Cosmic Ray Transport (in the Galaxy)

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A few disclaimers and preliminary remarks!

- Not my main field of research
- Views expressed are personal
- Quite elementary and didactic
- Please interrupt and ask questions!
The problem(s)

How to relate the flux of GCRs observed at and near the Earth to the production spectra at the sources?

How to calculate the diffuse galactic background for gamma-ray astronomy?

How to calculate the astrophysical backgrounds of anti-protons, positrons etc for indirect dark matter searches?
All three problems are closely related

Need to `de-propagate’ spectra to infer true production spectra in acceleration theory.

Need to accurately model GCR production of gamma-rays in gamma-ray astronomy.

Before claiming indirect evidence for decaying dark matter we need to understand the irreducible astrophysical backgrounds.

Also interesting astrophysical issue with significant implications for the physics of the ISM.
Sources

Nuclear spallation

Solar modulation and observation

Secondary particle production

Energy gains and losses
Charged cosmic rays gyrate about magnetic field lines

A proton at even 1 PeV in typical ISM field of about 0.3nT only has a gyro-radius of 1Pc, substantially smaller than Galactic scales.
Not true of course for UHECR

at 1EeV gyroradius of a proton is 1kPc, larger than the vertical thickness of the Galactic disc.

Strongly suggests that the UHECR are extragalactic in origin.

Of course smaller for high Z particles......

But for lower energies particles are strongly scattered and isotropized by magnetic field of Galaxy.
Observational constraints

- Abundances of secondary spallation nuclei relative to primary (mainly B/C, but also sub-Iron to Iron).
- Decay of radioactive secondaries (and stability of K-capture nuclides).
- Fluxes of positrons and anti-protons.
- Diffusive gamma-ray emission of the Galaxy.
- Arrival direction anisotropies.
- Interstellar cloud chemistry and heating.

Ideally want a physically motivated transport model that fits all the observational constraints simultaneously and is astrophysical plausible!
The GeV gamma-ray sky

Fermi-LAT, AGILE, EGRET, Cos-B, SAS-2....
Galactic diffuse gamma-ray emission at GeV energies

- Is dominated by gamma-rays from neutral pion decays.
- Traces product of CR intensity and gas density.
- Shows that the solar neighbourhood is quite normal and the CRs fill the entire Galaxy with a spectrum and intensity not too different from those we measure locally.
- Slightly higher intensity and hints of a harder spectrum near the galactic centre.
- Magellanic clouds are clearly sub-luminous relative to the Galaxy.
- The last two observations prove Galactic origin for the GeV part of the spectrum.
Figure 27.1: Fluxes of nuclei of the primary cosmic radiation in particles per energy-per-nucleus are plotted vs energy-per-nucleus using data from Refs. [2–13]. The figure was created by P. Boyle and D. Muller.

**Boron-to-Carbon ratio**

![Graph showing the boron-to-carbon ratio](image)

- *10% of total expected data*

- **B/C Ratio**

- **Kinetic Energy (GeV/n)**

Data sources include:
- Orth et al. (1972)
- Dwyer & Meyer (1973-1975)
- Simon et al. (1974-1976)
- HEAO3-C2 (1980)
- Webber et al. (1981)
- CRN-Spacelab2 (1985)
- Buckley et al. (1991)
- AMS-01 (1998)
- ATIC-02 (2003)
- TRACER (2006)
- AMS-02
Secondary to Primary ratios

Clearly decrease with energy; higher energy particles have made fewer nuclear interactions.

Rules out long slow acceleration during transport (this observation killed Fermi’s original proposal for CR origin and acceleration by ISM turbulence).

Surprisingly large amount of matter traversed - of order several g/cm².
To put this in context, assume a typical number density
\[ n \approx 1 \text{ cm}^{-3} \]
and a typical Galactic length scale
\[ L \approx 1 \text{ kPc} = 3 \times 10^{21} \text{ cm} \]
then the `grammage' is only
\[ Lm_H n = 5 \times 10^{-3} \text{ g} \]
The cosmic rays appear to have gone through a thousand times this amount of matter!
Radioactive secondaries

Some spallation secondaries are unstable as so can be used to probe the “age” of the cosmic rays.

One of the best is $^{10}\text{Be}$ with a half-life of 1.4 million years.

These all point to an “age” of about $10\text{Myr}$ at CR energies of a few GeV/nucleon.

$$10^7 \text{ yr} = 3 \times 10^{14} \text{ s} = 10^{25} \text{ cm/c} = 3 \text{ MPc/c}$$
K-capture nuclei

Some nuclides are stable when fully stripped but decay by capturing an electron from the innermost 1s orbital if they have attached electrons.

Can be used as probes of time between nucleosynthesis and acceleration (rules out prompt acceleration in the same SN).

Also sensitive to low-energy propagation, but interpretation is complex.
Anti-particles

Expect production of anti-protons and positrons by the same nuclear interactions that produce the spallation secondaries and neutral pion gammas.

Anti-protons appear to be at the levels expected and the low-energy positrons also fit well.

Clearly an additional source of positrons at high energies - Pamela and AMS data are convincing - probably pulsars.

No trace of heavy anti-nuclei (as expected).
The AMS data (red) v expectation from secondary production (green).
From Ting’s 18th Sep seminar at CERN
From Kappl and Winkler arXiv:1408.0299
Predictions of secondary anti-protons compared to data from BESS-Polar II (blue) and Pamela (red)
Arrival direction anisotropies

Very small! Serious constraint on models.

Typically less that one part in a thousand even at PeV energies - very isotropic distribution.

Evidence for structure on small angular scales - somewhat surprising and not anticipated, but there are a number of more or less plausible explanations.
Fig. 17.— Combined map of significances in the cosmic ray arrival direction distribution observed by Milagro in the northern hemisphere (Abdo et al. 2008) and IceCube in the southern hemisphere (this analysis). Both maps have been smoothed with a 10° radius.

Abassi et al 2011, arXiv:1105.2326v4
Toy models - focus on Galactic transport of lower energy GCRs

Dimensional analysis:

- Want to relate observed density of particles to production rate.
- Need to multiply production rate by a residence time scale to get total number in Galaxy.
- Then divide by a typical confinement volume to get spatial density.

\[ f \propto Q \frac{T}{V} \]
Motivates simplest (and clearly wrong) transport model - the leaky box.

Assume volume $V$ is fixed (the `box’)

Particles leak out of the box on an energy dependent time-scale $T(p)$ which decreases with energy (easier to escape at high energy).

Box is filled uniformly.

Then can very naturally explain the falling secondary to primary ratios....
\[ f_1 \propto \frac{Q_1(p)T(p)}{V} \]
\[ f_2 \propto \frac{Q_2(p)T(p)}{V} \]
\[ Q_2 \propto \sigma cn f_1 \implies f_2 \propto \sigma cn f_1 \frac{T(p)}{V} \]
\[ \implies \frac{f_2}{f_1} \propto \sigma cn \frac{T(p)}{V} \]
Fits fairly well with a `box' that is slightly larger than the Galaxy and an escape time falling as energy to the power 0.6 and of order 10Myr at a few GeV/n.

However the escape time would then have to drop to 10kyr at one PeV and it is very difficult to reconcile this with the low anisotropy.

Also the model is clearly physically absurd, but can be justified as an approximation to more realistic diffusion models.

Three ways to steepen the secondary spectra:
Either

\[ f(p) \]

\[ f \propto \frac{Q\tau}{V} \]

Injected

Observed

\[ Q(p) \]

Pure leaky box

\[ \ln(p) \]
Or

Re-acceleration of low energy particles

$ln(p)$

$f(p)$

Injected

Observed
Or

Deceleration of high energy particles!
Diffusion models (current paradigm)

Cosmic rays are injected from `sources’ in the Galaxy.

They then perform a random walk in position and in momentum by scattering off the magnetic field of Galaxy until they eventually escape into intergalactic space.

Can be described in terms of a diffusion process
\[
\frac{\partial f}{\partial t} = Q + \nabla (D_{xx} \nabla f) + \frac{1}{p^2} \frac{\partial}{\partial p} \left( p^2 D_{pp} \frac{\partial f}{\partial p} \right) + \ldots.
\]

Solved numerically in well known GALPROP code and semi-numerically in USINE.

For Alfvén wave scattering expect the two diffusion processes to be related by

\[
D_{xx} D_{pp} \approx \frac{1}{9} p^2 V_A^2
\]
In models with re-acceleration the steepening of the secondary to primary ratios results from two processes, the energy dependent escape and the re-acceleration at low energies.

Can show that if the two diffusion coefficients are inversely related as expected, then the steepening is by twice the power-law of the spatial diffusion in the region where the two effects overlap.

Leads to a spatial diffusion coefficient proportional to the 0.3 power of energy rather than 0.6.
Some issues with re-acceleration models

- At high energies must be just pure escape, so do expect to see flattening of the secondary to primary ratios.

- Not clear how much energy is needed at low energies, and what proportion of the total Galactic CR luminosity comes from the ISM turbulence in these models.

- Requires some fine-tuning of the input proton spectrum to fit the observations.

- Requires rather softer input spectra than theorists generally like.
Following the energy

How much power is required to maintain the observed GCR population? Conventional estimate is about $10^{41}$ erg/s or $10^{34}$ W.

- Ginzburg and Syrovatskii (1964) $0.3 \times 10^{34}$ W
- Galprop (Strong et al, 2010) $(0.7 \pm 0.1) \times 10^{34}$ W
- Drury, Markiewicz and Völk (1989) $< 3 \times 10^{34}$ W
Summary of energetics

- Can safely assume \( 0.3 \times 10^{34} \text{W} < L_{\text{GCR}} < 3 \times 10^{34} \text{W} \)

- As is well known \( P_{\text{SNe}} \approx 10^{35} \text{W} \)

- No other plausible source of enough energy although pulsar winds and OB winds may contribute at 10% level.

- Solar wind definitely accelerates GCR by pushing them out of the heliosphere, but total power in solar wind is only \( 3 \times 10^{20} \text{W} \) so even for all M stars in Galaxy only get \( 3 \times 10^{31} \text{W} \)
So only plausible source of bulk of energy is SNe

Adiabatic losses imply not in explosion itself

So mediated through shocks and/or turbulence driven by SNRs.

\[ P_{\text{SNe}} \approx 10^{35} \text{ W} \]

\[ L_{\text{GCR}} \approx 10^{34} \text{ W} \]
Other contributions not ruled out and indeed in some cases quite plausible!

- Pulsars - especially for electrons and positrons!
- OB associations, stellar winds.
- Galactic centre?? Needs variability?
- Differential rotation of Galaxy and magnetic instabilities/reconnection??
Effects of Outflows

- Diffusion models assume a static Galaxy.
- In reality likely to be a CR and hot gas driven outflow from the Galaxy.
- Adiabatic deceleration at high energies due to expansion of wind.
- Leads to the model of Zirakashvili et al…
Most ambitious attempt I know of at a fully self-consistent and physically motivated model of cosmic ray transport.
Assume that above plane of the disc there is an outflow (driven by the CR pressure) which in combination with the rotation of the Galaxy pulls the magnetic field lines out into very long flux tubes draped around a roughly hyperboloid surface.

The flow slowly accelerates as one goes out along one of these tubes.

At some point advection takes over from diffusion as the dominant transport process.

Crucially this is energy dependent and happens further out for higher energies.
In terms of the simple toy box models, this is in effect an expanding leaky box and not just a leaky box!

Makes is much easier to satisfy the anisotropy constraints (very large diffusive halo at high energies).

Is compatible with the harder source spectra anticipated from theory (in fact requires them).

Deserves to be further studied IMHO.
Conclusions

- Cosmic Ray transport in the Galaxy is complex!
- The numerical diffusion models are a big step forward, but still incomplete.
- Time to re-examine dynamical outflow models.
- Need to look at all the observational constraints and model them simultaneously.
- Models should explicitly state implications for source power and spectra.