DRAGON2 : A novel code for Cosmic-Ray transport in the Galaxy

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Cosmic rays origin - Beyond the standard models
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The DRAGON project
(2008 - ongoing)

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Major contribution from Luca Maccione to the first version
The DRAGON project
(2008 - ongoing)

**DRAGON1 (2008 - still maintained)**


**DRAGON2 (2016 - in development)**


[https://github.com/cosmicrays/DRAGON](https://github.com/cosmicrays/DRAGON)
The DRAGON project

aim: modeling CR transport in the Galaxy in the most general way

\[
\nabla \cdot (\mathbf{J} - \mathbf{v}_w N) + \frac{\partial}{\partial p} \left[ p^2 D_{pp} \frac{\partial}{\partial p} \left( \frac{N}{p^2} \right) \right] - \frac{\partial}{\partial p} \left[ \dot{p}N - \frac{p}{3} \left( \nabla \cdot \mathbf{v}_w \right) N \right] = Q
\]

Each process is associated to a position and rigidity dependent operator

+ state-of-the-art, updated models for the astrophysical distributions of sources, interstellar gas, radiation field, magnetic field
The new code will be released soon as a fully open-source package. A light version of the code with the new solver will be available online in a very short time.

The solver was mostly rewritten and new technical solutions have been considered for each operator.

**Main features**

- **Position-dependent** and **anisotropic** spatial diffusion
- **New numerical approach** for reacceleration, advection and energy losses (new discretization schemes, new boundary conditions)
- **New physical ingredients** (e.g. pion production energy losses)
- Possibility to use a **non-equidistant spatial grid** and of propagating **transient sources**

The user can implement a general, non-separable expression of the parallel and perpendicular diffusion coefficients. A variable normalization and rigidity scaling of the diffusion coefficient can be considered.

\[ D_{ij} = D_\perp \delta_{ij} + (D_\parallel - D_\perp) b_i b_j \]

This approach is required by both theory and observations.

- **Theory**: the presence of a large scale Galactic magnetic field breaks isotropy and introduces a preferred direction

- **Observations**: data are in tension with homogeneous propagation models
spatial diffusion in DRAGON2

-Gradient problem-

M.Ackermann et al. (Fermi-LAT Coll.), ApJ 726, 2010

the radial profile of the gamma-ray emissivity along the galactic plane is flatter than predicted on the basis of SNR catalogues
spatial diffusion in DRAGON2

-Gradient problem-

inhomogenous diffusion coefficient correlated with the turbulent strength of the magnetic field (to the CR source density)

C.Evoli et al., PRL 108, 2012

\[ D \propto Q(r)^\tau \]

the CR density profile flattens and the gradient problem is solved!
spatial diffusion in DRAGON2

-Slope problem-

C. Yang et al., PRD 93, 2016, Acero et al. (Fermi Coll.) ApJS 223 26 (2016)

Gamma-ray spectra in the inner Galactic plane point towards an hardening of CR spectra towards the center of the Galaxy

see Carmelo Evoli’s talk
Progressively harder scaling of the diffusion coefficient with rigidity.

D. Gaggero et al., PRD 91, 2015

\[ D(\rho) = D_0 \beta^n \left( \frac{\rho}{\rho_0} \right)^{\delta(r)} \]

with \[ \delta(r) = ar + b \]

the CR spectrum hardens towards the center and the slope problem is solved!
spatial diffusion in DRAGON2

-Slope problem-

Anisotropic diffusion can explain the hardening.

\[ D_{ij} = D_\perp \delta_{ij} + (D_\parallel - D_\perp) b_i b_j \]

Out-of-plane component of the GMF in the inner Galaxy

\[ D_{ij} \propto E^{1/3} \]
\[ D_\perp \propto E^{0.5\div0.6} \]

De Marco, Blasi. Stanev, JCAP 6 2007

S.S. Cerri, A. Vittino, D. Gaggero et al., in preparation

Jansson and Farrar 2012

Are we seeing parallel escape of CRs in the inner Galaxy?
Anisotropic diffusion can explain the hardening.

S.S. Cerri, A. Vittino, D. Gaggero et al., in preparation
spatial diffusion in DRAGON2

-Slope problem-

Anisotropic diffusion can explain the hardening.

The shape of the spectral index profile depends on the features of the parallel and perpendicular transports, the Galactic magnetic field, the degree of turbulence, the size of the halo …

Is there a way to explain the hardening inferred from gamma-ray data within this picture?

Halo size = 5 kpc, $\delta_{\text{par}} = 0.3$, $\delta_{\text{perp}} = 0.5$
other features of DRAGON2
-Use of a non-equidistant binning-

A non-equidistant binning (NEB) is useful to model CRs that are confined in a very compact region. This might occur if a CR source is within or close to a region where the diffusion coefficient drops (local bubble).

In some situations, using a NEB decreases sensibly the runtime!
other features of DRAGON2

- Possibility to model transient sources -

Point-like source active for 0.05 Myr.
Diffusion across the galactic plane dominates over the vertical one

The signature of the anisotropic diffusion is clearly visible
spectrum evolution at 1 kpc from the source

- Possibility to model transient sources -

Point-like source **active for 0.05 Myr**.
Diffusion across the galactic plane dominates over the vertical one.

Different timescales associated to the diffusion at different rigidities can be seen clearly.

High-energy particles diffuse faster than low-energy ones:

\[ t_{\text{arrival}} = \frac{1\ \text{kpc}}{6D(p)} \]
We implement a 2nd order discretisation scheme for the energy loss operator as done in the PICARD code Kissmann AP 55, 2014

We gain one order of magnitude in accuracy without increasing the number of iterations!
We use new boundary conditions in the treatment of momentum diffusion:

\[ N(p = p_{\text{max}}) = 0, \quad \left( \frac{d}{dp} \frac{N}{p^2} \right)_{p_{\text{min}}} = 0 \]

With the new solver the condition \( p_{\text{min}} = p_{\text{min}} \text{ (injection)} \) can be imposed without loss of accuracy!
DRAGON2 in a broader context

DRAGON2 is part of a suite of numerical packages that cover all the relevant processes in Astroparticle physics from MeV to PeV scale!

1) HeSky

- models gamma-ray diffuse emission from GeV to TeV due to:
  - Inverse Compton scattering
  - Bremsstrahlung
  - Pion decay
- synchrotron radiation
- diffuse neutrino emission due to pion decay up to PeV energy

2) HelioProp

computes the diffusion-loss equation in the Heliosphere allows to model charge-dependent solar modulation affecting CRs below few GeV
DRAGON2
and the Dark Matter community

The new features in DRAGON2 are very useful for the community interested in indirect DM detection!

Example: the inner Galaxy gamma-ray excess

D.Gaggero et al., JCAP, 2015 (also Carlson, Profumo, 2015)

with a more realistic modeling of the source distribution in the GC region the excess is reabsorbed!

To better investigate that, models including advection, anisotropic diffusion, and exploiting the non-equidistant binning are needed!
Conclusions and forthcoming work

We have presented DRAGON2, the new version of the DRAGON code.

The novel features of DRAGON2 make it suitable to be used to model a wide range of processes in CR physics and compete with the upcoming more precise measurements.

The complete suite of tools (DRAGON2, HeSky and HELIOPROP) provide an invaluable instrument to study both CR physics and dark matter indirect detection in a multi-messenger and consistent way.

Next steps of the DRAGON project:

- Public release of a light version of the code with the new solver (very soon!)
- Dedicated papers on cross-sections network and anisotropic diffusion
- Release of the full version of the code, that will be followed by HeSky and Helioprop
Thank you for your attention!
Backup slides
DRAGON2
state-of-the-art models for the astrophysical ingredients

**Source distribution**
- Case1998
- Yusifov2004
- Lorimer2006
- Ferriere2001

**Interstellar gas distribution**
- Ionized: Corders1991, NE2001

**Magnetic field model**
- Sun2007
- Pshirkov2011
- Jansson&Farrar2012

**Interstellar radiation field model**
- Porter2006
- Delahaye2010
for each operator:

— we derive an analytical solution

— we consider the relevant timescales

— we choose the timestep of the simulation

— we run the solver until convergence is reached (for the single operator, it is enough to look at the residual)

— we compare numerical and analytical solutions for different choices of the grid size

\[ N_a(x, y, z) = \cos \left( \frac{\pi x}{2L_x} \right) \cos \left( \frac{\pi y}{2L_y} \right) \cos \left( \frac{\pi z}{2L_z} \right). \]

In order to satisfy Eq. B.4, the source term must take the following form:

\[ Q(x, y, z) = \frac{\pi^2}{4} \left( \frac{D_{xx}}{L_x^2} + \frac{D_{yy}}{L_y^2} + \frac{D_{zz}}{L_z^2} \right) \cos \left( \frac{\pi x}{2L_x} \right) \cos \left( \frac{\pi y}{2L_y} \right) \cos \left( \frac{\pi z}{2L_z} \right). \]
new ingredients in DRAGON2

DRAGON2 implements nuclear energy losses by pion production!

pion-production energy losses are relevant in the whole energy range

They can affect the whole spectrum (especially if diffusion is slow)