (e.g. Dermer_Kachelriess) mean that the models are switched or interpolated going from low to high nucleon energies, typically at 30 GeV/nucleon. Dermer_Kachelriess_heavy has a factor allowing for projectiles or targets heavier than Helium, for CR and ISM composition. More details will follow. See routine ProductionMatrices.cc for the new models.

---

6We thank Chuck Dermer for providing his routine and collaboration.
7We thank Michael Kachelriess and Sergey Ostapchenko for providing their routines and collaboration.
IC_anisotropic = 0  1=compute anisotropic IC
Flag to indicate whether to compute anisotropic inverse Compton scattering according to MS2000. NB: takes lots of CPU, best in parallel mode.

bremss = 1  1=compute bremsstrahlung
from r1265: 2 = use C++ version instead of fortran. This is a translation from the fortran version, but also with its own energy integration. Gives (almost) identical results. Will be used for future developments of the bremsstrahlung physics treatment.

synchrotron = 2  1,2,3 = compute synchrotron skymaps
Flag to indicate whether to compute synchrotron skymaps. Also indicates which B-field is to be used to compute synchrotron energy losses of electrons and positrons, independent of whether synchrotron skymaps are computed. 0= old B-field format (deprecated) for synchrotron losses, but no synchrotron skymaps. 1= old B-field format (deprecated), 2 = use B_field_name, B_field_parameters. For more details see those parameters. 3 = as 2 but compute Stokes vectors in addition (under development). Synchrotron skymaps require primary_electrons =1 and/or secondary_electrons =1 and/or secondary_positrons =1.

free_free_absorption = 1  0=no free-free absorption or emission, 1= free-free absorption of synchrotron 2=replace synchrotron total with free-free emission
Controls whether to apply free-free absorption of synchrotron and free-free emission skymaps. Parameters nHII_Te and nHII_clumping_factor control the formulae used. Default = 1. 0 = no free-free emission or absorption. 1 = free-free emission and absorption.

Setting this parameter to 2 computes free-free emission and outputs the radio skymaps instead of total synchrotron (HEALPix only) in synchrotron_healpix_GALDEF_JD.

At present no option to have free-free emission without absorption is implemented, but it would be useful (at present option 0 produces a free-free map equal to zero).

**DM options**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>comment</td>
<td>= the dark matter (DM) switches and user-defined parameters</td>
</tr>
<tr>
<td>DM_positrons</td>
<td>= 0  1=compute DM positrons</td>
</tr>
<tr>
<td>DM_electrons</td>
<td>= 0  1=compute DM electrons</td>
</tr>
<tr>
<td>DM_antiprotons</td>
<td>= 0  1=compute DM antiprotons</td>
</tr>
<tr>
<td>DM_gammas</td>
<td>= 0  1=compute DM gammas</td>
</tr>
<tr>
<td>DM_double0</td>
<td>= 2.8  core radius, kpc</td>
</tr>
<tr>
<td>DM_double1</td>
<td>= 0.43  local DM mass density, GeV cm^-3</td>
</tr>
<tr>
<td>DM_double2</td>
<td>= 80.  neutralino mass, GeV</td>
</tr>
<tr>
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<td>= 40.  positron width distribution, GeV</td>
</tr>
<tr>
<td>DM_double4</td>
<td>= 40.  positron branching</td>
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<td>DM_double5</td>
<td>= 40.  electron width distribution, GeV</td>
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<td>= 30.  electron branching</td>
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<td>= 50.  pbar width distribution, GeV</td>
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<td>= 40.  pbar branching</td>
</tr>
<tr>
<td>DM_double9</td>
<td>= 3.e-25 &lt;cross_sec*V&gt;-thermally overaged, cm3 s^-1</td>
</tr>
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<td>= 1  isothermal profile</td>
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<td>DM_int3</td>
<td>= 1</td>
</tr>
<tr>
<td>DM_int4</td>
<td>= 1</td>
</tr>
</tbody>
</table>
5 Description of Basic Routines

This refers mainly to v50 and needs updating for v54.

5.1 galdef.read

Reads the galdef file and assigns initial parameter values.
5 DESCRIPTION OF BASIC ROUTINES

5.2 read_nucdata & set_sigma_cc

5.3 create_galaxy

Creates spatial grid and defines distributions of gas (H\textsubscript{2}, HI, HII — nH\textsubscript{2}, nH\textsubscript{2_av}, nHI, nHI_av, nHII, nHII_av), magnetic field (B-field_model), reads the interstellar radiation field from a file (read_isrf) and defines the ISRF energy density (gen_isrf_energy_density), creates supernova remnants (create_SNR), and defines the skymap parameters for gamma rays and synchrotron emission.

5.3.1 nH\textsubscript{2}, nH\textsubscript{2_av}, nHI, nHI_av, nHII, nHII_av, nH_av

The routines nH\textsubscript{2}, nHI define the gas number densities in the form of a table, which gives the gas densities in the Galactic plane. The extension of the gas distribution to an arbitrary height above the plane is made using some analytical approximations. The routine nHII uses only analytical approximations.

The routines nH\textsubscript{2_av}, nHI_av, nHII_av provide a calculation of an average gas density over a step in the z-grid using a smaller step. These are now replaced by a generic routine nH_av which takes a gas densitz routine as input argument.

nH\textsubscript{av}: a bug was introduced at trunk r878, which caused too high gas densities, both HI and H\textsubscript{2}, hence wrong B/C, ionization losses etc. It was corrected in r2192. The bug is not present in the public version branch.

nH\textsubscript{2}: The routine calculates H\textsubscript{2} number density in mol cm\textsuperscript{-3}

\[ n_{H_2}(R,Z) = \epsilon_0(R) X e^{-\ln 2 (Z-z_0)^2/z_h^2} \text{ cm}^{-2} \text{ kpc}^{-1}, \]

where $\epsilon_0(R)$ (K km s\textsuperscript{-1}) - CO volume emissivity, and $z_0(R)$, $z_h(R)$ - the height scale and width are taken from Bronfman et al. \textsuperscript{[4]}, Table 3/Cols 4,7,10, and $X = n_{H_2}/n_{CO} = 1.9 \times 10^{20}$ is the conversion factor taken from Strong & Mattox \textsuperscript{[40]}.

nH\textsubscript{I}: The routine calculates HI number density in atom cm\textsuperscript{-3}. The relative distribution is from Gordon & Burton \textsuperscript{[14]}, Table 1, but renormalized to agree with Dickey & Lockman \textsuperscript{[9]}, where on page 252 they give their best model for the z-distribution and state the total integral perpendicular to the plane = $6.2 \times 10^{20}$ cm\textsuperscript{-2}:

\[ n_{H_1}(R,Z) = Y(R) f(Z), \]

where $Y(R)$ is the renormalized distribution by Gordon & Burton (R < 16 kpc), and $f(Z)$ is the z-dependence which is calculated following Dickey & Lockman for R < 8 kpc, following Cox et al. \textsuperscript{[6]} for R > 10 kpc, and interpolated in between. For R > 16 kpc the exponential tail is assumed with scale high 3 kpc.

nH\textsubscript{II}: The ionized component currently calculated using a cylindrically symmetrical model based on NE2001 by Cordes et al. \textsuperscript{[3]}, Eq.(6) and Table 1. More sophisticated 3D model for the inner Galaxy is developed by Taylor & Cordes \textsuperscript{[54]} and outer Galaxy by Lazio & Cordes \textsuperscript{[19]}. Galactic center region has been considered by Lazio & Cordes \textsuperscript{[20]}. These latter models can be used in future for 3D calculations. A revised scale-height using more pulsar DMs was determined by Gaensler et al. (2008) which has been implemented as option to replace this component in NE2001. more details required.

5.3.2 read_isrf

Reads 3D interstellar radiation field (ISRF) from a file, currently isrf_interp_04_000015. The units of the ISRF stored is $[\lambda U_\lambda] = \mu \text{ eV cm}^{-3} \mu^{-1}$. In the routine read_isrf the units are changed to $[\nu U_\nu] = \text{Hz eV cm}^{-3} \text{Hz}^{-1}$.

5.3.3 gen_isrf_energy_density

5.4 create_gcr

5.5 propagate_particles

The routine organizes a loop over the cosmic ray species: calls a routine to create transport arrays, generates secondary source, calls propel to propagate particles and finally normalizes nuclei and electrons.
5 DESCRIPTION OF BASIC ROUTINES

5.5.1 create_transport_arrays

Generates arrays for use by propel for the given species: assigns primary source function, diffusion coefficient, fragmentation rate, momentum loss rate, decay rate. Normalizes injection source spectra according to source abundances, interpreting these as relative injection rate in (momentum per nucleon)$^{-1}$ at the same $E_{\text{kin}}$ (kinetic energy per nucleon) or at the same momentum per nucleon $p'$ (not the usual $p$ which is momentum per nucleon).

Normalizing of the nucleon primary source function: The source function is assumed to be a power-law in rigidity $\rho$ with reference value at $\rho_{\text{ref}}$ (same for all nuclei)

$$q_A(\rho) = c_A \left( \frac{\rho}{\rho_{\text{ref}}} \right)^{-\gamma},$$

and the source abundance is defined as the ratio

$$X = \frac{Q_A(p')}{Q_1(p')} = \frac{A q_A(p_A)}{q_1(p_1)}$$

where $Q_A$ refers to (momentum per nucleon)$^{-1}$, $q_A$ refers to (momentum per nucleus)$^{-1}$ and where $q_1$ refers to protons. Note that $q_A$ is the quantity used by GALPROP in eq (1).

Since $\rho = \frac{E_{\text{kin}}}{Z}$, $\rho/\rho_{\text{ref}} = \frac{E_{\text{kin}}}{Z}(\rho_{\text{ref}}/\rho_{\text{ref}})$ and $p_A = A p_1$,

$$X = \frac{A c_A}{c_1} \left( \frac{p_A}{Z \rho_{\text{ref}}} \right)^{-\gamma} \left( \frac{p_1}{\rho_{\text{ref}}} \right)^{\gamma} = \frac{c_A A^{1-\gamma} Z^{\gamma}}{c_1}.$$  

This derivation assumes a power-law in rigidity, that the reference rigidity is the same for all nuclei, and that $\gamma$ is the same for all nuclei in the part of the spectrum containing $E_{\text{kin}}$ where the normalization is defined. Further, in the current implementation it is assumed that $\gamma$ is given by the parameter nucl$\gamma$2, i.e. the index above the rigidity break. These restrictions are not necessary and a more general approach will be adopted in future, using eq 3 directly.

The global normalization to the absolute proton flux is applied at the end of the source function generation, in nuclei_normalize. A reference list of abundances relative to protons can be found in Meyer, Drury, & Ellison [22], Table 1 and is used as the baseline set in the standard galdef files.

Assigning fragmentation rate

The fragmentation rate is assigned using the total cross section calculation on proton target (in nuclon_cs_cc), cross section on He target is calculated using phenomenological scaling (He_to_HCS).

In case of protons “fragmentation” means inelastic scattering in which particle loses a substantial part of its energy. In case of antiprotons “fragmentation” means inelastic scattering plus annihilation. Finally, the fragmentation rate is calculated in every spatial and energy point as:

$$F = \beta c (n_{H_2} + n_{H_1} + n_{HII}) \left( \sigma_p + \sigma_{He} \frac{n_{He}}{n_H} \right), \ s^{-1},$$

where $n_H = n_{H_2} + n_{H_1} + n_{HII}$.

Energy losses

The energy losses for nucleons, ionization and Coulomb losses, are calculated in nuclon_loss. Those for electrons, ionization, Coulomb losses, bremsstrahlung, synchrotron, and Compton losses (Thompson scattering), are calculated in electron_loss. The routine e KH loss allows to calculate Klein-Nishina energy losses.

Klein-Nishina energy losses are calculated using ISRF calculated separately and read by routine read_isrf. The ISRF units are $[\nu U_{\nu}] = \text{Hz eV cm}^{-3} \text{Hz}^{-1}$. The energy losses in every spacial point can be calculated as

$$\frac{dp}{dt} = \int d\nu \frac{U_{\nu}}{h \nu} \frac{dp}{dt}(\nu, \gamma) = \int d(\log \nu) \frac{\nu U_{\nu}}{h \nu} \frac{dp}{dt}(\nu, \gamma), \ eV \ s^{-1},$$

where $\gamma$ is the electron Lorentz-factor, and $dp(\nu, \gamma)/dt$ is calculated in e_loss_compton.
5 DESCRIPTION OF BASIC ROUTINES

5.5.2 gen_secondary_source

Combines calculation of all the secondary source functions.

**gen_secondary_positron_source**: secondary $e^+$ and $e^−$

The routine **PPMESON** written in **FORTRAN-77** is designed to calculate the secondary positron (or sec. electron) production spectrum vs. energy (barn/GeV). Positron/electron energy and total nucleus momentum are used as input parameters as well as beam and target nuclei atomic numbers.

The secondary positron/electron source function as used in **galprop** is defined as follows (cm⁻² sr⁻¹ s⁻¹ MeV⁻¹):

$$q_e(E_{tot}) = \frac{c}{4\pi} \frac{dn(p)}{dt} = \frac{c}{4\pi} \sum_{i=H,He} n_i \sum_j \int dp' \beta n_j(p') \frac{d\sigma_{ij}(E_{tot},p')}{dE_{tot}},$$  \hspace{1cm} (12)

where $n_i$ is the gas density, $d\sigma_{ij}(E_{tot},p')/dE_{tot}$ is the production cross section, $n_j(p')$ is the CR species density, and $p'$ is the total momentum of a nucleus. Substitution of $dp'$ with $d(\log E'_{kin})$ gives:

$$q_e(E_{tot}) = \frac{c}{4\pi} A \Delta(\log E'_{kin}) \sum_{i=H,He} n_i \sum_j E'_{kin} \sum_{j} n_j(E'_{kin}) \frac{d\sigma_{ij}(E_{tot},E'_{kin})}{dE_{tot}},$$  \hspace{1cm} (13)

where we used $dp' = \frac{1}{4} AE'_{kin} d(\log E'_{kin})$.

Since positron/electron is assumed massless $E_{tot} = p$. The units should be transferred to cm²/MeV, a factor applied is $10^{-27}$.

**gen_secondary_antiprotons_source**

The routine **ANTIPROTON** written in **FORTRAN-77** is designed to calculate the antiproton (+antineutron) production spectrum vs. momentum (barn/GeV). Antiproton momentum and nucleus momentum per nucleon are used as input parameters as well as beam and target nuclei atomic numbers.

The antiproton source function as used in **galprop** is defined as follows (cm⁻² sr⁻¹ s⁻² MeV⁻¹):

$$q_p(p) = \frac{c}{4\pi} \frac{dn(p)}{dt} = \frac{c}{4\pi} \sum_{i=H,He} n_i \sum_j \int dp' \beta n_j(p') \frac{d\sigma_{ij}(p,p')}{dp},$$  \hspace{1cm} (14)

where $n_i$ is the gas density, $d\sigma_{ij}(p,p')/dp$ is the production cross section, $n_j(p')$ is the CR species density, and $p'$ is the total momentum of a nucleus. Substitution of $dp'$ with $d(\log E'_{kin})$ gives:

$$q_p(p) = \frac{c}{4\pi} A \Delta(\log E'_{kin}) \sum_{i=H,He} n_i \sum_j E'_{kin} \sum_{j} n_j(E'_{kin}) \frac{d\sigma_{ij}(p,E'_{kin})}{dp},$$  \hspace{1cm} (15)

where we used $dp' = \frac{1}{4} AE'_{kin} d(\log E'_{kin})$.

The units should be transferred to cm²/MeV, a factor applied is $10^{-27}$.

**gen_secondary_protons_source** and **gen_tertiary_antiprotons_source**

**Gen_secondary_protons_source** and **gen_tertiary_antiprotons_source** are made very similar using the same formalism. The secondary protons and tertiary antiprotons are essentially those which survived after inelastic scattering with protons and He nuclei of the interstellar gas. It is convenient and correct to consider them as additional populations of particles.

The tertiary $p$’s are calculated using

$$q_{tert. p}(p) = c \Delta(\log E'_{kin}) \sum_{i=H,He} n_i \sum_j E'_{kin} n_{sec.p}(E'_{kin}) \frac{d\sigma_{ij}(p,E'_{kin})}{dp},$$  \hspace{1cm} (16)
where \( d\sigma_i(p, E_{\text{kin}}')/dp \) is the “production cross section” of tertiary \( \bar{p} \)'s. It can be further expanded as

\[
\frac{d\sigma_i(p, E_{\text{kin}}')}{dp} = \sigma_{i}^{\text{non}}(E_{\text{kin}}') \beta \frac{dN}{dE_{\text{kin}}}, \tag{17}
\]

where \( \sigma_{i}^{\text{non}}(E_{\text{kin}}') \) is the total non-annihilation inelastic cross section, and \( dN/dE_{\text{kin}} \) is the distribution of \( \bar{p} \)'s after scattering. Using an approximation given by Tan & Ng (1983):

\[
\frac{dN(E_{\text{kin}}', E_{\text{kin}})}{dE_{\text{kin}}} = \frac{1}{E_{\text{kin}}}. \tag{18}
\]

The final expression can be obtained by combining eqs. (16)-(18).

**secondary source for nuclei: decayed cross sections**

The formalism is similar to the above, except that the cross section of the disintegration process is convenient to write in energy or momentum per nucleon:

\[
\frac{d\sigma_{ij}(p, p')}{dp} = \sigma(p') \delta \left( p - \frac{A_{\text{sec}}}{A_{\text{prim}}} p' \right), \tag{19}
\]

where \( A_{\text{prim}}, A_{\text{sec}} \) are the atomic numbers of primary and secondary nucleus, correspondingly. Integrating over \( dp' \) then yield a factor \( A_{\text{prim}}/A_{\text{sec}} \):

\[
q_{\text{sec}}(p) = \beta c \sum_{i=H,He} n_i \sum_{j} A_j \frac{A_{\text{sec}}}{A_{\text{prim}}} \sigma \left( \frac{A_j p}{A_{\text{sec}}} \right) n_j \left( \frac{A_j p}{A_{\text{sec}}} \right). \tag{20}
\]

The decayed cross sections routine calculates the cross section \( \sigma \) of a given channel taking into account short-lived intermediate states and nuclear reaction network.

**pp fusion source for deuterium: gen_secondary_deuterium_fusion_source**

The fusion reaction \( p + p \rightarrow d + \pi^+ \) is a significant source of secondary deuterium\(^8\), in addition to the fragmentation of He etc. It has not been included previously in \textit{galprop} but is now implemented (from r2478). The implementation is based on Meyer, J.P., \textit{A&A Supp} 7, 417 (1972) and Coste, B., et al., \textit{A&A} 539, A88 (2012).

The cross-section for the reaction has a threshold at a proton kinetic energy 300 MeV, extends to 3 GeV, and peaks at 600 MeV with a maximum value of about 3 mb. It produces deuterons with kinetic energy mainly between about 70 and 500 MeV/nucleon. Despite the small width and cross-section, the fact that CR protons are very abundant at these energies means that it is comparable or exceeds fragmentation as a source of deuterium at low energies.

The computation of the secondary source is similar to that for antiprotons above. The total cross-section is taken from Meyer (1972) Fig 5, using a digitized version of the curve reproduced in Coste et al. (2012), Fig B3. The treatment of the kinematics follows Meyer (1972), section 3.1. A complete description of the method will be added in future.

The fusion source is invoked by \texttt{gen_secondary_source.cc} and is added to the fragmentation source previously computed.

\(^8\)We thank Nicolas Picot-Clemente (U. Maryland) for pointing out the importance of the process and for help in implementation and testing.
5 DESCRIPTION OF BASIC ROUTINES

5.5.3 propel

The basic routine for calculation of the finite-differencing coefficients and numerical solution of the propagation equation.

Numerical solution of propagation equation

Recall the propagation equation:

\[
\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \nabla \cdot \left( D_{xx} \nabla \psi - \vec{V} \psi \right) + \frac{\partial}{\partial p} \frac{p^2 D_{pp}}{2} \left( \frac{1}{p} \frac{\partial \psi}{\partial p} \right) - \frac{\partial}{\partial p} \left[ \frac{\partial \psi}{\partial p} - \frac{p}{3} (\nabla \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi , \tag{21}
\]

Full explicit method. The diffusion, reacceleration, convection and loss terms in eq. (1) can all be finite-differenced for each dimension \((R, z, p)\) or \((x, y, z, p)\) in the form

\[
\frac{\partial \psi_i}{\partial t} = \frac{\psi_i^{t+\Delta t} - \psi_t}{\Delta t} = \frac{\alpha_1 \psi_{i-1}^{t+\Delta t} - \alpha_2 \psi_i^{t+\Delta t} + \alpha_3 \psi_{i+1}^{t+\Delta t}}{\Delta t} + q_i ,
\]

where all terms are functions of \((R, z, p)\) or \((x, y, z, p)\).

This is the fully time-explicit method \[33\] where the updating scheme is

\[
\psi_i^{t+\Delta t} = \psi_i^t + \alpha_1 \psi_{i-1}^t - \alpha_2 \psi_i^t + \alpha_3 \psi_{i+1}^t + q_i \Delta t . \tag{23}
\]

which generalizes simply to any number of dimensions since all the quantities are known from the current step. The explicit method has been implemented at r705. It is controlled by the galdet parameter solution (see parameter descriptions). It gives more accurate solutions, which tend to exact according to the \(\alpha\)lpha-based diagnostics, but are not unconditionally stable (while Crank-Nicolson is). For this reason it is only applicable for short enough timesteps. Since no solution of matrix equations is required, this method is faster than Crank-Nicolson for the same timesteps, and this compensates for the need for smaller steps.

Fully implicit method. The diffusion, reacceleration, convection and loss terms in eq. (1) can all be finite-differenced for each dimension \((R, z, p)\) or \((x, y, z, p)\) in the form

\[
\frac{\partial \psi_i}{\partial t} = \frac{\psi_i^{t+\Delta t} - \psi_t}{\Delta t} = \frac{\alpha_1 \psi_{i-1}^{t+\Delta t} - \alpha_2 \psi_i^{t+\Delta t} + \alpha_3 \psi_{i+1}^{t+\Delta t}}{\Delta t} + q_i ,
\]

where all terms are functions of \((R, z, p)\) or \((x, y, z, p)\).

This is the fully time-implicit method \[33\] where the updating scheme is

\[
\psi_i^{t+\Delta t} = \psi_i^t + \alpha_1 \psi_{i-1}^t - \alpha_2 \psi_i^t + \alpha_3 \psi_{i+1}^t + q_i \Delta t . \tag{25}
\]

This method is unconditionally stable for all \(\alpha\) and \(\Delta t\), but is only 1st-order accurate in time. The tridiagonal system of equations

\[
- \alpha_1 \psi_{i-1}^{t+\Delta t} + (1 + \alpha_2) \psi_i^{t+\Delta t} - \alpha_3 \psi_{i+1}^{t+\Delta t} = \psi_i^t + q_i \Delta t ,
\]

is solved for the \(\psi_i^{t+\Delta t}\) by the standard method \[33\]. Note that for energy losses we use ‘upwind’ differencing to enhance stability, which is possible since we have only loss terms (adiabatic energy \(\text{gain}\) is not included here).

Crank-Nicolson method. Alternatively, the propagation equation can be finite-differenced in the form

\[
\frac{\partial \psi_i}{\partial t} = \frac{\psi_i^{t+\Delta t} - \psi_t}{\Delta t} = \frac{\alpha_1 \psi_{i-1}^{t+\Delta t} - \alpha_2 \psi_i^{t+\Delta t} + \alpha_3 \psi_{i+1}^{t+\Delta t}}{2 \Delta t} + \frac{\alpha_1 \psi_{i-1}^{t+\Delta t} - \alpha_2 \psi_i^{t+\Delta t} + \alpha_3 \psi_{i+1}^{t+\Delta t}}{2 \Delta t} + q_i . \tag{27}
\]

This is the Crank-Nicolson method \[33\] where the updating scheme is

\[
\psi_i^{t+\Delta t} = \psi_i^t + \frac{\alpha_1}{2} \psi_{i-1}^{t+\Delta t} - \frac{\alpha_2}{2} \psi_i^{t+\Delta t} + \frac{\alpha_3}{2} \psi_{i+1}^{t+\Delta t} + \frac{\alpha_1}{2} \psi_{i-1}^{t+\Delta t} - \frac{\alpha_2}{2} \psi_i^{t+\Delta t} + \frac{\alpha_3}{2} \psi_{i+1}^{t+\Delta t} + q_i \Delta t . \tag{28}
\]
It thus uses a combination of implicit and explicit terms, forming the time-average of the differentials. Like the fully implicit method, this method is unconditionally stable for all $\alpha$ and $\Delta t$, but is 2nd-order accurate in time, so that larger time-steps are possible than with the 1st-order scheme.

The tridiagonal system of equations

$$-\frac{\alpha_1}{2} \psi_{i-1}^{t+\Delta t} + (1 + \frac{\alpha_2}{2}) \psi_i^{t+\Delta t} - \frac{\alpha_3}{2} \psi_{i+1}^{t+\Delta t} = \psi_i^{t} + q_i \Delta t + \frac{\alpha_1}{2} \psi_{i-1}^{t} - \frac{\alpha_2}{2} \psi_i^{t} + \frac{\alpha_3}{2} \psi_{i+1}^{t}$$

or

$$-\frac{\alpha_1}{2} \psi_{i-1}^{t+\Delta t} + (1 + \frac{\alpha_2}{2}) \psi_i^{t+\Delta t} - \frac{\alpha_3}{2} \psi_{i+1}^{t+\Delta t} = \frac{\alpha_1}{2} \psi_{i-1}^{t} + (1 - \frac{\alpha_2}{2}) \psi_i^{t} + \frac{\alpha_3}{2} \psi_{i+1}^{t} + q_i \Delta t$$

is again solved for the $\psi_i^{t+\Delta t}$ by the standard method. Note that the RHS has all known quantities from the current time-step.

GALPROP uses the Crank-Nicolson method. Our original paper [41] describes the fully implicit method, which was in fact never used.

**Multidimensional case.** The Crank-Nicolson method described above applies to a one-dimensional case; the application to 2 or 3 spatial and one momentum dimension requires a generalization. A straightforward expansion to more dimensions implies solving large matrix equations (no longer tridiagonal); instead the so-called ADI (alternating direction implicit) method is used, in which the implicit solution is applied to each dimension in turn. Each application uses just the operator for that dimension, so the tridiagonal scheme can still be used. This however is not completely valid since it solves a slightly different problem from that with the full operator; however for small enough timesteps the solution is accurate (see Section on Tests of GALPROP). Other possible strategies are given in Press (1992), which could be considered in future.

The explicit method, where the full operator can be used in each timestep without any overhead for solving matrix equations, is also useful for obtaining an accurate solution at the end of a run. Although it is not unconditionally stable, this does not matter provided the timesteps are small enough, which is in any case required for the implicit methods to maximise their accuracy. A suitable mix of explicit and implicit methods to obtain an accurate solution with minimum computing requirements, is the goal. The explicit method has been implemented at r705. It is controlled by the galdel parameter solution-method (see parameter descriptions). It gives demonstrably more accurate solutions, which tend to exact according to the $\alpha$-based diagnostics, but are not unconditionally stable (while Crank-Nicolson is). For this reason only use for short timesteps (typically 100-1000 years). Since no solution of matrix equations is required, method 2 is faster than 1 for the same timesteps, and this compensates for the need for smaller steps.

**Boundary conditions.** For 2D, three spatial boundary conditions

$$\psi(R, z_h, p) = \psi(R, -z_h, p) = \psi(R_h, z, p) = 0$$

may be imposed at each iteration. This is not physically expected, although it is a common conventional assumption. More physically plausible is free escape at the boundaries, which is not the same. This is implemented as an option at r2254. For this, it is sufficient simply to not impose the above conditions in the updating scheme, since the $\alpha_1, \alpha_3$ coefficients do not act outside the boundaries, so there is no diffusive or convective flux inwards at the boundaries. The resulting solutions then have $\psi > 0$ at the boundaries. In future more physical boundary conditions will be implemented, e.g. specifying the outward streaming velocity or the escape probability at the boundaries. No boundary conditions are imposed or required at $R = 0$ or in $p$. Grid intervals are typically $\Delta R = 1$ kpc, $\Delta z = 0.1$ kpc; for $p$ a logarithmic scale with ratio typically 1.2 is used. Although the model is symmetric around $z = 0$ the solution is generated for $-z_h < z < z_h$ since this is required for the tridiagonal system to be valid.

For 3D, the spatial boundary conditions

$$\psi(\pm x_h, y, z, p) = \psi(x, \pm y_h, z, p) = \psi(x, y, \pm z_h, p) = 0$$

may be imposed at each iteration, and from r2254 free escape is an option as for 2D. Again no boundary conditions are imposed in $p$. Grid intervals are typically $\Delta x = \Delta y = 0.5$ kpc, $\Delta z = 0.1$ kpc.
Table 1: Coefficients for the finite-differencing scheme in 2 spatial dimensions and one momentum dimension.

<table>
<thead>
<tr>
<th>Process</th>
<th>Coordinate</th>
<th>$\alpha_1/\Delta t$</th>
<th>$\alpha_2/\Delta t$</th>
<th>$\alpha_3/\Delta t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion</td>
<td>$R$</td>
<td>$D_{xx} \frac{2R_z - \Delta R}{2R_z(\Delta R)^2}$</td>
<td>$D_{xx} \frac{2R_z}{2R_z(\Delta R)^2}$</td>
<td>$D_{xx} \frac{2R_z + \Delta R}{2R_z(\Delta R)^2}$</td>
</tr>
<tr>
<td></td>
<td>$z$</td>
<td>$D_{xx}/(\Delta z)^2$</td>
<td>$2D_{xx}/(\Delta z)^2$</td>
<td>$D_{xx}/(\Delta z)^2$</td>
</tr>
<tr>
<td>Convection</td>
<td>$z &gt; 0 (V &gt; 0)$</td>
<td>$V(z_{i-1})/\Delta z$</td>
<td>$V(z_i)/\Delta z$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$z &lt; 0 (V &lt; 0)$</td>
<td>0</td>
<td>$-V(z_i)/\Delta z$</td>
<td>$-V(z_{i+1})/\Delta z$</td>
</tr>
<tr>
<td></td>
<td>$p \ (\frac{dV}{dz} &gt; 0)$</td>
<td>0</td>
<td>$\frac{1}{3} \frac{dV}{dz} \frac{p_i}{p_{i+1}^\gamma}$</td>
<td>$\frac{1}{3} \frac{dV}{dz} \frac{p_{i+1}}{p_i^\gamma}$</td>
</tr>
<tr>
<td>Diffusive</td>
<td>$p$</td>
<td>$-\frac{D_{xx}}{P_{i-1}} \frac{D_{pp,i}}{P_{i-1}}$</td>
<td>$-\frac{D_{xx}}{P_{i-1}} \frac{D_{pp,i-1}}{P_{i-1}}$</td>
<td>$\frac{2D_{xx}}{P_{i+1}^\gamma} \frac{D_{pp,i+1}}{P_{i+1}^\gamma}$</td>
</tr>
<tr>
<td>Reacceleration</td>
<td>$a$</td>
<td>$\frac{2}{P_{i-1}} \left( \frac{D_{pp,i}}{P_{i-1}} + \frac{D_{pp,i-1}}{P_{i-1}} \right)$</td>
<td>$\frac{2D_{xx}}{P_{i+1}^\gamma} \left( \frac{1}{P_{i+1}} + \frac{1}{P_i^\gamma} \right)$</td>
<td></td>
</tr>
<tr>
<td>Energy loss</td>
<td>$p$</td>
<td>0</td>
<td>$-\dot{p}<em>i/P</em>{i+1}^\gamma$</td>
<td>$-\dot{p}<em>{i+1}/P</em>{i+1}^\gamma$</td>
</tr>
<tr>
<td>Fragmentation</td>
<td>$R, z, p$</td>
<td>0</td>
<td>$1/3\tau_f$</td>
<td>0</td>
</tr>
<tr>
<td>Radioactive</td>
<td>$R, z, p$</td>
<td>0</td>
<td>$1/3\tau_r$</td>
<td>0</td>
</tr>
</tbody>
</table>

$^a P_i^\gamma \equiv p_i - p_j$

**Differencing scheme** The coefficients of the finite-differencing scheme we use for 2 spatial dimensions are given in Table 1. Since we have a 3-dimensional ($R, z, p$) problem we use ‘operator splitting’ to handle the implicit solution, as follows. We apply the implicit updating scheme alternately for the operator in each dimension in turn, keeping the other two coordinates fixed. The source and fragmentation, decay terms are used in every step, so to account for the 3 substeps, $\frac{\dot{q}_i}{\gamma}$ and $\frac{1}{\gamma}$ are used instead of $q_i$, $1/\gamma$ for the source term and the fragmentation, decay terms respectively. The coefficients for 3 spatial dimension are the same except that $R$ is replaced by $(x,y)$ and the finite differencing coefficients have the same form as for $z$, and $\frac{1}{\gamma}$ are used for the source term and the fragmentation, decay terms respectively, to account for the 4 substeps. With this scheme the solution can be done via the tridiagonal solution for each dimension in turn, as described in Press (1992). The spatial 3D scheme is simpler than the 2D one since the diffusion operator is easier to formulate ($x,y,z$ have the same form), and in addition it does not have the problem of the boundary condition at $R=0$.

In the case of anisotropic diffusion, $D_{xx}$ is used in the $z$-direction.

**Stability, convergence, accuracy.** The method was found to be stable for all $\alpha$, and this property can be exploited to advantage by starting with $\alpha \gg 1$ (see below). The standard alternating direction implicit (ADI) method, in which the full operator is used to update each dimension implicitly in turn, is more accurate but was found to be unstable for $\alpha > 1$. This is a disadvantage when treating problems with many timescales, but can be used to generate an accurate solution from an approximation generated by the non-ADI method.

A check for convergence is performed by computing the timescale $\frac{\Delta t}{\delta t}$ from eq. 1 and requiring that this be large compared to all diffusive and energy loss timescales. The main problem in applying the method in practice is the wide range of time-scales, especially for the electron case, ranging from $10^4$ years for energy losses to $10^6$ years for diffusion around 1 GeV in a large halo. Use of a time step $\Delta t$ appropriate to the smallest time-scales guarantees a reliable solution, but requires a prohibitively large number of steps to reach the long time-scales. The following accelerated technique was found to work well: start with a large $\Delta t$ appropriate for the longest scales, and iterate until a stable solution is obtained. This solution is then accurate only for cells with $\alpha \ll 1$; for other cells the solution is stable but inaccurate. Then reduce $\Delta t$ by a factor (0.5 was adopted).
and continue the solution. This process is repeated until \( \alpha \ll 1 \) for all cells, when the solution is accurate everywhere. It is found that the inaccurate parts of the solution quickly decay as soon as the condition \( \alpha < 1 \) is reached for a cell. As soon as all cells satisfy \( \alpha < 1 \) the solution is continued with the ADI method to obtain maximum accuracy. A typical run starts with \( \Delta t = 10^9 \) years and ends with \( \Delta t = 10^4 \) years for nucleons and \( 10^2 \) years for electrons performing \( \sim 60 \) iterations per \( \Delta t \). In this way it is possible to obtain reliable solutions in a reasonable computer resources, although the CPU required is still considerable.

NB the part about continuing with ADI depending on \( \alpha \) is not implemented in the current GALPROP version. It was in the f90 version. To be updated.

added 4 Jan 2011): A detailed evaluation of the accuracy of the solutions by both the accelerated and constant-step techniques has been added, see Section ‘Tests of GALPROP’. It is recommended to vary the number of repetitions per stepsize in the accelerated method, and to compare with a constant step run a least once as a check on the accuracy for the particular case being run. For the constant step runs, a typical timestep is \( 10^6 \) years, repeated \( 10^6 \) times to get a steady-state solution.

All results are output as FITS datasets for subsequent analysis.

Derivations of differencing formulae. The differencing schemes for the various terms are derived in detail below, with the relevant code in each case.

2D DIFFUSION

\[
\frac{\partial \psi}{\partial t} = \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi) \quad (33)
\]

\( R \) term

\[
\frac{1}{R} \frac{\partial}{\partial R} \left( RD_{xx} \frac{\partial \psi}{\partial R} \right) = \frac{2}{R_i R_{i+1} - R_{i-1} R_i} \left\{ \frac{R_{i+1}}{R_{i+1} - R_{i-1}} \left( \psi_{i+1} - \psi_i \right) - \frac{R_{i-1}}{R_{i-1} - R_i} \left( \psi_i - \psi_{i-1} \right) \right\}. \quad (34)
\]

Setting \( R_{i+1} - R_i = R_i - R_{i-1} = \Delta R_i \), one can obtain the following expressions in terms of our standard form (eq. [27])

\[
\frac{\alpha_1}{\Delta t} = D_{xx} \frac{2R_i - \Delta R}{2R_i(\Delta R)^2},
\]

\[
\frac{\alpha_2}{\Delta t} = D_{xx} \frac{2R_i}{R_i(\Delta R)^2},
\]

\[
\frac{\alpha_3}{\Delta t} = D_{xx} \frac{2R_i + \Delta R}{2R_i(\Delta R)^2}. \quad (35)
\]

\( z \) term

\[
\frac{\partial}{\partial z} \left( D_{xx} \frac{\partial \psi}{\partial z} \right) = \frac{2D_{xx}}{z_{i+1} - z_i} \left\{ \frac{\psi_{i+1} - \psi_i}{z_{i+1} - z_i} - \frac{\psi_i - \psi_{i-1}}{z_i - z_{i-1}} \right\} = \frac{D_{xx}}{(\Delta z)^2} \left( \psi_{i+1} - 2\psi_i + \psi_{i-1} \right). \quad (36)
\]

Setting \( z_{i+1} - z_i = z_i - z_{i-1} = \Delta z \), we obtain the following expressions in terms of our standard form (eq. [27])

\[
\frac{\alpha_1}{\Delta t} = \frac{D_{xx}}{(\Delta z)^2},
\]

\[
\frac{\alpha_2}{\Delta t} = \frac{2D_{xx}}{(\Delta z)^2},
\]

\[
\frac{\alpha_3}{\Delta t} = \frac{D_{xx}}{(\Delta z)^2}. \quad (37)
\]

The relevant code in galprop.cc:
for (ir = 0; ir < particle.n_rgrid; ++ir) {
  for (iz = 0; iz < particle.n_zgrid; ++iz) {
    for (ip = 0; ip < particle.n_pgrid; ++ip) {

      alpha1_z.d2[ir][iz].s[ip] = particle.Dxx.d2[ir][iz].s[ip]*pow(particle.dz,-2.)
      alpha2_r.d2[ir][iz].s[ip] = particle.Dxx.d2[ir][iz].s[ip]*pow(particle.dr,-2.);

      if (0 == ir) // use: Dxx/(R[i-1/2] dR)*{Ri(U[i+1]-Ui)-R[i-1](Ui-U[i-1])}; R[i-1]=0
        alpha3_r.d2[ir][iz].s[ip] = alpha2_r.d2[ir][iz].s[ip] *2.;
      else { // use: Dxx/(Ri dR)*{R[i+1/2](U[i+1]-Ui)-R[i-1/2](Ui-U[i-1])}
        alpha1_r.d2[ir][iz].s[ip] = alpha2_r.d2[ir][iz].s[ip]*(1. - particle.dr/2./particle.r[ir]);
        alpha3_r.d2[ir][iz].s[ip] = alpha2_r.d2[ir][iz].s[ip]*(1. + particle.dr/2./particle.r[ir]);
      }
    }
  }
}

alpha2_z = alpha1_z;
alpha2_z *= 2.;
alpha3_z = alpha1_z;

alpha2_r *= 2.;

double factor = dt*pow(kpc2cm, -2.);

alpha1_r *= factor;
alpha1_z *= factor;
alpha2_r *= factor;
alpha2_z *= factor;
alpha3_r *= factor;
alpha3_z *= factor;

3D DIFFUSION

This is the same as 2D except that the R-term is replace by x, y, and the coefficients are then exactly analogous to those for z. In the case of anisotropic diffusion, $D_{zz}$ is used in the z-direction.

**x term**

\[
\frac{\alpha_1}{\Delta t} = \frac{D_{xx}}{(\Delta x)^2},
\]

\[
\frac{\alpha_2}{\Delta t} = 2\frac{D_{xx}}{(\Delta x)^2},
\]

\[
\frac{\alpha_3}{\Delta t} = \frac{D_{xx}}{(\Delta x)^2},
\]

(38)

**y term**

\[
\frac{\alpha_1}{\Delta t} = \frac{D_{yy}}{(\Delta y)^2},
\]

\[
\frac{\alpha_2}{\Delta t} = 2\frac{D_{yy}}{(\Delta y)^2},
\]

\[
\frac{\alpha_3}{\Delta t} = \frac{D_{yy}}{(\Delta y)^2},
\]

(39)
DIFFUSIVE REACCELERATION

In terms of 3-D momentum phase-space density \( f(\vec{p}) \) the diffusive reacceleration equation is

\[
\frac{\partial f(\vec{p})}{\partial t} = \vec{\nabla}_p \cdot [D_{pp} \vec{\nabla}_p f(\vec{p})] = \frac{1}{p^2} \frac{\partial}{\partial p} \left[ p^2 D_{pp} \frac{\partial f(p)}{\partial p} \right].
\] (40)

The distribution is assumed isotropic so \( f(\vec{p}) = f(p) \) where \( p = |\vec{p}|. \) First we rewrite the equation in terms of \( \psi(p) = 4\pi p^2 f(p) \) instead of \( f(p) \) and expand the inner differential:

\[
\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial p} \left[ p^2 D_{pp} \frac{\partial \psi}{\partial p} \right] = \frac{\partial}{\partial p} D_{pp} \left[ \frac{\partial \psi}{\partial p} \frac{2\psi}{p} \right].
\] (41)

The differencing scheme is then

\[
\frac{2}{p_{i+1} - p_{i-1}} \left[ D_{pp,i+1} \left( \frac{\psi_{i+1} - \psi_i}{p_{i+1} - p_i} - \frac{2\psi_{i+1}}{p_{i+1}} \right) - D_{pp,i-1} \left( \frac{\psi_i - \psi_{i-1}}{p_i - p_{i-1}} - \frac{2\psi_{i-1}}{p_i - p_{i-1}} \right) \right].
\] (42)

In terms of our standard form (eq. [27]) the coefficients for reacceleration are

\[
\frac{\alpha_1}{\Delta t} = \frac{2D_{pp,i-1}}{p_{i+1} - p_{i-1}} \left( \frac{1}{p_i - p_{i-1}} + \frac{2}{p_{i-1}} \right),
\]

\[
\frac{\alpha_2}{\Delta t} = \frac{2}{p_{i+1} - p_{i-1}} \left( \frac{D_{pp,i+1}}{p_{i+1} - p_i} + \frac{D_{pp,i-1}}{p_i - p_{i-1}} \right),
\]

\[
\frac{\alpha_3}{\Delta t} = \frac{2D_{pp,i+1}}{p_{i+1} - p_{i-1}} \left( \frac{1}{p_{i+1} - p_i} - \frac{2}{p_{i+1}} \right).
\] (43)

One more scheme (#2) comes from further detailization

\[
\frac{d\psi}{dt} = \frac{\partial D_{pp}}{\partial p} \frac{\partial \psi}{\partial p} + D_{pp} \frac{\partial^2 \psi}{\partial p^2} + \frac{2}{p} \frac{\partial D_{pp}}{\partial p} \frac{\partial \psi}{\partial p}.
\] (44)

Here it is

\[
\frac{\alpha_1}{\Delta t} = -\frac{D_{pp,i} - D_{pp,i-1}}{(p_{i+1} - p_{i-1})^2} + \frac{2D_{pp,i}}{(p_{i+1} - p_{i-1})(p_i - p_{i-1})} + \frac{2D_{pp,i-1}}{(p_i - p_{i-1})p_{i-1}},
\]

\[
\frac{\alpha_2}{\Delta t} = -\frac{D_{pp,i} - D_{pp,i-1}}{(p_{i+1} - p_{i-1})^2} + \frac{2D_{pp,i}}{(p_{i+1} - p_{i-1})(p_i - p_{i-1})} + \frac{1}{p_{i+1} - p_i} + \frac{1}{p_i - p_{i-1}} + \frac{2D_{pp,i-1}}{(p_i - p_{i-1})p_i},
\]

\[
\frac{\alpha_3}{\Delta t} = \frac{2D_{pp,i+1}}{(p_{i+1} - p_{i-1})(p_{i+1} - p_i)}. \]

This scheme is used in propel.cc. The relevant part of the code is as follows:

```c
for (ir = 0; ir < particle.n_rgrid; ++ir) {
    for (iz = 0; iz < particle.n_zgrid; ++iz) {
        for (ip = 1; ip < particle.n_pgrid-1; ++ip) {
            // alternative scheme #2, most detailed
            alphal_p.d2[ir][iz].s[ip] +=
                // alternative scheme #2, most detailed
                for (ip = 1; ip < particle.n_pgrid-1; ++ip) {
                    // alternative scheme #2, most detailed
                    alphal_p.d2[ir][iz].s[ip] +=
                // alternative scheme #2, most detailed
                for (ip = 1; ip < particle.n_pgrid-1; ++ip) {
                    // alternative scheme #2, most detailed
                    alphal_p.d2[ir][iz].s[ip] +=
```
+ 2.*particle.Dpp.d2[ir][iz].s[ip-1]/particle.p[ip-1])
   /(particle.p[ip] - particle.p[ip-1]);
alpha2_p.d2[ir][iz].s[ip] +=
   /pow(particle.p[ip] - particle.p[ip-1], 2.)
   + 2.*particle.Dpp.d2[ir][iz].s[ip]
   /(particle.p[ip+1] - particle.p[ip-1])
   *(1./(particle.p[ip+1] - particle.p[ip])
   + 1./(particle.p[ip] - particle.p[ip-1]))
   + 1./(particle.p[ip] - particle.p[ip-1]))
   + 2.*particle.Dpp.d2[ir][iz].s[ip]
   /(particle.p[ip] - particle.p[ip-1])
   /particle.p[ip];
alpha3_p.d2[ir][iz].s[ip] +=
   2.*particle.Dpp.d2[ir][iz].s[ip]
   /(particle.p[ip+1] - particle.p[ip-1])
   /(particle.p[ip+1] - particle.p[ip]);

CONVECTION

Spatial part:

\[ \frac{\partial \psi}{\partial t} = \vec{\nabla} \cdot (-\vec{V} \psi) \] (46)

The wind is assumed to blow outwards from the disc, so \( V \) is +ve for \( z > 0 \), -ve for \( z < 0 \). For the differencing we use the physical fact that for convection \( \psi \) can only depend on upstream values, so gridpoint \( i \) depends on \( i, i - 1 \) for \( z > 0 \), and on \( i, i + 1 \) for \( z < 0 \) (upstream differencing).

\[
\begin{align*}
  z > 0: & \quad -\frac{V_{i+1}\psi_i - V_{i-1}\psi_{i-1}}{\Delta z} \\
  \alpha_1 \Delta t & = \frac{V_{i+1}}{\Delta z} \\
  \alpha_2 \Delta t & = \frac{V_i}{\Delta z} \\
  \alpha_3 \Delta t & = 0
\end{align*}
\] (47)

\[
\begin{align*}
  z < 0: & \quad -\frac{V_{i+1}\psi_{i+1} - V_i\psi_i}{\Delta z} \\
  \alpha_1 \Delta t & = 0 \\
  \alpha_2 \Delta t & = -\frac{V_i}{\Delta z} \\
  \alpha_3 \Delta t & = -\frac{V_{i+1}}{\Delta z}
\end{align*}
\] (48)

Since \( V \) is +ve for \( z > 0 \), -ve for \( z < 0 \), so in propel.cc the spatial convection \( \alpha \)'s are all finally +ve.

The relevant code in propel.cc : (\( V \) in km s\(^{-1}\), \( \frac{dV}{dz} \) in km s\(^{-1}\) kpc\(^{-1}\))

for (iz = 0; iz < particle.n_zgrid; ++iz) {
  \( \text{// numerator = abs convection velocity in cm s}^{-1} \)
  \( \text{double az1 = (particle2.z[iz] > 0.0) ? } \)
  \( \text{(galdef.v0_conv + galdef.dvdz_conv*fabs(particle.z[iz-1]))*1.e5/particle.dz*dt/kpc2cm: 0.;} \)
  \( \text{double az2 =} \)
5 DESCRIPTION OF BASIC ROUTINES

\[ \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial p} \frac{p^3}{3} (\nabla \cdot \vec{V}) \psi \]  

(49)

Momentum part:

\[ \frac{dV}{dz} p_{i+1} \psi_{i+1} - p_i \psi_i \]

\[ \frac{1}{3} \frac{dV}{dz} p_{i+1} - p_i \]

\[ \frac{\alpha_1}{\Delta t} = 0 \]

\[ \frac{\alpha_2}{\Delta t} = \frac{1}{3} \frac{dV}{dz} \frac{p_i}{p_{i+1} - p_i} \]  

\[ \frac{\alpha_3}{\Delta t} = \frac{1}{3} \frac{dV}{dz} \frac{p_{i+1}}{p_{i+1} - p_i} \]  

(50)

The relevant code in propel.cc: (V in km s\(^{-1}\), \(\frac{dV}{dz}\) in km s\(^{-1}\) kpc\(^{-1}\))

\[ \text{double ap2 = particle.p[ip] /3.*galdef.dvdz_conv/(particle.p[ip+1]-particle.p[ip])*1.e5/kpc2cm;} \]

\[ \text{double ap3 = particle.p[ip+1]/3.*galdef.dvdz_conv/(particle.p[ip+1]-particle.p[ip])*1.e5/kpc2cm;} \]

5.5.4 nuclei_normalize & electrons_normalize

Normalizes all nuclei to proton flux from galdef file. Applied at end of all nuclei processing but before computation gamma-rays (which use p, He and electrons). The value of \(E_{\text{kin}}\) is taken as the reference value for the proton normalization since this is already available in the galdef file.

Method: compute the proton flux \(\frac{d^2}{dz} n(p)\) at the reference \(E_{\text{kin}}\) at \(R = R_0\) and \(z = 0\) by interpolation, and hence obtain the normalizing factor to get the correct value as specified in the galdef file. Renormalizes the proton and all other nuclei fluxes by this same factor. The units of all spectra are then \(\frac{c^4 \pi n(p)}{\text{cm}^2}\). Note that the source abundances are already taken into account in create_transport_arrays.

5.6 store_gcr & store_gcr_full

5.7 Synchrotron radiation

The routines involved are gen_synch_emiss, synchrotron_emissivity_B_field, synchrotron_emissivity, gen_synch_skymap.

These compute the synchrotron emissivity including Stokes Q and U, and generates skymaps from these for total and Stokes Q and U.

synchrotron_emissivity.cc is the basic physics routine computing the emissivity using Bessel functions, for a given B-field (projected onto perpendicular to the line-of-sight) and random B-field. Total emissivity and Stokes Q and U emissivities are computed, for a given synchrotron frequency and electron/positron energy. The formulae in the literature are somewhat confusing using various conventions, and a unifying survey is contained in this routine, which to the best of our knowledge is correctly coded.
5.7.1 Regular field

The synchrotron emissivity of an isotropic distribution of monoenergetic relativistic particles in a uniform magnetic field has polarized components parallel and perpendicular to the projection of the field on the line-of-sight to the observer (Longair: High Energy Astrophysics, Rybicki and Lightman: Radiative Processes in Astrophysics)

$$\epsilon_\perp(\nu) = \sqrt{\frac{3}{2}} \frac{e^3}{mc^2} B_{\text{perp}} [F(x) + G(x)]$$  \hspace{1cm} (51)

$$\epsilon_\parallel(\nu) = \sqrt{\frac{3}{2}} \frac{e^3}{mc^2} B_{\text{perp}} [F(x) - G(x)]$$  \hspace{1cm} (52)

where $x = \nu/\nu_c$, with $\nu_c = \frac{3}{4\pi} \frac{e}{mc} B_{\text{perp}} \gamma^2$ and with $\gamma$ the electron Lorentz factor, and $B_{\text{perp}}$ is the projection of $B$ on the plane perpendicular to the line-of-sight. The functions $F(x)$ and $G(x)$ are defined in terms of Bessel functions (Longair: High Energy Astrophysics, Rybicki and Lightman: Radiative Processes in Astrophysics) with:

$$F(x) = \frac{\nu}{\nu_c} \int_{\nu_c}^{\nu} K_{5/3}(x') dx'$$

$$G(x) = \frac{\nu}{\nu_c} K_{2/3}(x)$$  \hspace{1cm} (53)

where $K_{5/3}(x)$ and $K_{2/3}(x)$ are the modified Bessel functions of order $5/3$ and $2/3$. They are conveniently provided as C library functions in the GNU Scientific Library, and this implementation is used by GALPROP.

The resulting synchrotron spectrum has a broad maximum centred roughly at the frequency $\nu_c$ and the maximum has a value $\nu_{\text{max}} = 0.29 \nu_c$

The total emissivity is given by the sum of the two terms above:

$$\epsilon(\nu, \gamma) = \sqrt{3} \frac{e^3}{mc^2} B_{\text{perp}} F(x)$$  \hspace{1cm} (54)

5.7.2 Random field

For a randomly oriented field the emissivity is isotropic and obtained by integrating the regular field expressions over all solid angles. The result is given by (Ghisellini et al. 1988 ApJ 334,5)

$$\epsilon_{\text{rand}}(\nu) = C \frac{\nu}{\nu_c} [K_{4/3}K_{1/3} - \frac{3}{5}x(K_{4/3}K_{4/3} - K_{1/3}K_{1/3})]$$  \hspace{1cm} (55)

where $K_{4/3}(x)$ and $K_{1/3}(x)$ are the modified Bessel functions of order $4/3$ and $1/3$. They are conveniently provided as C library functions in the GNU Scientific Library.

In the GALPROP implementation, the code has been checked by integrating the regular field expression over solid angle, giving exact agreement with this formula.

5.7.3 synchrotron_emissivity_B_field.cc

uses the selected B-field model to invoke synchrotron_emissivity.cc for a particular position, synchrotron frequency and electron/positron energy, and computes the Stokes parameters in a uniform reference system suitable for line-of-sight integration.

For the regular field, the emissivities perpendicular and parallel to the projection of $B$ onto the line-of-sight from the observer to the emitting volume element $\epsilon_\perp, \epsilon_\parallel$ are given above.


The emissivities for Stokes parameters $I, Q, U$ are then defined by

$$I = \epsilon_\perp + \epsilon_\parallel$$
\[ P = \epsilon_\perp - \epsilon_\parallel \]
\[ Q = P \cos(2\chi) \]
\[ U = P \sin(2\chi) \]

\( I \) is the total intensity, \( P = \sqrt{Q^2 + U^2} \) is the polarized intensity, \( I - P = 2\epsilon_\parallel \) is the unpolarized intensity. The polarized fraction is \( \frac{P}{I} \). Unpolarized radiation has \( Q = U = 0 \), totally polarized has \( I = P \).

\[ \chi = \frac{1}{2} \arctan(U/Q) \]

\( \chi \) is the angle between the polarization direction of the electric vector and the Galactic longitude meridian (N-S) (convention as in Page et al. 2007 ApJ 170, 335.) The projection of \( B \) on the plane perpendicular to the line-of-sight then has direction \( \chi + \pi/2 \) since the emission is polarized perpendicular to the projection \( B \) onto the line-of-sight (NB \( \epsilon_\perp > \epsilon_\parallel \) for synchrotron radiation). With this definition of \( \chi \), \( B \) parallel to the Galactic plane has \( \chi = 0, Q > 0, U = 0 \), while \( B \) pointing towards the North Galactic Pole has \( \chi = \pi/2, Q < 0, U = 0 \). \( B \) at \( \pi/4 \) to the meridian has \( \chi = \pi/4, Q = 0, U > 0 \), and at \( -\pi/4 \) to the meridian \( \chi = -\pi/4, Q = 0, U < 0 \).

This routine uses direction cosines to perform the necessary angular calculations.

Setting the galdef parameter verbose = -1100 produces a detailed output of the calculation at every point, useful for testing.

Note that the formulation here is more general than that often used which gives the Stokes parameters directly in terms of the components of \( B \) (e.g. Page et al. 2007 WMAP, Ensslin et al. 2009 Astr. Nachrichten 327,626); the latter is only possible under the assumption of an electron spectral index of 3, while ours (and Waelkens et al., Hammurabi) is for any electron spectrum. The simplified formulae are useful for understanding the relation between the topology of \( B \) and the Stokes parameters, and for checking the code. These relations are of the kind

\[ I \propto \int (B_x^2 + B_z^2)ds \]
\[ Q \propto \int (B_x^2 - B_z^2)ds \]
\[ U \propto \int (2B_xB_z)ds \]

where \( B_x, B_z \) are projected on the plane of the sky to the observer, \( s \) is the line-of-sight.

### 5.7.4 synchrotron emissivity aws.cc

provides a convenient interface to invoke `synchrotron_emissivity.cc` and `synchrotron_emissivity_B_field.cc`. `gen_synch_emiss.cc` uses the above routines to generate total, \( Q \) and \( U \) emissivities for the whole 2D or 3D grid, for all required frequencies. The integration over electron (primary and secondary) and positron spectra is done here.

`gen_synch_skymap` integrates the emissivities (total, \( Q, U \)) over the line-of-sight to produce the corresponding synchrotron skymaps. The integration step is taken from GALDEF parameter LoS step. With GALPROP calculation of emissivity on the grid, we integrate over the electron (or positron) spectrum and the line-of-sight to get the synchrotron intensity for the regular and random fields. The synchrotron intensity at frequency \( \nu \) is then given by

\[ I(\nu) = \frac{1}{4\pi} \int \epsilon(\nu) \, ds \]  \hspace{1cm} (56)

The observed brightness of the radiation seen in a given direction is

\[ T(\nu) = \frac{c^2 I(\nu)}{2k\nu^2} \]  \hspace{1cm} (57)

Note the internal units of emissivity (gamma rays, synchrotron, etc) in GALPROP are always \( \text{sr}^{-1} \), i.e. \( \frac{1}{4\pi} \epsilon(\nu) \), so here the units are \( \text{erg} \, \text{cm}^{-3} \, \text{s}^{-1} \, \text{Hz}^{-1} \, \text{sr}^{-1} \). These are also the units of the output datasets with names `synchrotron_emiss...` etc.
5.7.5 Free-free absorption and emission

Free-free absorption by ionized hydrogen (WIM: warm interstellar medium) is important at low radio frequencies (below 100 MHz in the plane, below 10 MHz at high latitudes). This is now implemented \( r951 \). It is controlled by the electron temperature \( T_e \) and the clumping factor since absorption depends on the square of the electron density. The clumping factor is related to the filling factor; for equal-size clouds, clumping factor = 1/filling factor. Clumping factors of 10-100 are typical based on a variety of data (pulsar DM, Hα EM, free-free emission, synchrotron absorption). Free-free emission can also be computed, with a special option to replace the synchrotron skymaps with free-free skymaps, using the same frequency grid as for synchrotron. The free-free skymap is always output to a separate file when synchrotron is selected \( r979 \). The free-free emission is subject to absorption using the same scheme. The free electron density uses the model described in \texttt{nhII.cc}. Controlled by parameters \texttt{free_free_absorption}, \texttt{HII_Te}, \texttt{HII_clumping_factor}. Future developments will include spatial dependence of these quantities, which are known to vary in the Galaxy, and a more sophisticated model of the WIM. \textit{Full details required.}

5.8 \texttt{gen_bremss_emiss}, \texttt{gen_IC_emiss}, & \texttt{gen_pi0_emiss}

\( \pi^0 \)-decay emissivity from CR protons and Helium on interstellar hydrogen and Helium.

Units: \((\text{H atom})^{-1} \text{sr}^{-1} \text{s}^{-1} \text{MeV}^{-1} \).

IC emissivity from CR primary electrons and secondary electrons and positrons.

Units: \(\text{cm}^{-3} \text{sr}^{-1} \text{s}^{-1} \text{MeV}^{-1} \).

The integral over particles is over \( \log(E_{kin}) \), see section General Principles. This explains the formula used in this routine. The factor includes GeV\(^{-1}\) to MeV\(^{-1}\) and barn to \(\text{cm}^2\). A correction for the Helium abundance of the gas as in the \texttt{galdef} file is applied in computing the emissivities. Helium nuclei in CR are explicitly included here.

5.9 \texttt{gen_bremss_skymap}, \texttt{gen_IC_skymap}, & \texttt{gen_pi0_skymap}

\( \pi^0 \)-decay, bremsstrahlung and IC skymaps as function of \((l, b, E_x)\).

Units: internal: \(\text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1} \text{MeV}^{-1} \), for output: \(\text{MeV}^2 \text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1} \text{MeV}^{-1} \).

The skymaps are produced by integrating the emissivities over the line-of-sight for an observer at the Solar position, for each \((l, b)\) direction in the map. For IC this is straightforward since the volume emissivity is directly calculated using the ISRF and electron, positron spectra.

For bremsstrahlung and \( \pi^0 \)-decay the emissivity is per nucleon of gas. To best implement observed Galactic structure in the gas, HI and CO radio-astronomical surveys in Galacticentric rings are used together with the user-defined \( \text{H}_2 \)-to-CO relation given in the \texttt{galdef} file. These data only give column densities per ring, so that the variation of emissivity and gas density \textit{within} each ring has to be taken into account by some approximation. This is done using a gas-density model as a function of \((R, z)\) as follows:

\[
I_\gamma = \sum_i \frac{N_{\text{H}I,i} + 2X_{\text{CO},i}W_{\text{CO},i}}{(n_{\text{HI}} + 2n_{\text{H}_2})ds} \times \int_{\text{ring } i} q_i(n_{\text{HI}} + 2n_{\text{H}_2})ds
\]

where \(i\) indexes the Galactocentric rings. Here \((n_{\text{HI}} + 2n_{\text{H}_2})\) is the model gas density at any point \((R, z)\) as described in Section 2.1.1, \(s\) is the line-of-sight distance, \((N_{\text{H}I,i} + 2X_{\text{CO},i}W_{\text{CO},i})\) is the survey-based column density in ring \(i\). The integral is thus corrected for the observed column density while maintaining the model-based variation within the ring. The integrals are performed with a resolution in \(s\) of 10 pc.

6 Point sources of CR: spatial and temporal aspects

A new development from version 4 is the inclusion of spatial and temporal variations, which can be followed explicitly in the 3D case. Supernova remnants are produced at some rate (e.g. 1/100 yr) and produced cosmic rays for some time (e.g. 10,000 yr). The first step is to include point sources at arbitrary positions specified by the user, by this is mainly useful for testing and does not address the problem of fluctuations.

The correct approach is to consider the source function as \(f(x, y, z, t)\). The problem is that the solution has to be followed on a time scale comparable to the SN rate, i.e. 100 years or less. This would not allow the
advantages of the equilibrium solution scheme used in \texttt{galprop}. However provided the equilibrium solution is first derived, the short time steps can be started afterwards and will lead to the correct “recent” history of the system.

To model the source function we need an explicit $f(x, y, z, t)$ which has the right properties of producing short-lived events at different positions. This can be done by defining first a regular grid on which SNR can occur, and then generating a random phase for each grid point. The function of time at each point is then a suitable function with the required duty cycle and period.

The basic spatial grid itself can be used, there is no need to define a separate one for the sources. The required parameters are: the probability per unit time and volume of a SNR events, and the time for which it is active. To express both as a time, define \texttt{SNR\_time\_interval} as the time between events in a kpc$^3$ volume in the Solar vicinity for the first parameter.

The structure Galaxy contains an array giving the phase and rate for each cell. The phases are chosen randomly at the start of the program. The rates are determined from the time interval and the source distribution which is taken as the same as that defined for constant sources. At any time, the on/off state of an SNR in a cell is determined from the time relative to the phase, the time between SNR in the cell (\texttt{SNR\_cell\_time}) and the live time.

The propagation code (\texttt{propel.cc}) is divided into two sections to handle the smooth source function using the decreasing timesteps, followed by a section with constant timesteps to handle the SNR events on a fine timescale. These are called \texttt{timestep\_mode} = 1, 2 respectively. The number of timesteps in each mode can be specified independently, but in mode 2 the shortest timestep of mode 1 is used.

If the number of timesteps in mode 1 is set to zero then only mode 2 is used. For a combination of modes it is necessary to normalize the source functions to be consistent: this has to be done by adjusting the input per SNR ($Q_{SNR}$) since the rate and live time are given. The source function returned by \texttt{source\_distribution.cc} is defined as production per unit volume (cm$^{-3}$) per second. (it gets multiplied by spectral and abundance factors later).

The assigned source function in source\_SNR\_event has to satisfy

$$source\_function * SNR\_livetime/\text{SNR\_cell\_time} = source\_distribution(x, y, z)$$

so

$$source\_function = source\_distribution(x, y, z)/SNR\_livetime * SNR\_cell\_time$$

and the SNR input when on should be always same everywhere by construction.

\texttt{create\_SNR\_cc} uses

$$SNR\_cell\_time = SNR\_interval * source\_distribution(Sun)/source\_distribution(x, y, z)/cellvolume$$

so the formula used by \texttt{source\_SNR\_event\_cc} is

$$source\_function = source\_distribution(x, y, z)/SNR\_livetime * SNR\_interval * source\_distribution(Sun)/source\_distribution(x, y, z)/cellvolume$$

which simplifies to

$$source\_function = SNR\_interval/\text{SNR\_livetime} * source\_distribution(Sun)/cellvolume$$

and the output rate of an SNR =

$$source\_function * cellvolume = SNR\_interval/\text{SNR\_livetime} * source\_distribution(Sun)$$

which is a constant as required. Note that $SNR\_interval$ is for 1 kpc$^3$ and so has units of years * kpc$^3$ while $source\_distribution(Sun)$ has units of cm$^{-3}$ s$^{-1}$ so the SNR output rate units are s$^{-1}$ as required. Similarly $source\_function$ has the same units as $source\_distribution$, as required.
7 ANALYTICAL SOLUTIONS

7 Analytical solutions

Analytical solutions can be obtained for simple cases which provide an essential test of the correct working of galprop.

7.1 Simple diffusion equation without losses

The propagation equation for the particle density $\psi$ in this case is:

$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot D_{xx} \vec{\nabla} \psi$$ (58)

Consider the 1-D case with boundary condition $\psi(z_h) = \psi(-z_h) = 0$ and $q = 0$ except at $z = 0$. The steady-state 1-D form is

$$q(z) = D_{xx} \frac{d^2 \psi}{dz^2}$$ (59)

The solution is

$$\psi = A(z_h - |z|)$$ (60)

The constant $A$ is determined from $\int q(z)dz = D_{xx} \left[ \frac{d\psi}{dz} \right]_1^z = 2AD_{xx}$ so the solution for primaries is

$$\psi_p = \frac{Q}{2D_{xx}}(z_h - |z|)$$ (61)

where $Q = \int q(z)dz$ is the surface CR emissivity. The solution is just the expression of the conservation of particles, hence the equality of the source term with the the diffusive CR current $-D_{xx} \frac{d\psi}{dz}$, with half the current going in each $z$-direction.

Secondary production just replaces the source term $q$ by the spallation term $\psi_p(0)n\sigma/\beta c$ where $\sigma$ is the production cross-section and $n$ the gas density:

$$\psi_s = \frac{\psi_p(0)n\sigma/\beta c \Delta z}{2D_{xx}}(z_h - |z|)$$ (62)

so the secondary/primary ratio in the disk is

$$\psi_s(0)/\psi_p(0) = \frac{n\Delta z\sigma/\beta cz_h}{2D_{xx}}$$ (63)

This ignores the destruction terms. They can be included by replacing $q$ by $q - n\sigma_p/\beta c\psi_p(0)$ giving

$$\psi_p = \frac{Q(z_h - |z|)}{2D_{xx} + n\Delta z\sigma_p/\beta cz_h}$$ (64)

and correspondingly

$$\psi_s = \frac{\psi_p(0)n\sigma/\beta c \Delta z}{2D_{xx} + n\Delta z\sigma_p/\beta cz_h}(z_h - |z|)$$ (65)

where $\sigma_p, \sigma_s$ are the primary and secondary destruction cross-sections.

The secondary/primary ratio in the disk is

$$\psi_s(0)/\psi_p(0) = \frac{n\Delta z\sigma/\beta cz_h}{2D_{xx} + n\Delta z\sigma_p/\beta cz_h}$$ (66)
7.2 Simple diffusion equation without losses, with decay

The propagation equation for the particle density $\psi$ in this case is:

$$\frac{\partial \psi}{\partial t} = q(r, p) + \vec{\nabla} \cdot D_{xx} \vec{\nabla} \psi - \frac{\psi}{\tau_r}$$  \hspace{1cm} (67)

Consider the 1-D case with boundary condition $\psi(z_h) = \psi(-z_h) = 0$ and $q = 0$ except at $z = 0$. The steady-state 1-D form is

$$q(z) = D_{xx} \frac{d^2 \psi}{dz^2} - \frac{\psi}{\tau_r}$$  \hspace{1cm} (68)

Outside the source region $q(z) = 0$:

$$D_{xx} \frac{d^2 \psi}{dz^2} - \frac{\psi}{\tau_r} = 0$$  \hspace{1cm} (69)

The general solution is of the form $\psi = A e^{-kz} + B e^{+kz}$ where $k = \frac{1}{\sqrt{(D_{xx} \tau_r)}}$. The boundary conditions give $A e^{-kz_h} + B e^{+kz_h} = 0$ and $A e^{-kz_h} + B e^{+kz_h} = 0$ (so $A/B$ different for $z > 0, z < 0$). For $z > 0$, $B = -A e^{-2kz_h}$, so $\psi = A(e^{-kz} - e^{-2kz_h} e^{+kz}) = A e^{-kz} (1 - e^{-2kz_h})$. For $z < 0$, $A = -B e^{+2kz_h}$, so $\psi = B e^{+kz} (1 - e^{-2kz_h})$.

The constant $A$ is determined from

$$\int q(z)dz = D_{xx} \left[ \frac{d\psi}{dz} \right]_z^{z_h} = 2D_{xx} \left[ \frac{d\psi}{dz} \right]_{z=0} = 2A \left[ (-ke^{-kz} - ke^{kz}) \right]_{z=0} = -4AkD_{xx}$$

(should not be negative, formula for flux?) so $A = \frac{Q}{4kD_{xx}}$ giving the solution for primaries

$$\psi_p = \frac{Q}{4kD_{xx}} e^{-kz} (1 - e^{2k(z-z_h)})$$  \hspace{1cm} (70)

where $Q = \int q(z)dz$ is the surface CR emissivity.

For $\tau \rightarrow \infty$, $k \rightarrow 0$ the solution tends to $\psi = \frac{Q}{4kD_{xx}} (1 - kz) / (2k(z-z_h)) = \frac{Q}{2kD_{xx}} (2k(z-z_h) + 2k^2 z(z-z_h)) \rightarrow \frac{Q}{2kD_{xx}} (z-z_h)$ keeping only terms to $O(k)$. (NB sign, should be $z_h - z$). This recovers the linear form for the stable nuclei case above.

We are interested in e.g. $^{10}$Be/$^9$Be i.e. unstable/stable secondaries at $z = 0$.

$$\frac{\psi_{ss}}{\psi_{su}} = \frac{Q_{ss}}{4kD_{xx}} (1 - e^{-2kz_h}) / \frac{Q_{su}}{4kD_{xx}} (z_h - z) = \frac{\sigma_{ss} (1 - e^{-2kz_h})}{\sigma_{su} 2kzh}$$

$$\frac{\psi_{su}}{\psi_{ss}} = \frac{\sigma_{su}}{\sigma_{ss}} \left( \frac{1 - e^{-2kz_h}}{\sqrt{(D_{xx} \tau_r)}} \right)$$

where $\frac{\sigma_{su}}{\sigma_{ss}}$ is the ratio of production cross-sections for unstable and stable secondaries from the same primary. For $\tau_r \rightarrow 0$ i.e. rapid decay, the exponential $\rightarrow 0$ and

$$\frac{\psi_{su}}{\psi_{ss}} = \frac{\sigma_{su}}{\sigma_{ss}} \frac{\sqrt{(D_{xx} \tau_r)}}{2z_h}$$

This can be interpreted as the diffusion distance $\sqrt{(D_{xx} \tau_r)}$ before decay compared with the halo height $z_h$, giving the ratio of decaying to non-decaying secondaries.

This shows how the combination of secondary/primary which constrain $\frac{\psi_{su}}{\sqrt{D_{xx}}} \rightarrow 0$ and unstable/stable secondaries which constrain $\frac{\psi_{su}}{\sqrt{D_{xx}}} \rightarrow 0$ together allow both $D_{xx}$ and $z_h$ to be determined.

7.3 Simple convection equation without losses

The propagation equation for the particle density $\psi$ in this case is:

$$\frac{\partial \psi}{\partial t} = q(r, p) - \vec{\nabla} \cdot (\vec{V} \psi)$$  \hspace{1cm} (71)

As before we assume $q = 0$ except at $z = 0$. In the steady-state this is just $\vec{\nabla} \cdot (\vec{V} \psi) = 0$ except at $z=0$ where the source is located. For convection only in the $z$-direction, this becomes $V \psi = \text{constant}$, i.e. just conservation
of particles in a uniform flow. Then $V \psi = q$ for $q$ per surface area. So $\psi \propto \frac{1}{V}$, and so if $V \propto z$, $\psi \propto \frac{1}{z}$. For secondaries,

$$V \psi_s = q_s = n \Delta z \psi_p \sigma \beta c$$

so the secondary/primary ratio in the disk is

$$\frac{\psi_s(0)}{\psi_p(0)} = \frac{n \Delta z \sigma \beta c}{V}$$

An order-of-magnitude estimate of the values: $n \Delta z = 10^{21}$ atoms cm$^{-2}$, $\sigma_{BC} = 100$ mb, $V = 100$ km s$^{-1}$ giving $B/C = 0.3$, of the right order. This indicates that quite high wind velocities are required to compete with diffusion. This estimate is valid for $V=$constant, otherwise it is not clear at which $z$ it should be taken. A better solution for $V(z)$ will be added in future.

8 Enhancements and changes to the code

8.1 Current version end 2010

A description of some of the enhancements can be found in Strong et al. (51); Vladimirov et al. (56) from which the following is taken:

- Shared-memory parallel support with OpenMP to take advantage of multi-processor machines
- Memory usage optimization
- Implementation of the HEALPix output of gamma-ray and synchrotron skymaps. The HEALPix format is a standard for radioastronomy applications, as well as for such instruments as WMAP, Planck etc.
- Implementation of the MapCube output for compatibility with Fermi-LAT Science Tools software
- Implementation of gamma-ray skymaps output in Galactocentric rings to facilitate spatial analysis of the Galactic diffuse gamma-ray emission
- More accurate line-of-sight integration for computing diffuse emission skymaps
- 3D modeling of the Galactic magnetic field, both regular and random components, with a range of models from the literature, extensible to any new model as required
- Calculations of synchrotron skymaps on a frequency grid, using both regular and random magnetic fields
- Improved gas maps, which are computed using recent HI and CO (H2 tracer) surveys, with more precise assignment to Galactocentric rings
- A new calculation of the Galactic interstellar radiation field using the FRaNKIE code (Fast Radiation transport Numerical Kode for Interstellar Emission, as described in ) and implementation of the corresponding changes in GALPROP
- Considerably increased efficiency of anisotropic inverse Compton scattering calculations
- GALPROP code is compiled to a library for easy linking with other codes (e.g. DarkSUSY, SuperBayeS)
- Numerous bug fixes and code-style improvements
- Improved configuration management via the GNU autotools. Multiple *NIX system and compiler targets (gcc, intel, llvm, open64) are supported
- Bugzilla available at the GALPROP WebRun URL for user-submitted bug tracking

8.2 Version 54

This version replaces Version 50p, and has many enhancements and corrections.

Visible to users:

- Many new parameters, see the parameters description.
- HI, CO surveys specified by file names.
- etc.

Internal changes:

- etc
8.3 Version 50

This version replaced Version 42.3p, and had many enhancements and corrections.

Visible to users:
* Xco(R) user-defined in GALDEF file.
* Output of components from HI, CO separately, in Rings.
* ISRF specified via filename
* high energy IC now OK (was affected by float rounding error)
* synchrotron corrected (factor c was missing)
* wave damping

Internal changes:
* "extern" global variables eliminated, instead placed in Class Galprop. (= better C++ style)
* all functions are members of Class Galprop (except a few generic routines).
* program structure otherwise identical
* all double instead of float, including Class Distribution
* runs on 64-bit machines so will handle larger cases

9 To do list

9.1 Documentation

1. More details on output data (energy scales, projection, etc).
2. Bug list
3. Feedback/user forum.
4. List of papers using galprop
5. Platforms e.g. 64-bit
6. Sample galdef, output data, plots for e.g. 3 useful cases.
7. Summary of galdef parameters for standard published models with galdef files.

9.2 Code

1. Improve FITS headers, e.g. at present they do not have the units.
2. Output synchrotron emissivities.
3. Work towards all c++ and eliminate fortran.

10 Program architecture

This new section provides an overview of the structure and processing of the galprop package.

10.1 Classes

The main classes are:

Galprop: encapsulates the entire processing. Can be instantiated as required. Advantage is sharing of all data within one class, no global variables exist. All the other classes are instantiated within the Galprop class.

Galaxy: contains all the structures describing the Galaxy used in the program.

Galdef: the parameters used by galprop, as entered by the user via the GALDEF parameter file.

Distribution: general purpose array of objects of type Spectrum, in 2D or 3D. Used throughout the program.

Spectrum: a 1D array for holding a spectrum (or any other quantity)

Particle: contains all the information about particular species of particle (mass, Z, A etc) and all the arrays required to propagate it.

Skymap: used for all skymaps generated, and has general-purpose output method.

GalacticRadiationField: handles all aspects of the Galactic interstellar radiation field
Configure: used to configure the program for the input/output data directories, and the directory containing GALDEF parameter files.

GCR_data: handles a database of cosmic-ray data with access routines. Not used by the standard main program, but may be used if required by other programs.

10.2 The program
Main program galprop.cc: instantiates Galprop class, runs it, deletes it, and exits.

10.3 Processing
The processing can be described schematically as follows:

Read GALDEF file using method of Galdef class.

Create a Galaxy object and initialize it.

Compute all Galaxy arrays for CR particles as specified in GALDEF parameters
  | Arrays for x,y,z,r, p, Ekin, dp/dt, fragmentation, decay, Dxx, Dpp
  | ISRF, magnetic field, cross-sections ....

Loop over network iterations
  |
  | Loop over particle species starting from most massive
  | |
  | | Propagate particle species
  | | | Compute source function as primary and as secondaries from all heavier species
  | | |
  | | | Time steps decreasing as specified in GALDEF parameters
  | |

Output CR distributions

Generate gamma-ray emissivities
Output gamma-ray emissivities

Generate gamma-ray skymaps
Output gamma-ray skymaps

Generate synchrotron emissivities
Output synchrotron emissivities

Generate synchrotron skymaps
Output synchrotron skymaps

Delete everything

Exit
11 Tests of GALPROP

11.1 Propagation algorithm

The technique has been described in Section 5.5.3. Here we test the accuracy of the method comparing the constant small step (CSS) and accelerated solutions. The routine propel_diagnostics.cc gives information during a run, while various solutions can also be compared for complete runs. The first question is how accurate the CSS method is since this is the benchmark method. Here we assume that the coefficients of the propagation are coded correctly and seek to check only whether the steady-state solution is correctly computed. The benchmark case here is electrons, $10^3 - 10^6$ MeV, energy factor 1.2, with a 4 kpc halo and standard diffusion coefficient and reacceleration parameter. For timesteps of 1000 yr the timescale is below all energy-loss timescales so that $10^6$ steps will give the solution for $10^9$ years which suffices for a 4 kpc halo (using $z \approx \sqrt{D_{xx} t}$). Note that physically the steady-state is an approximation since the injection of CR will certainly not be constant over $10^9$ years. This should be remembered when evaluating the results, but in any case we want to be sure that the mathematical solution to a given model is correctly obtained independent of its physical validity.

Solutions are compared by computing the fractional difference for all positions and energies, outputting the result in FITS.

The basic finding of these tests are:

1. The CSS solution: the diagnostic minimum timescale based on the formula for $\frac{d\psi}{dt}$ in terms of the $\alpha$’s given by propel_diagnostics.cc reaches a constant value for any given timestep, while the CR density continues to increase. Hence this diagnostic is apparently not sufficient. Continuing the solution until the CR density is constant leads to an apparently accurate solution after $10^6$ steps of 1000 yr. The diagnostic timescale reached based on the formula for $\frac{d\psi}{dt}$ in terms of the $\alpha$’s given by propel_diagnostics.cc decreases with increasing stepsize, i.e. the solutions become less reliable according to this diagnostic; for example a timestep of 1000 yr reaches a constant minimum timescale $10^5$ yr after about 10000 steps(check), which would not indicate an accurate solution. Nevertheless continuing the solution for the nominal $10^6$ reaches a time-independent CR density and hence apparently a reliable solution, but this is not necessarily the case (see next paragraph). An alternative diagnostic provided by propel_diagnostics.cc uses the maximum fractional change since the last call of this routine, combined with the number of steps elapsed and the timestep; this gives a steadily increasing timescales, and reaches very large values ($> 10^{18}$ years) after 6 $10^5$ steps of 1000 years for the benchmark case and then goes to machine infinity (i.e. $\frac{d\psi}{dt} = 0$ everywhere) at 8.4 $10^5$ steps, indicating an accurate solution within machine accuracy. This can be used as a criterion for terminating a timestep loop, since further steps at this timestep value give no change in the solution. This is implemented at r722 via the galdef parameter solution_convergence (see parameter descriptions).

The reason for the deviation of the differencing diagnostic from the $\alpha$-based estimate lies in the ADI method used to handle our multi-dimensional problem: the $\alpha$-based diagnostic uses the full operator for all dimensions, while our adopted ADI method applies the operator for each dimension in turn, which leads to a slightly different solution; using small enough timesteps the operators are sufficiently well mixed to give a good solution by the $\alpha$-based diagnostic (the timescale becomes very large). It has been verified that for small timesteps the two timescales are consistent, i.e. that the method works correctly in this case and is coded correctly. However this means that the differencing diagnostic is not a completely reliable indicator of a converged solution. To obtain a good solution according to reliable $\alpha$-based diagnostic requires a very long CSS run, but can also be achieved with the accelerated method provided enough steps per timestep are used and that the final timestep is small enough. More specific examples of this aspect will be added.

This suggests other strategies for the future: an explicit method can be used with the full operator for small enough timesteps to ensure stability, and this could be appended to the solution at the end of an accelerated run. This would avoid the ADI problem described above. Non-ADI methods solving the full system of equations are expensive since the matrix is no longer tridiagonal. The explicit method is now implemented at r705 (see galdef parameter solution_method and description of propel.cc). Alternative methods using the full operator are possible, or more sophisticated operator splitting methods (see Press 1992), and these could also be investigated.

The diagnostics for a sample CSS run for electrons for the benchmark case are shown below. They show how the differencing-based timescale increases to a machine-accuracy solution at the end.

Network iteration 1 species 0 primary\_electrons (Z,A) = (-1,0)
propel: Entry
propel: Generating alpha for 2D

Here is also a run for protons with no reacceleration and Dxx=constant (i.e. the simplest case, since no energy losses either). It reaches a solution with the machine accuracy after 8.6 \times 10^7 years.

Network iteration 1 species 0 Hydrogen_1 \((Z,A) = (1,1)\)

propel: Entry

propel: Generating alpha for 2D
11. TESTS OF GALPROP

and for protons with reacceleration and $D_{xx}$ with $\delta = 0.33$:  

Timestep modes 2 follows timestep mode 1 seamlessly as the following example shows. It uses with $10^3 − 10^9$ years with 100 steps per timestep in mode 1, and then continues in mode 2. The diagnostics show that the changeover is smooth, while as expected the $\alpha$-based timescale is still too small in mode 1, but then starts to increase in steady mode 2 (and eventually reaches $10^3$ years as in the mode-2 only case). Hence mode 1 can be used to accelerate the initial solution and mode 2 to refine this to an accurate solution, with an overall reduction in CPU requirements.

2. The accelerated solution: start timestep $10^9$ yr, end timestep $1 yr$, ratio $0.25$. The suggested repeat per timestep of 20 (section 5.5.3) leads to deviations of up to 20% from the accurate solution, although at most energies and positions the deviations are within 10%. The largest deviations are at large $R$ and large $z$. Increasing to the number of repeats to 100, 1000, 10000 improves the accuracy, with the latter giving deviations from the accurate solution of 0.1% and hence verifying the validity of such solutions. NB The use of the propel_diagnostics.cc diagnostics for the accelerated solution will need to be clarified since the variable timestep may affect the interpretation; the only reliable check is to compare with a CSS solution.
The conclusions of these studies so far are: (i) the accelerated solutions should use at least 100 repeats per timestep, and preferably 1000 or more, (ii) the solutions should be compared for various timesteps and the accelerated solution compared with a long CSS run, (iii) the diagnostics provided by propel diagnostics should be activated (via the appropriate GALDEF parameters) and their output studied. The reference should ideally be a run for which the differencing-based timescale from propel diagnostics becomes machine infinity everywhere in space and energy. The tests should be done for every species considered since e.g. protons, radioactive nuclei and electrons have quite different propagation characteristics.

(19 Jan 2011: ) The explicit time method is now available in GALPROP, and tests with diagnostics will be added soon in this section.

12 Document history

This documents the history of this manual.

01 July 2009 AWS: new for v54 based on v50 manual
05 July 2009 AWS: added section on program architecture
23 July 2009 AWS: documented all new parameters
05 May 2010 AWS: description of format of galdef file
07 May 2010 AWS: description of CR electron source parameters
11 May 2010 AWS: description of nuclei files and headers
14 Sept 2010 AWS: convection differencing scheme etc explained
01 Oct 2010 AWS: explained ELENORM and NUCNORM in 3D nuclei file.
05 Oct 2010 AWS: added description of parameters source_norm and electron_source_norm provided by Gulli.
21 Oct 2010 AWS: added warning about parameter use symmetry
03 Nov 2010 AWS: started section on synchrotron calculation details
10 Nov 2010 AWS: started section on coordinate system; reference to Vladimirov etal 2010, and copy of enhancements from there.
31 Dec 2010 AWS: started section on tests.
13-17 Jan 2011 AWS 5.5.3: covered 3D as well as 2D case. Explained that SM98 described the wrong method. Formulated the real CN method. Formulated the explicit method. Updated authors affiliations, added Andrey.
19-21 Jan 2011 AWS explicit method implementation described, and corresponding parameter explained. Convergence parameter described.
25 Jan 2011 AWS added description of parameters network_iter_compl and network_iter_sec
03 Feb 2011 AWS added example of changeover from timestep mode 1 to 2. Described turbo method in galdef parameters.
09 Mar 2011 AWS description of Stokes calculation, calculation of synchrotron emissivities.
06 May 2011 AWS started analytical solution for decay case
20 May 2011 AWS B-field parameters: no restriction on number of parameters
10 Jun 2011 AWS synchrotron emissivity formulae corrected
05 Jul 2011 AWS free-free absorption parameters added
07 Sep 2011 AWS free-free maps always output. in output description, skymap names for healpix described.
19 Sep 2011 AWS synchrotron polarization angle maps described
22 Sep 2011 AWS copied from galprop_v54.tex and changed title accordingly. Described synch. polarized fraction.
16 Nov 2011 AWS copied from galprop_v55.tex, changed title, no longer with version number.
16 Dec 2011 AWS updated notes on synchrotron options.
07 Feb 2012 AWS corrected formula for exponential B-field: $R_o$ was missing.
20 Feb 2012 AWS added synchrotron emissivity units and Q, U emissivity files.
18 Apr 2012 AWS documented Huang option for pib_decay and c++ option for bremss.
REFERENCES

20 Mar 2013 AWS documented new convection model with wind starting at given z.
11 Apr 2013 AWS Healpix skymap intensity units stated: no $Eg^2$ factor
29 Apr 2013 AWS new convection = $3 \tanh$ function
02 May 2013 AWS convection = $3$: formula for $dv/dz$ in convection
13 Oct 2013 AWS info on versions added. $n_{H_{av}}$ bug correction noted.
16 Oct 2013 AWS anisotropic diffusion parameters described.
23 Oct 2013 AWS primary positrons parameters described
28 Oct 2013 AWS spatial boundary conditions parameter described
04 Nov 2013 AWS new hadronic gamma-ray models described
08 Nov 2013 AWS described more source distribution parameters. corrections and additions to synchrotron section, source function output files described.
11 Nov 2013 AWS parameters for 3rd break in injection spectra described
06 Jan 2014 AWS described column format for HEALPix skymaps, corrected description of free-free emission and absorption.
10 Feb 2014 AWS noted that spectral parameters per isotope only in v55
16 Apr 2014 AWS sec 3.4 (output files) and 5.5.2 (secondary production): corrected units of source functions, inline and in def of sourcefunctionunits.
17 Apr 2014 AWS proton norm type, electron norm type: luminosity normalization note.
23-25 Apr 2014 AWS Expanded explanation of source abundances in 5.5.1, improved notation. Fixed duplicate labels A.1 (NB there are more duplicates to be fixed).
12 May 2014 AWS deuterium fusion source described in 5.5.2
05 June 2014 AWS B_field_name: described JF12 B-field model implementations

References

REFERENCES


Code available from http://sourceforge.net/projects/ppfrag
REFERENCES


