DM GALPROP

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1 Introduction

In general, the GALPROP code solves the transport equation for various species of cosmic rays in the Galaxy and computes various types of emission from them. A full description of the code and respective updates can be found at [1]. Also a detailed general manual is included in the "doc" folder of the code distribution (i.e. the whole tarball for download). This brief manual describes the DM part only AND supersedes the respective part of the general manual. The current DM version is based on GALPROP v54r2766. Comments and questions on DM GALPROP can be addressed to the author's e-mail above.

2 DM source

WIMP annihilation everywhere in the Galaxy is expected to produce various energetic final products: electrons, protons, gammas, neutrinos etc. and their respective antiparticles. Then they propagate and give a rise to various emissions from radio to gamma through synchrotron, ICS, bremsstrahlung etc. Gammas and neutrinos are obviously free-streaming products. The injection of all these species is described by the following source term $q(r, p)$, which would enter the transport equation:

$$q(r,p) = \frac{1}{2}\langle\sigma v\rangle \left(\frac{\rho_{\rm DM}(r)}{m_\chi}\right)^2 \xi_{\rm DM}(r)\frac{dN}{dp}(p), \tag{2.1}$$

where $\langle\sigma v\rangle$ denotes the WIMP annihilation cross section, $\rho_{\rm DM}(r)$ is the DM density distribution, m_χ is the WIMP mass, $\xi_{\rm DM}(r)$ is the DM annihilation rate boost factor due to substructures and $\frac{dN}{dp}(p)$ represents the spectral yield of any specie of interest. The latter depends on both WIMP mass and annihilation channel, and comes from particle physics data. Below some details are provided on every key component of the source term.

- ***DM density distribution.*** Currently GALPROP supports four different profiles: generalized NFW, Isothermal, Einasto and Burkert. Their exact definitions are:

$$\begin{aligned}
\text{gNFW}: \rho_{\text{gNFW}}(r) &= \frac{\rho_s}{(\text{Max}[r, r_{tr}]/r_s)^{\gamma}\,(1+\text{Max}[r, r_{tr}]/r_s)^{3-\gamma}} \\
\text{Einasto}: \quad \rho_{\text{Ein}}(r) &= \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\} \\
\text{Isothermal}: \quad \rho_{\text{Iso}}(r) &= \frac{\rho_s}{1+(r/r_s)^2} \\
\text{Burkert}: \quad \rho_{\text{Bur}}(r) &= \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}
\end{aligned} \tag{2.2}$$

  GALPROP does averaging of the DM density squared (which enters eq. (2.1)) inside every spatial grid cell in order to take into account possible steep variations of the density. Also, considering that the gNFW profile in eq. (2.2) is singular in the center, there is an option (see below) to leave the density flat below some radius for that profile. This prevents formation of an artificial spike in the center, where the real DM distribution is known quite poorly in fact.

- ***DM annihilation rate boost factor.*** Substructures boost the DM density and, hence, the annihilation rate. However, in a small vicinity of the Galactic center ∼1 kpc they almost don't survive due to tidal disruption. Hence, the boost factor can be negligible there. However, it can reach significant values up to ∼10 far from the center. This local boost factor is assumed to be a function of the radial distance only and implemented based on the results of [2] (which were presumably derived assuming the NFW profile for the smooth component). If one would like to stay conservative in computation of the emission intensity due to DM, there is an option to turn off the boost at all.

- ***DM annihilation yields.*** This comes from particle physics and defines how many stable products (like electrons and others) are being produced in one annihilation depending on their energy. Such a spectra begin at kinematic threshold $m_\chi c^2$ and typically rise with energy decrease. The yields are implemented as numerical tables for every final product and annihilation channel based on results of [3–5]. Specifically, the latest version of the yields is used, which includes electroweak corrections. Yields are taken as non-polarized (if applicable), meaning average of the Left/Right or Longitudinal/Transverse. Currently, 12 annihilation channels are implemented: $\chi\chi \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, \gamma\gamma, gg, W^+W^-, ZZ, hh$ (with $q \equiv u, d, s$).

3 Installation

Generally installation procedure consists of two major components - building the original GALPROP and embedding the DM upgrade into it. Naturally we provide here at Github only the DM upgrade part in a form of patch file, since the whole GALPROP source code is not supposed to be freely copied and re-distributed. Hence, a user has to download first the GALPROP from its original repository. More specifically, one has to go through the

following steps to build/install the whole DM GALPROP product. Order of steps below may be varied, but the scheme below is guaranteed to work.

1. Download the whole DM GALPROP repo from Github, which will contain this manual, galdef example file, DM folder (with annihilation yield tables) and DM_upgrade patch file.

2. Download the general data files provided by the GALPROP team at http://galprop.stanford.edu/code.php?option=download. Over there you can find instructions on how to compose the necessary data directory.

3. Unpack our file "DM.tar.gz" from Github and place the resulting folder without renaming into the data directory created in the previous step (so-called FITS-data directory).

4. The current DM upgrade is essentially tied to the specific GALPROP version - v54r2766. This (the source) has to be downloaded from https://sourceforge.net/projects/galprop/. Note that if the newer version will appear in the future at the front page of the cited repo, you can always find older versions in the "Files" section.

5. Unpack the source folder from the previous step and place our "DM_upgrade2.patch" file from Github into the "source" subdirectory.

6. Go to the "source" subdirectory by "cd" command and issue the following command in the terminal: "patch -i DM_upgrade2.patch" .

7. Now you can install GALPROP following instructions provided by their authors in the "README" file. Don't forget to pass the path to the FITS-data folder created at the steps 2-3 to ./configure option "-with-fitsdata=".

8. After installation you can test whether DM upgarde works by running the simple DM example "galdef_54_testDM". In this galdef file you can also see some typical parameter choices.

4 Usage

In general, it's recommended to run the 3D version of the code rather than 2D. The former one is more precise and better tested. Currently, DM GALPROP is capable to compute propagation of DM electrons, positrons and antiprotons. Regarding computation of an emission, the synchrotron from electrons and positrons is currently well developed and tested (see e.g. our work [6] based on the current version). A user can compute gamma rays due to DM too. However, the gamma ray part is not well tested yet. In order to get any gammas, one has to set in galdef file gamma_rays = 1. Then if ONLY the prompt gammas are needed, set DM_gammas = 2. In case anything else is needed - DM_gammas = 1. In order to get secondary gammas due to DM, which come from ICS and bremsstrahlung of DM electrons, one has to turn on respectively IC_ and bremss.

Notes on 3D version: it's extremely recommended to choose the spatial grid steps dx,dy,dz in a way that one of the grid points would fall exactly at the Galactic center x=0,y=0,z=0. This is because the DM source is very concentrated around the center and, hence, the central grid point has a very important role among all others. And it has to be

"resolved" in computation through the best way possible, especially for the case of cuspy profiles like NFW. Realistic runs typically require $dx \approx dy \approx dz \approx 0.2$ kpc.

DM parameters in galdef file are described below. As was already mentioned, all other parameters are described in the general GALPROP manual. There is also an example of a typical galdef file for the DM run in the "GALDEF" folder of the main distribution - "galdef_54_testDM".

DM_positrons = 0 1=compute DM positrons
DM_electrons = 0 1=compute DM electrons
DM_antiprotons = 0 1=compute DM antiprotons
DM_gammas = 0 1=compute DM gammas, 2=compute DM gammas ONLY AND NOTHING ELSE

DM_int0 = 1 DM density profile $\rho_{\rm DM}(r)$: 0=generalized NFW; 1=Isothermal; 2=Einasto; 3=Burkert; 9=DarkSUSY
DM_int1 = 1 9=DarkSUSY DM source
DM_int2 = 1 DM annihilation channel: $1 = e^+e^-,\ 2 = \mu^+\mu^-,\ 3 = \tau^+\tau^-,\ 4 = q\bar{q},\ 5 = c\bar{c},\ 6 = b\bar{b},\ 7 = t\bar{t},\ 8 = \gamma\gamma,\ 9 = gg,\ 10 = W^+W^-,\ 11 = ZZ,\ 12 = hh$
DM_int3 = 1 Substructure on/off ($\xi_{\rm DM}(r)$): 1=based on Kamionkowski (which is likely for NFW only)
DM_int4 = 1 doubles lepton source function (0=no) in order to save comp. time by propagating only one specie; if turned on, requires either one of DM_positrons or DM_electrons to be 0; should be a good approximation; doesn't work in case of the presence of positron annihilation
DM_int5 = 1 not used
DM_int6 = 1 not used
DM_int7 = 1 not used
DM_int8 = 1 not used
DM_int9 = 1 0=fixed increment synchrotron frequency grid (set by nu_synch_min, nu_synch_max, nu_synch_factor), >0=number of arbitrary desired frequencies

DM_double0 = 28.44 scale radius r_s of the DM density profile, kpc
DM_double1 = 0.033 scale density ρ_s of the DM density profile, GeV cm^{-3}
DM_double2 = 19.1 DM particle mass m_χ, GeV; must be in the range [5..100000] AND greater than the rest mass of the primary products (set by DM_int2); inaccuracies are possible close to the thresholds
DM_double3 = 15.0e6,30.0e6,45.0e6 list of coma-separated arbitrary desired synchrotron frequencies (Hz), if DM_int9>0
DM_double4 = not used
DM_double5 = not used
DM_double6 = 1.1 inner slope parameter γ for the gNFW DM density profile (1.0 gives the canonical NFW)
DM_double7 = 0.17 α parameter for the Einasto profile

DM_double8 = 0.05 truncation radius r_{tr} for the gNFW profile, below which the DM density stays constant, kpc. It's strictly NOT recommended to set it lower than ∼0.01 kpc, since the gNFW profile steeply blows up near the central point, which may lead to unphysical source term value in the central cell; DM numerical simulations anyway don't resolve anything below such a limit.

DM_double9 = 3.0e-26 thermally averaged annihilation cross section $\langle\sigma v\rangle$, cm^3/s

5 Changes between v2 and v1

- New annihilation channels added: $\chi\chi \to e^+e^-, c\bar{c}, t\bar{t}, \gamma\gamma, gg$;
- Bugs fixed that now the code is capable to compute the prompt DM gammas alone (with DM_gammas = 2);
- No redundant synchrotron polarization files are produced if not requested (i.e. with synchrotron = 2 in galdef).

Acknowledgments

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References

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