cosmic-ray propagation with DRAGON2
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): some relevant literature


DRAGON2 (2016 - in development)

all relevant processes are taken into account:
— spatial diffusion
— energy losses
— reacceleration
— advection
— spallation

the equation is solved for all species in a time-dependent way, until convergence is reached

each process is associated to a position-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 entirely rewritten and new technical solutions have been considered for each operator

all the aspects of the code, all the details on the numerical schemes, boundary conditions, convergence, accuracy are fully documented in detail

**Main features**

- Position-dependent (non-separable) and anisotropic spatial diffusion (fully tested); all operators are general and position-dependent
- New numerical approach for reacceleration, advection and energy losses (new discretization schemes, new boundary conditions), careful testing
- New physical ingredients (e.g. pion production energy losses)
- Possibility to use a non-equidistant spatial grid and of propagating transient sources
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
- looking forward for new models!
new ingredients in DRAGON2

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.

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 conventional propagation models:

- Gradient problem: the radial profile of the gamma-ray emissivity along the galactic plane is flatter than predicted

- Slope problem: gamma-ray spectra in the inner Galactic plane point towards an hardening of CR spectra towards the center of the Galaxy
new ingredients in DRAGON2

DRAGON2 can simulate anisotropic propagation from a transient source

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!

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

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

\[ t_{\text{arrival}} = \frac{1 \text{kpc}}{6D(p)} \]
new ingredients in DRAGON2

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 many situations, NEB decreases the runtime in a significant way!
an application of DRAGON2

The slope problem in gamma-ray data

The gamma-ray data are a very important tracer of the CR distribution across the Galaxy. Fermi-LAT data are crucial to test and constrain CR propagation models!

A progressively harder slope of the proton spectrum towards the inner Galaxy has been recently inferred from Fermi-LAT gamma-ray data [Fermi collab. 2016; Yang et al. 2016]: see also Carmelo Evoli’s talk!

This result is in tension with conventional GALPROP-based predictions.

A serious challenge for CR propagation models based on homogeneous diffusion!
The gamma-ray data are a very important tracer of the CR distribution across the Galaxy. Fermi-LAT data are crucial to test and constrain CR propagation models!

This effect may be the hint of a harder scaling of the diffusion coefficient with rigidity.

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

\[ \delta(r) = ar + b \]
The slope problem in gamma-ray data

The gamma-ray data are a very important tracer of the CR distribution across the Galaxy. Fermi-LAT data are crucial to test and constrain CR propagation models! This effect may be the hint of a harder scaling of the diffusion coefficient with rigidity [D. Gaggero et al., PRD 91, 2015]
The slope problem in gamma-ray data

The gamma-ray data are a very important tracer of the CR distribution across the Galaxy. Fermi-LAT data are crucial to test and constrain CR propagation models!

Why a harder diffusion in the inner Galaxy?

parallel diffusion: $\delta \sim 0.3$
perpendicular diffusion: $\delta \sim 0.5$

[De Marco, Blasi, Stanev, 2007]

out-of-plane Galactic magnetic field component in the inner Galaxy

[Jansson and Farrar, 2012]

$\rightarrow$ are we seeing parallel escape of CRs in the inner Galaxy? $\leftarrow$

[Cerri, Vittino et al., in preparation]

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**an application of DRAGON2**

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![Gamma-ray data](image)

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**Numerical propagation of high energy cosmic rays in the Galaxy**

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**Figure 3.** Parallel and perpendicular diffusion coefficients as a function of energy for different fields: 0.5, 1.0, 2.0, and 5.0. The results of Ref. [12] show no dependence of the ratio $D_{\parallel}/D_{\perp}$ on energy and for all components. This means the striated field is everywhere aligned with the local large-scale field and has the same relative magnitude everywhere in the Galaxy. 

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**Table 1.** Best-fit values and 1 standard deviation errors for the disk and the 3-kpc region. The parameters are given by $X_{\mu}$, where $X$ is the toroidal halo component and the relativistic electron density, with a rescaling factor for the relativistic electron density, with a multiplicative factor to the calculation of $B_{\parallel}$, such that when this factor is equal to unity the model describes a purely regular field. We parametrize striated fields by adding a multiplicative factor to the calculation of $B_{\parallel}$.

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**RESULTS**

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The best-fit field in the disk is shown in the top panel as a symmetric toroidal halo component. At the boundary between the outer region with constant elevation angle and the inner region with varying elevation, the field strength is $\delta \sim 0.5$.

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**Figure 3.** Parallel and perpendicular diffusion coefficients as a function of energy for different fields: 0.5, 1.0, 2.0, and 5.0. The results of Ref. [12] show no dependence of the ratio $D_{\parallel}/D_{\perp}$ on energy and for all components. This means the striated field is everywhere aligned with the local large-scale field and has the same relative magnitude everywhere in the Galaxy.

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an application of DRAGON2

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

Example: the Galactic bulge emission

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 future 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 over a wide range of energies.

The complete suite of tools (DRAGON2, HeSky and Helioprop) provide a comprehensive set of instruments 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, followed by HeSky and Helioprop
Thank you for your attention!

Daniele Gaggero

TeVPa 2016
**DRAGON2**
new features, a complete documentation

<table>
<thead>
<tr>
<th>Feature</th>
<th>GALPROP</th>
<th>PICARD</th>
<th>DRAGON2</th>
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<tr>
<td>- inhomogeneous sources</td>
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</tr>
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</table>
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
new ingredients in DRAGON2

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

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