The status of constraints on cosmic ray propagation models

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with the collaboration of
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Dark Matter all around workshop, 2010
Cosmic rays in the Galaxy

CRs propagate into the turbulent Galactic magnetic field \((B \approx 2 \mu G \text{ locally})\)

The Larmor radius of a CR is

\[
\rho_L(E) = \frac{E}{ZeB} \approx 1 \text{ pc} \left(\frac{E}{10^{15} \text{ eV}}\right) \left(\frac{B}{1 \mu G}\right)^{-1}
\]

m.f. coherence length \(\approx 100 \text{ pc} \Rightarrow \text{ propagation is diffusive up to } \sim 10^{16-17} \text{ eV.}\)
The transport equation

CRs obey essentially a diffusion equation (Ginzburg & Syrovatsky, 1964)

\[
\frac{\partial N_i}{\partial t} - \nabla \cdot (D \nabla v_c) N_i + \frac{\partial}{\partial p} \left( \dot{p} \frac{p}{3} \nabla \cdot v_c \right) N_i - \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} N_i = Q^i(p, r, z) + \sum_{j>i} c \beta n_{gas}(r, z) \sigma_{ji} N_j - c \beta n_{gas} \sigma_{in}(E_k) N_i
\]

**Diffusion tensor**

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

\(\rho = \text{rigidity} \sim p/Z\)

**Energy loss**

**Convection term**

\[v_c\]

**Reacceleration**

\[D_{pp} \propto \frac{p^2 v_A^2}{D}\]

**SN source term.**

We assume everywhere a power law energy spectrum

**Spallation cross section. Appearance of nucleus i due to spallation of nucleus j**

**Total inelastic cross section. Disappearance of nucleus i**

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Main transport parameters

- diffusion coefficient

\[ D(\rho) \propto \beta^\eta D_0 \left( \frac{\rho}{\rho_0} \right)^\delta \]

- diffusive halo height (degenerate with \( D_0 \) for stable species)

\[ Z_{\text{max}} \quad (\text{L}) \]

- reacceleration (relevant up to \(~ 10-100 \text{ GeV/n}\) )

\[ \mathbf{V}_A \quad (\text{Alfven velocity}) \]

- convective velocity (relevant up to \(~ 10 \text{ GeV/n} \) )

\[ \mathbf{V}_c , \quad d\mathbf{V}_c/dz \]

- solar modulation (relevant up to \(~ 10 \text{ GeV/n} \) )

\[ \Phi \quad (\text{may be charge dependent}) \]

Astrophysical source parameters

- source spectral indexes and breaks

\[ Q_i(\rho) \propto \beta^{\eta_S} Q_{0,i} \left( \frac{\rho}{\rho_0} \right)^{\gamma_i} \]

\( \gamma_i , \quad Q_{0,i} , \quad \eta_s \quad (\text{relevant only at low energy}) \)

more general source spectra can be used.
Equation solvers

Several ways of solving the diffusion equation:

- **leaky-box / slab analytical models:**
  
  **Pro:** Analytic and meaningful solutions for some species. Benchmark model!
  
  **Con:** cannot account for many effects; cannot model $e^\pm$, synchrotron and $\gamma$-rays

- **semi-analytic models:** assume simplified distributions for sources and gas, and try to solve the diffusion equation analytically
  
  **Pro:** fast, easy interpretation;
  
  **Con:** can hardly model $e^\pm$ at high $E$; cannot model synchrotron and $\gamma$-rays em.;

- **numerical models** required to deal with more realistic physical conditions
  
  GALPROP most used package  
  DRAGON recently developed/tested  
  
  **Pro:** comprehensive. They allow multi-messenger analysis including synch. and $\gamma$-rays
  
  **Con:** slower (can be compensate by faster parallel comput.)
Solar modulation

In the “force field” approximation modulation, just one (time dependent) parameter, $\Phi$, which has to be fixed against data.

This depend on the LIS spectrum hence it is model dependent!

$$J(E_k, Z, A) = \frac{(E_k + m)^2 - m^2}{(E_k + m + \frac{Z|e|}{A}\Phi)^2 - m^2} \quad J_{\text{LIS}}(E_k + \frac{Z|e|}{A}\Phi, Z, A)$$

Warning: demodulation should performed for each isotope!
Main features can be understood in terms of a relatively simple scenario in which

- CR are injected with a power law spectrum (as expected from Fermi acceleration)

- the diffusion coefficient is uniform and scale with rigidity ($\rho = p/Z$) as $D(\rho) \propto \rho^\delta$

- solar modulation shapes the observed spectra below few GeV
Secondary/primary nuclei

modulation and convection are expected to be irrelevant for $E > \text{few GeV/n}$

reacceleration and spallation losses are expected to be irrelevant for $E > 100 \text{ GeV/n}$

B/C is the preferred probe (well measured fluxes, cross sections)
Secondary Antiprotons

CR proton/He spallation onto the Galactic gas is an avoidable antiproton source

\[ p + p_{\text{gas}} \rightarrow p + p + p + \bar{p} \]

kinematical threshold 7 GeV.

Common approach

B/C data \(\Rightarrow\) propagation parameters \(\Rightarrow\) antiproton spectrum

antiprotons data may then be used to constraint a primary component which may produced by astrophysical sources or by dark matter annihilation/decay

Caution! Even with no-exotic components the informations coming from nuclear and \(\bar{p}\) data are not exactly degenerate!!
Indeed not all models allow a consistent fit!

- Plain Diffusion ($D_{xx} \sim \beta^{-3} R^{0.6}$)
  - Require breaks to fit antiprotons and B/C

- Diffusive Reacceleration
  - Fits B/C, other CR species, but underproduces antiprotons by a factor of \( \sim 2 \)

Strong & Moskalenko 2002,'03
The interpretation of Galactic CR nuclear and antiproton data
results of groups working with semi-analytical codes

- Relatively large values of $\delta$ (0.4 - 0.8) are favored
- Antiproton and secondary nuclear data are compatible
- **LARGE MODEL SCATTER**, in spite of detailed statistical analysis. It is mainly due to the large number of relevant parameters at low energy!

<table>
<thead>
<tr>
<th>Model</th>
<th>$\delta$</th>
<th>$K_0$ [kpc$^2$/Myr]</th>
<th>$L$ [kpc]</th>
<th>$V_c$ [km/s]</th>
<th>$V_a$ [km/s]</th>
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<td>0.46</td>
<td>0.0765</td>
<td>15</td>
<td>5</td>
<td>117.6</td>
</tr>
</tbody>
</table>
Recent results

very stringent constraints on exotic components were found.
Are they solid under those systematic uncertainties on the propagation models?

Donato et al. 2008

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The interpretation of Galactic CR nuclear and antiproton data

recent results of groups working with the USINE semi-analytical code and Markov chain MC analysis

Large scatter among the models

• at low energy this is dominated by the strong degeneracy (large number of unknown relevant parameters)

• at high energy it is dominated by the experimental errors!
The interpretation of Galactic CR nuclear and antiproton data
results of groups working with the GALPROP code

Best fit model
\[ \delta \approx 0.31 \pm 0.02, \quad z_{\text{max}} \approx 5.4 \pm 1.4 \text{ kpc}, \quad v_A \approx 38.4 \pm 2.1 \text{ km/s}, \quad v_c = 0 \]

✦ a break in the proton source spectrum is required!
✦ antiprotons are still underproduced at low energy

Trotta et al. [GALPROP team] arXiv:1011.0037
analysis based on Markov chain MC

**not included in the analysis**

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Charge dependent Solar modulation?

It should be there at some level. Up to which rigidity?

almost negligible above 1 GeV/n
Electrons and positrons
CR electrons

Synchrotron and Inverse-Compton losses play an important role above 10 GeV, the loss rate increasing with energy as $E^2$.

For $1 < E < 100$ GeV an analytical solution of the diff.eq. provides a good description of the data in the ~ 1 - few 100 GeV range.

$$N_e(E) \propto E^{-(\gamma_0(e) + \frac{\delta}{2} + \frac{1}{2})}$$

Boulanov & Dogiel 1974

At higher energies $\lambda_{\text{loss}} \equiv$ average distance of astrophysical sources (~ few 100 pc) ⇒ only few local sources should contribute and some bumpiness may be expected.
CR positrons

In the standard scenario $e^+$ are not expected to be significantly produced in the SNRs (see however Blasi, PRL 2009) but they are mainly produced by the spallation of primary nuclei

For $1 < E < 100$ GeV (scaling regime)

$$\frac{e^+}{e^- + e^+} \propto \frac{E^{-(\gamma_p + \delta/2 + 0.5)}}{E^{-(\gamma_0 + \delta/2 + 0.5)}} = E^{-\gamma_p + \gamma_0}$$

Since $\gamma_p \approx 2.7$ a decreasing ratio is expected for $\gamma_0(e^-) < 2.7$

as expected from Fermi acceleration and implied from radio observation of SNRs
The experimental situation before 2008

**Electron + positron spectrum**

Above few GeV the spectrum was fitted by a $\sim E^{-3.2}$ power-law (with large uncertainty)

In the figure GALPROP model with
\[ \delta = 0.33 \quad \gamma_0 = 2.54 \]
(Alfven vel. $V_A = 30$ km/s, no convection)

**Positron fraction**

Tension with AMS-01, HEAT and CAPRICE, incompatible with PAMELA

PAMELA coll., PRL 2009

It decreases since $\gamma_0 < \gamma_p \approx 2.7$

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The situation in 2009: ATIC, Fermi and H.E.S.S.

**Electron + positron spectrum**
*Fermi-LAT coll., PRL 2009*

Harder injection spectrum are required which however it is at odd with low energy pre-Fermi data
\[ \delta = 0.33 \quad \gamma_0 = 2.42 \]
a larger \( \gamma_0 \) (harder source spectrum) is required

**Positron fraction**

*even more incompatible with PAMELA*
*PAMELA coll., PRL 2009*

since it decreases like
\[ E^{-\gamma_p + \gamma_0} \]
The Fermi-LAT + HESS CRE spectrum

Electron + positron spectrum published in PRL, May 2009 based on 6 months data

compared with most significant previous data and the conventional GALPROP model with

\[ \delta = 0.33 \quad \gamma_0 = 2.54 \]

Fermi-LAT spectrum based on 1 yr data, extended down to 7 GeV

Latronico et al. - 2nd Fermi symp. 2009

[Fermi-LAT coll.] PRD 2010

The spectrum is fitted by a \( E^{-3.08} \) power-law

with hints for a hardening at ~100 GeV and a steeping above 500 GeV

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2010: new Fermi data down to 7 GeV

Drawbacks of single components models

- they do not allow a consistent interpretation of Fermi-LAT and PAMELA fraction data neither above nor below 10 GeV

Even without PAMELA:

- they cannot reproduce Fermi, and pre-Fermi, spectral slope below 100 GeV
- they can hardly explain the steepening observed by HESS above 1 TeV (and the hardening at ~100 GeV)

performed with GALPROP

$\gamma_0 = 1.6/2.5$ below/above 4 GeV
normaliz. @ 100 GeV

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The interpretation of Galactic CR electron and positron data
results of GALPROP team

Trotta at al. [GALPROP team] arXiv:1011.0037

e⁻ + e⁺

\( e^− \) source spectral index \( \gamma_e = 1.6/2.5 \) below/above 4 GeV + softening above 1 TeV
A fully numerical CR transport package developed by L. Maccione, C. Evoli, D. Gaggero & D.G.

Why we need a new code?

- GALPROP was the only numerical code. We need an independent check!
- It is important to know the code details
- Possibly, we need a faster code
- We need a more flexible code to account for new CR physics
- We need a code optimized to be interfaced with dark matter annihilation/decay simulators
DRAGON vs GALPROP

- same numerical methods

- same fragmentation cross sections, but also includes the new Webber (2003) cross sections

- practically the same results under the same conditions

- D. already implement position dependent diffusion (to be implemented to account anisotropic diffusion)

- D. takes advantage of full flexibility of C++ and it is few times faster than G.

- D. it is interfaced with DarkSUSY

- D. only 2D (to be implemented to 3D)
Introduction

The CR propagation equation from a continuous distribution of sources can be written in the general form

\[ \frac{\partial N_i}{\partial t} - \nabla \cdot (D \nabla - v_c) N_i^t + \frac{\partial}{\partial p} \left( \beta - \frac{2}{3} \nabla \cdot v_c \right) N_i^t - \frac{\partial}{\partial p} \beta^2 D_{pp} \frac{\partial}{\partial p} N_i^t = Q_i^t(p, r, z) + \sum_{j=1}^{n} c \omega_{gas}(\rho, z) \sigma_{ji} N_i^t - c \omega_{gas} \sigma_{cc}(E_c) N_i^t \]

Here, \( N_i^t(p, r, z) \) is the number density of the \( i \)-th atomic species; \( p \) is its momentum; \( \beta \) its velocity in units of the speed of light \( c \); \( \sigma_{in} \) is the total inelastic cross section onto the ISM gas, whose density is \( \rho_{gas} \); \( \sigma_{ji} \) is the production cross-section of a nuclear species \( j \) by the fragmentation of the \( i \)-th one; \( D \) is the spatial diffusion coefficient; \( v_c \) is the convection velocity. The last term on the l.h.s. describes diffusive reacceleration of CRs in the turbulent galactic magnetic field.

DRAGON adopts a second-order Cranck-Nicholson scheme with Operator Splitting and time overrelaxation to solve the diffusion equation. This provides fast a solution that is enough accurate for the average user. Occasionally, users may want to have very accurate solutions to their problem. To enable this feature, users may get close to the accurate solution by using the fast method, and then switch to a more accurate solution scheme, featuring the Alternating-Direction-Implicit (ADI) Cranck-Nicholson scheme.

Some parts of DRAGON are built following GALPROP, v50p. The first reason is that it is a waste of time to reimplement standard parts, like energy losses, in which nothing new has to be found. The second reason is that it is essential to be able to compare our predictions with that of the Galprop code, and this can be done only by following the details of its implementation. Therefore, we kept in the code some features and models used in Galprop, like nuclear cross-sections, the gas distribution, the convergence "technique". However, each of these models is accompanied by other models, which can be selected by setting the appropriate switch. This is done very easily using the well known C++ structure of abstract/derived classes. The code is then very flexible and easy to manage and to modify or update.

The code was built having in mind a few motivations:

- in order to find good propagation models one needs to run the code thousand times. Therefore we wrote the code aiming at performances and with an efficient memory management.
- we wanted to propagate DM originated cosmic rays. Therefore we wrote DRAGON as a library that can be coupled to, e.g., DarkSUSY.
- from the physics point of view, we wanted to have a position dependent diffusion model, which requires a substantial modification of the discretization scheme.

Installation

DRAGON comes with one library and one executable. The library contains the whole structure that is used to solve the CR propagation equation, and can be linked against other programs exploiting DRAGON classes. The executable is the result of coupling the DRAGON library with a driver routine, which reads user's input and solves the transport equation.
A new analysis approach:

- use B/C + N/O + C/O (as well p to fix modulation) + antiprotons
- energy dependent (we constraint $\delta, D_0/z_t, V_A$ using only data with $E_k > 5$ GeV/n)
- assume no spectral breaks in the nuclei source spectra

We first exploited CREAM (B/C) and PAMELA (antiproton/p) data
HEAO-3, CRN (light nuclei) AMS-01, BESS, CAPRICE (antip.) are also used

<table>
<thead>
<tr>
<th>$v_0$[km/s]</th>
<th>$E_{\text{min}}$[GeV/n]</th>
<th>B/C analysis</th>
<th>Joint analysis</th>
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<td>0.41</td>
<td>0.98</td>
</tr>
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A first combined analysis of updated CR nuclei and antiproton data

\( E_{\text{min}} = 5 \text{ GeV} \)

\( v_A = 10 \text{ km/s} \)

\( v_A = 20 \text{ km/s} \)

\( v_A = 30 \text{ km/s} \)

\( \delta \)
High reacceleration models need a spectral break

$V_A = 30 \text{ km/s}$

with no break in the source spectrum

the same with

$\gamma = 1.9 / 2.4$

down/above 9 GeV

$\Phi = 550 \text{ MV}$

this however does not help with antiprotons
Moderate reacceleration models need a break in the diffusion coefficient to fit data at low energy. This may be physically justified by Alfvén wave dissipation (see Ptuskin et al. 2006)

Here we think of it as an effective handling of a number of poorly known low energy effects.
Best fit model comparison

light nuclei

\( \Phi = 550\ \text{MV} \)

B/C

N/O

C/O

Oxygen

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Unstable nuclei

both models agree
Best fit model comparison

antiprotons

\[ \Phi = 550 \text{ MV} \]

the effect of changing \( v_A \) only
Best fit model comparison

light nuclei and antiproton summary

Moderate reacc. - Kraichnan diff.
\[ \delta = 0.5 \quad v_A = 15 \text{ km/s} \]
- it needs \( \eta = -0.4 \)
- it needs no source break
ok with antiprotons

Strong reacc. - Kraichnan diff.
\[ \delta = 0.3 \quad v_A = 38 \text{ km/s} \]
- ok with \( \eta = 1 \)
- it needs a source break
undershoot antiprotons
Antiproton uncertainty
under the condition to reproduce the B/C at 95% C.L.
How our results compare with semi-analytical models?

\[ V_A = 45 \text{ km/s in the disk corresponds to } V_A \sim 7 \text{ km/s in the halo} \]

Good agreement with the \( V_c = 0 \) model!

\[ \text{Maurin et al. 2009} \]
Electrons and positrons
Why the single component models do not work

Something is missing!
Adding an extra $e^\pm$ component

Toy model with a Galactic disk originated extra-component added to the conventional GALPROP background with a Kolmogorov set-up

$N_{extra}^{e\pm} \propto E^{-1.5} \exp(-E/1 \text{ TeV})$

$e^+/ (e^- + e^+)$

\[ e^+ / (e^- + e^+) \]

\[ N_{extra}^{e\pm} \propto E^{-1.5} \exp(-E/1 \text{ TeV}) \]
Adding an $e^\pm$ extra component

Toy model with a Galactic disk originated extra-component added to the conventional GALPROP background with a Kraichnan set-up

$N_{stand}^{e^-} \propto E^{-2.6}$

Di Bernardo, Evoli, Gaggero, D.G. Maccione, 2010
$e^\pm$ extra component with a moderate reacc. setup

$e^- + e^+$

$\Phi = 500 \text{ MV}$

Moderation actually looks charge independent!

$e^-$ only

$\Phi = 500 \text{ MV}$
A fully consistent scenario

- **Di Bernardo, Evoli, Gaggero, D.G. Maccione, 2010**

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**B/C**

- Data from different experiments:
  - Ballese (1989)
  - HEAO-3 (1990)
  - CRN (1993)
  - ATIC (2007)
  - CREAM 04 (2008)

**Energies**

- $E$ [GeV/nucleon]

---

**Protons**

- Data from different experiments:
  - BESS 93
  - BESS 98
  - CAPRICE 98
  - BESS 02
  - AMS-01
  - MAX
  - PAMELA 09

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**Antiprotons**

- Data from different experiments:
  - BESS 95+97
  - BESS 98
  - CAPRICE 98
  - AMS 01
  - PAMELA 09

---

**Preliminary**

- Data from different experiments:
  - Fermi (2010)
  - AMS (2002)
  - ATIC-1,2 (2008)
  - HEAT (2001)
  - PPB-BETS (2008)
  - BETS (2001)
  - HESS (2006-09)

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**Energies**

- $E$ [GeV]

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Physical realizations
Dark matter annihilation interpretation

Viable models invoke new (pseudo)scalar particle(s) which may decay mainly into leptons (such to avoid PAMELA antiproton constraints) and boost the annihilation cross above the value expected from standard cosmology due to the Born-Sommerfeld effect.

Benchmark DM model: 3 TeV DM annihilating mainly in $\tau^\pm$
see e.g. Bergstrom et al. 2009 and ref. therin

Computed with DRAGON + DARKSUSY
by L. Maccione

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Gamma-ray diffuse emission

**DRAGON + DARKSUSY**

Benchmark DM model: 3 TeV DM annihilating mainly in $\tau^\pm$
see e.g. Bergstrom et al. 2009 and ref. therin
Secondary antimatter production in SNRs?

Blasi, PRL 2009

$e^+/(e^- + e^+)$

$\bar{p}/p$

based on Blasi & Serpico 2009

Mertsch & Sarkar 2009

$e^- + e^+$
In D.G. et al. [Fermi coll.] 2009, 2010, the CRE background computed with GALPROP or DRAGON was summed to the analytically computed flux from actually observed **middle age** pulsars taken from the ATNF radio catalogue. A consistent choice of the propagation parameters and loss rates were used. Including the contribution of all observed pulsars with $d < 2 \text{ kpc}$ and assuming they inject $e^\pm$ with a spectrum $N_{e^\pm}(E) \propto (E/E_0)^{-\Gamma} \exp(-E/1 \text{ TeV})$ with $-1 < \Gamma < -1.8$.

Di Bernardo, Evoli, Gaggero, D.G. Maccione, 2010

Pulsar $e^\pm$ conv. efficiency $\approx 30\%$ for dipole like pulsar braking.
Astrophysical vs dark matter interpretations
CRE anisotropy

\[
\text{Anisotropy} = \frac{3D}{c} \frac{\Delta N_e}{N_e} = \frac{3}{2c} \frac{r}{t - t_0} \left( \frac{1 - (1 - E/E_{\text{max}}(t))^{1-\delta}}{(1 - \delta)E/E_{\text{max}}(t)} \right)^{-1} \frac{N_e^{\text{PSR}}(E)}{N_e^{\text{tot}}(E)}
\]


a positive detection in the Monogem direction may be at hand of Fermi-LAT!

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Conclusions

• Antiproton data should be accounted constraining CR propagation models. Present data clearly favor propagation models with moderate reacceleration and Kraichnan diffusion.

• Under the same conditions electron and positron data are reproduced at low energy with no need of invoking charge dependent modulation

• High energy PAMELA and Fermi-LAT data implies the presence of an $e^\pm$ extra-component with spectral slope $-1.5$ and peaked at $\sim 1$ TeV

• Pulsars may provide such extra-component under reasonable conditions

• Dark matter annihilation (decay) is still an interesting open possibility but it is difficult to validate.