Transport Models for Galactic Cosmic Rays in the Era of PAMELA, FERMI and AMS-02

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Outline

- Introduction to Cosmic Ray (CR) transport models
- Results of a Markov Chain Monte Carlo (MCMC) study
- Pulsar interpretation of the anomalous rise in the positron fraction
- The local bubble: facts and prospects
Cosmic Ray measurements

Proton
- AMS
- BESS
- ATIC
- JACEE
- KASCADE(SIBYLL)
- Tibet(SIBYLL)

All-particle
- Tibet(SIBYLL)
- KASCADE(SIBYLL)
- Akeno
- GAMMA
- TUNKA
- Yakutsk
- Auger
- AGASA
- HiRes

Electron (or positron)

AMS-02

ACE

CREAM

Fermi

Pamela

Caprice

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Transport models

- Aim: Reproduction of the locally measured spectra of cosmic rays
- Modeling of the transport processed the particles underly
- Numerical solution of the transport equation (e.g. Galprop, Dragon)
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Source distribution

→ Supernova remnants are believed to be the dominant sources for galactic cosmic rays

→ Injection spectrum is assumed to be a power law

\[ Q \propto E^{-\alpha} \]
Transport models

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Diffusion

→ CR particles scatter off the turbulences of the magnetic field

\[ D(R) \propto D_0 \cdot R^\delta \]
Transport models

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\[ V, \frac{dV}{dz} \]

Convection (galactic winds)
Transport models

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Diffusive reacceleration

→ CR particles scatter off randomly moving clouds, in which the magnetic fields are frozen

$v_{\text{alfven}}$
Transport models

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Particle losses

- Fragmentation
- Radioactive decays

Momentum losses

e.g. Bremsstrahlung
Transport models

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Transport models depend on many unknown parameters!
Our model: 16

e.g. Diffusion strength and rigidity dependence
Halo height
Injection spectrum
...

Compare model predictions with experimental data: \( p, \bar{p}, \frac{\bar{p}}{p}, \frac{B}{C}, \frac{10}{9} Be \)
Observables

Protons: *primary* CRs, directly produced and accelerated by SNRs

Proton spectrum
Pamela (2006 - today)
Observables

**Antiprotons:** *secondary* CRs, produced by interactions of CRs with the interstellar medium (ISM)

![Antiproton spectrum](image)

![Ratio antiprotons/protons](image)
Observables

**Boron/Carbon:** Secondary-to-Primary ratio

\[ \text{C + gas} \rightarrow \text{B} + \text{X} \]

measure for the gas, 'seen' by CRs

- **HEAO-3** Satellite (1979 - 1981)
- **ACE** Spacecraft (1997 - today)
- **CREAM** Balloon borne (5 flights, 2004 - 2010)
Observables

$^{10}\text{Be}/^{9}\text{Be}$: Ratio of radioactive nuclei

Half life of $^{10}\text{Be}$: $1.39 \times 10^6$ years

$^{9}\text{Be}$: stable

measure for the time, CRs spend in the galaxy: 'Cosmic Clock'

- ISOMAX: Balloon borne (1998)
- ACE: Spacecraft (1997 - today)
A Markov Chain Monte Carlo approach

Why use MCMC and not a simple minimizing algorithm?

→ not feasible for such a high dimensional problem
   Evaluation of a single model takes minutes to hours

→ We do NOT just want to find a best fit model, so no fine tuning.
   Instead, want to explore wide ranges of parameter space (exotic models?)
   Examine the full potential and the limitations of these kind of models

→ Use MCMC in order to sample the parameter space efficiently

Results are based on ~ 10 Mio. Models

> 1 year with ~ 1.500 CPU cores
How well are the transport parameters constrained by these data sets?

averaged deviation to data $\leq 1 \sigma$ ($\sim$ top 100 models)
MCMC Results

How well are the transport parameters constrained by the data sets?

more scattering

less scattering

Top 100

Log(Diffusion Coefficient)
MCMC Results

Preferred diffusion coefficient by the single observables

Range of agreement
MCMC Results

Rigidity dependence of diffusion

Height of diffusion halo [kpc]

\( \chi^2_{\text{min}} \)

Top 100

Compatible
MCMC Results
Preferred halo size by the single observables

- Protons
- Antiprotons
- Antiprotons/protons
- Boron/Carbon
- Beryllium ratio

slightly preferred
slightly preferred
Compatible
MCMC Results
Preferred halo size by the single observables

Halo size cannot be constrained

\[ \frac{1}{X^2} \]

\[ \text{beryllium ratio} \]

- Protons
- Antiprotons
- Antiprotons/protons
- Boron/Carbon
- Beryllium ratio

\[ \frac{^{10}\text{Be}}{^{9}\text{Be}} \]

Need more precise data!
MCMC Results

Summary

• Sampling of parameter space using MCMC

• Some transport parameters can and some cannot be constrained by the experimental data

• The preferred models can be used as background models and allow predictions for other observables
  → Leptons
Most favored explanations are additional primary positrons by:
- Pulsars
- Dark matter annihilation
(not covered in this talk)

Impossible to mimic with a pure secondary production of positrons!

Dowgoing behaviour expected from standard CR transport

Leptons

\[
\frac{e^+}{(e^+ + e^-)}
\]

MCMC result

AMS-02

Downgoing behaviour expected from standard CR transport

Impossible to mimic with a pure secondary production of positrons!

Most favored explanations are additional primary positrons by:
- Pulsars
- Dark matter annihilation

(not covered in this talk)
Pulsars

→ highly magnetized, rotating neutron stars
Electrons are extracted from the surface by electric fields and later transformed into electron-positron pairs through electromagnetic cascading

**Expected flux can be modeled**\(^1\), but large uncertainties due to

- transport
- pulsar properties: distance, age, energy output, injection, efficiency, ...

\(^1\) e.g. arXiv:1001.4540
Pulsars

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- pulsar properties: distance, age, energy output, injection, efficiency, ...

**Fit to data:**
- use the 10 most contributing (known) pulsars
- allow pulsar parameters to vary inside their observational limits
- use the very latest data of Pamela, Fermi and AMS-02
- fit the available $e^+$, $e^-$ data sets simultaneously: $e^-, e^+, (e^+ + e^-)$, $e^+/(e^+ + e^-)$

¹ e.g. arXiv:1001.4540
Pulsars Fit Results

Electrons

\[ E^2 \phi_e [\text{GeV}^2 \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}] \]

Positrons

\[ E^2 \phi_p [\text{GeV}^2 \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}] \]

Background

Additional pulsar contribution

Same for \( e^+ \) and \( e^- \)
Pulsars Fit Results

**Positron fraction**

- AMS-02

**Electrons + Positrons**

- Fermi

Background

Additional pulsar contribution

Is there a way to disprove the pulsar/point like source explanation?
Anisotropy of Pulsars

- Most of the SNR (the sources of 'usual' CRs) are located towards the galactic center at ~ 4 kpc

→ Expect dipole anisotropy of background itself

- Anisotropies of several pulsars can cancel each other completely

\[ \delta = 0 \quad \delta = 1 \]
Anisotropy of \((e^+ + e^-)\)

→ Current and upcoming upper limits may challenge the pulsar explanation
Local transport

$\rightarrow$ $e^+$ and $e^-$ suffer from large energy losses due to synchrotron radiation and inverse compton scattering
$\rightarrow$ loose energy much faster than e.g. protons

$\rightarrow$ short propagation lengths of 0.5 – 1 kpc
  Protons: few kpc

$\rightarrow$ *local transport*: highly affected by the local environment
The local bubble

- lower gas density, factor 100–1000
- irregular shape, radii 50-150 pc → very local!
- Age: 5 –12 Myr
- Origin: SN explosions

This structure could significantly affect the transport of local CRs!

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The local bubble

Lower gas density → Effect on diffusion?

Reminder: CR particles scatter off the turbulences of the magnetic field

Connection between turbulences and gas density?

less turbulence being washed out: → more scattering?

or

less magnetic focus points: → less scattering?
The local bubble

Electrons are blocked out of the bubble! A possible isotropizer?

Local bubble: $R = 0.3$ kpc, $D_{LB}/D_{out} = 0.1$ → more scattering centers

Work in progress...
The local bubble

Local bubble: $R = 0.3$ kpc, $D_{LB} / D_{out} = 10$ → less scattering centers

Electrons are pulled into the bubble

0.64 GeV electrons

Point source

M. Weinreuter

Work in progress...
Summary

• By using MCMC sampling, the parameter space of transport parameters was studied

• Positron fraction cannot be described with the assumption of a pure secondary production of positrons
  → Additional positron sources are needed

• Nearby pulsars could explain the positron fraction and lead to an anisotropy, which may challenge the pulsar explanation with upcoming upper limits

• The local environment could significantly affect the transport of local CRs and the expected anisotropies. Work in progress...