Cosmic rays: lots of data... and a few theoretical challenges

Disclaimer: I will only deal with (Galactic) hadronic cosmic rays & on direct detection range (no EAS/UHECRs)

P. D. Serpico (Annecy-le-Vieux, France)
06/12/2016 - NBI Copenhagen
• We only have access to cosmic ray fluxes “modulated” by heliosphere

• Primary fluxes have power-law spectra

• Primary spectra have universal (species independent) spectral indices

• Positron flux dominated by secondaries

• Propagation parameters as dominating uncertainty in theory predictions
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Probably all of them wrong! (Still trusting theorists?)
### SOME THINGS WE BELIEVE(D) ABOUT CR

- **We only have access to cosmic ray fluxes “modulated” by heliosphere** ✗
- **Primary fluxes have power-law spectra** ✗
- **Primary spectra have universal (species independent) spectral indices** ✗
- **Positron flux dominated by secondaries** ✗?
- **Propagation parameters as dominating uncertainty in theory predictions** ？

**Probably all of them wrong!** *(Still trusting theorists?)*

### “Sec.1.2: Is progress in the cosmic ray field slow?”

It certainly looks like that. *From T. Stanev’s “High Energy Cosmic Rays” textbook*

It does not look like that over the last decade (mostly triggered by experimental progress)!

Let me detail some of these facts and theoretical implications
THE REMARKABLE VOYAGER SAGA

Voyager 1 exited the solar system and gives us access to “unmodulated” CRs
THE (PRE-EXISTING) CONSENSUS
Probably the most obvious expectation about cosmic rays (0\textsuperscript{th} order picture we teach in CR 101) is that, above a few GeV and below the PeV (Galactic CR regime) they have "featureless power-law energy* spectra"

* I will focus on the relativistic regime, hence I won’t be pedantic and will often use energy or momentum interchangeably

Lots of work rely on/predict e.g. self-similarity (Fermi Theory, Kolmogorov spectrum...)

CR HAVE POWER-LAW SPECTRA
How is cosmic ray acceleration taking place?

*Via “diffusive shock acceleration”*

In what type of objects?

*Supernova remnants*

Where are they located? When did the events happen?

*Randomly in the Galaxy, well approximated by a continuum injection term*

How do cosmic rays get to us, after leaving their acceleration sites?

*Diffusing into an externally assigned, scale-invariant turbulent medium (ISM)*
WHAT ABOUT THE CR SOURCE TERM?

A Crash Course

All acceleration mechanisms have electromagnetic nature
Note: from the astrophysical point of view, finding “CR from DM annihilation” would represent a “new acceleration mechanism”!

B-fields cannot increase charged particles’ energies, therefore E-fields are needed for acceleration to occur

Two conceptual possibilities

REGULAR ACCELERATION
THE ELECTRIC FIELD IS LARGE SCALE:

\[
\langle \vec{E} \rangle \neq 0
\]

STOCHASTIC ACCELERATION
THE ELECTRIC FIELD IS SMALL SCALE:

\[
\langle \vec{E} \rangle = 0 \quad \langle \vec{E}^2 \rangle \neq 0
\]
REGULAR FIELD

Very special in astrophysical environments to achieve this condition, because of the high electrical conductivity of astrophysical plasmas. Examples: “fast”, transient phenomena, “charge starved” configurations...

REGULAR ACCELERATION
THE ELECTRIC FIELD IS LARGE SCALE:

\[ \langle \vec{E} \rangle \neq 0 \]

MAGNETIC RECONNECTION
Regions with opposite orientation of magnetic field merge, local electric field \( E \sim LB \), where \( L \) is the size of the reconnection region. Known to be operational in the Sun, probably also in PWN...

UNIPOLAR INDUCTOR:
rotating B-fields as in pulsars establish an electric potential \( \Delta V \) between surface & \( \infty \). But \( \Delta V \) usable to accelerate only where condition \( \vec{E} \cdot \vec{B} = 0 \) is violated (“gaps”). MHD is broken in the gaps!

For (hadronic) CRs, people focus on...

STOCHASTIC ACCELERATION
THE ELECTRIC FIELD IS SMALL SCALE:

\[ \langle \vec{E} \rangle = 0 \quad \langle \vec{E}^2 \rangle \neq 0 \]
Think of any physical process requiring a time $\tau$ per cycle (with escape probability $P_{\text{esc}}$) repeating randomly for a time $T$ leading to a fixed fractional energy gain $\xi$

\[ E_{n+1} - E_n = \xi E_n \implies E_n = E_0 (1 + \xi)^n \]
\[ (1 - P_{\text{esc}}) \implies (1 - P_{\text{esc}})^n \]

The resulting (cumulative) spectrum is [sum geometric series with $x=(1-P)$]

\[ N(\geq E) \propto \sum_{m=n}^{\infty} (1 - P_{\text{esc}})^m = \frac{(1 - P_{\text{esc}})^n}{P_{\text{esc}}} = \frac{1}{P_{\text{esc}}} \left( \frac{E}{E_0} \right)^{-\gamma} \]
\[ \gamma = \frac{\ln(1 - P_{\text{esc}})^{-1}}{\ln(1 + \xi)} \simeq \frac{P_{\text{esc}}}{\xi} \]
\[ n = \frac{\log(E/E_0)}{\log(1 + \xi)} \]
\[ a^{\ln b} = b^{\ln a} \]
A shock (e.g. from a supernova remnant) can sweep the interstellar medium.

The shock front brings with it magnetic turbulence, causing change of particle momenta.

plenty of shocks available in the Galaxy…
(beautiful and numerous enough to regularly sell magazines)
A shock (e.g. from a supernova remnant) can sweep the interstellar medium. The shock front brings with it magnetic turbulence, causing change of particle momenta.

\[
\begin{align*}
  v' &= -v - V \\
  v'' &= +v + V
\end{align*}
\]

When the “mirror” is magnetic, in the Lab there is a moving B-field, i.e. an electric field is available to accelerate the particles wrt the Lab frame.

Gain of energy in the Lab frame:

\[
\begin{align*}
  -v &\quad +V \\
  v + 2V &\quad \text{Lab}
\end{align*}
\]

Please note:

No gain of energy in the shock frame:

\[
\begin{align*}
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\end{align*}
\]

plenty of shocks available in the Galaxy… (beautiful and numerous enough to regularly sell magazines)
Some fraction of particles can enter the shock again... a smaller and smaller fraction of them enters the shock more and more often...

together with the E-independence of the fractional E gain, explains the power-law shape of the spectrum.
Some fraction of particles can enter the shock again… a smaller and smaller fraction of them enters the shock more and more often…

Good features of the model

I. Acceleration 1st order in the large shock velocity: efficient!

\[ \frac{\Delta E}{E} \sim \frac{V_{sh}}{c} \sim 10^{-3} - 10^{-2} \]

II. Spectral index is universal for strong (M>>1) shocks in ordinary matter (does not depend on chemical composition, for instance)

III. Spectral index value for cumulative E spectra Ok with inferred\( \sim 1+\varepsilon \)

IV. Estimated E-budget stored in kinetic energy of SNRs \~1\ o.o.m. larger than what stored in CRs (efficiency of O(10%) ok)

\[ \gamma_I \sim 1 + \frac{4}{M^2} \]
HOW DO CRs PROPAGATE?

Charged particles deflected in B-fields, known to permeate the interstellar medium. Their “Larmor Radius” is

\[ r_L = \frac{p_\perp}{Z e B} \approx \frac{1 \text{ pc}}{Z} \left( \frac{p_\perp}{\text{PeV}/c} \right) \left( \frac{1 \mu\text{G}}{B} \right) \]

Even for protons, this distance is comparable to distance between neighboring stars up to \(~\text{PeV}\) and smaller than Galactic Sizes up to \(\text{EeV}\).
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Even for protons, this distance is comparable to distance between neighboring stars up to ~PeV and smaller than Galactic Sizes up to EeV.

CRs probe thus “small-scale inhomogeneities” in the field, changing direction by what appear “random kicks”, similar to brownian motion.

Macroscopically, described as diffusion (+ a drift)

$$\frac{\partial \Phi}{\partial t} + \nabla \cdot \mathbf{J}_\Phi = Q$$

Continuity Equation

$$\mathbf{J}_\Phi = -D(x, \Phi, E \ldots) \nabla \Phi$$

Fick's law

Let’s get a closer look to some properties of this diffusion
Describe B-field as regular component $B_0$ + magnetostatic perturbations (power spectrum $\mathcal{W}(k)$).

CR direction of motion changes diffusively: spatial diffusion coefficient $D$ depends on $\mathcal{W}(k)$ at wavenumbers corresponding to the CR Larmor radius.

$$D(p) = \frac{1}{3} r_L(p) v(p) \left. \frac{1}{k W(k)} \right|_{k = qB_0/pc} \int_{k_0}^{\infty} dk \ W(k) = \eta_B = \frac{\delta B^2}{B_0^2},$$
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\( \uparrow \) CR direction of motion changes diffusively: spatial diffusion coefficient \( D \) depends on \( \mathcal{W}(k) \) at wavenumbers corresponding to the CR Larmor radius.

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\]

The resonance condition tells us that:

if \( k^{-1} \gg r_L \) the CRs surf adiabatically the waves,

if \( k^{-1} \ll r_L \) the CRs hardly feel their presence

Each time a resonance occurs, the CR changes pitch angle by \( \delta B/B \) with random sign.

To diffusion one should add E-losses, sources/sinks, drift, the movement of diffusion centers…
Kolmogorov theory of fluid turbulence assumes:

- E-injection @ large scales (e.g. SNRs @ \( L_0 \sim O(10) \) pc)
- dissipation into heat at small scales
- scale invariant inertial regime where turbulence is isotropic and just “receives energy” from large scales and transfers it to small ones.

It leads to \( \mathcal{W}(k) \sim k^{-5/3} \) & the prediction \( D(R) \sim R^{0.33} \)
STANDARD EXPECTATIONS

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But that’s hydrodynamics, not MHD!
Is the B-field changing anything?

- keeping the hypothesis of isotropic turbulence, Kraichnan & Iroshnikov argued that predictions modify to \(\mathcal{W}(k) \sim k^{-3/2}\) & \(D(R) \sim R^{0.5}\) if the background field is strong wrt turbulence.

- But turbulence is expected to be anisotropic, with different power scaling \(\perp\) & \(\parallel\) to the field (e.g. Goldreich and Sridhar find Kolmogorov-like index for high turbulence & modes \(\perp\))
THE “NEWS”
(PART 1)
HINTS OF POSSIBLE SURPRISES

When the TeV/n range became to be explored with sufficient precision—notably with ATIC-2 (A. Panov et al 2009, Bull. Russ. Acad. Sci. Phys, 73, 564) & CREAM (Y. S.Yoon et al 2011 ApJ 728 122)—hints of possible departures from extrapolations of lower energies spectra clearly emerging in p, He... but also seen in nuclei!

Yet, conceivable concerns: systematics, possibly related to different experimental technologies?
1ST ANOMALY: BROKEN PL’S BELOW KNEE!

Soon after, PAMELA seemed for the first time to have a glimpse at the transition in p & He

Evidence in a single instrument seemed to settle the issue!

NOT YET! LIKE IN A GOOD THRILLER...

Preliminary results by AMS-02 @ ICRC 2013 did not confirm the picture!!!

How to make sense of the situation?
NOT YET! LIKE IN A GOOD THRILLER...

Preliminary results by AMS-02 @ ICRC 2013 did not confirm the picture!!!

How to make sense of the situation?
For He, the published analysis agrees at least qualitatively with a change of spectral slope of ~0.12 (although less prominent than PAMELA reports), at a rigidity ~250 GV comparable to the $p$ one

M. Aguilar et al. (AMS Collaboration)

M. Aguilar et al. (AMS Collaboration)

For $p$, agreement among AMS-02, PAMELA, CREAM (to some extent also quantitatively)

Exp. hardening (AMS) = 0.13 (~±0.05, sys. dom)

Finally, happy ending
To assess that, take simplest expectation:
(which, nonetheless, matched data till now…)

For **stationary, homogeneous & isotropic** problems & observations at a single location, the diffusion operator can be effectively replaced by an effective “diffusive confinement” time $\tau_{\text{diff}}$

\[
\frac{\partial \Phi}{\partial t} - D \nabla^2 \Phi = Q \Rightarrow \frac{\partial \Phi}{\partial t} + \frac{\Phi}{\tau_{\text{diff}}(E)} = Q
\]
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At steady state

$\Phi = Q(E)\tau_{\text{diff}}(E)$
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\]

At steady state

\[
\Phi = Q(E)\tau_{\text{diff}}(E)
\]

If both $Q$ and $\tau \sim 1/D$ are power-laws… then puzzling!

Naturally suggests (classes of) solutions:

- Drop $D$ homogeneity (and possibly isotropy)
- Drop power-law behaviour in $D$
- Drop power-law behaviour in $Q$
- Drop homogeneity (and possibly stationarity, isotropy…) in $Q$
- …
Power-law injection, feature reflects corresponding one in the diffusion coefficient, $D$ (naturally accounts for universality in rigidity). Different models differ in what causes the feature in $D$, e.g.

D not separable into rigidity and space variables:

Qualitatively reflecting the fact that turbulence in the halo (mostly CR-driven) should be different than close to the disk (mostly SNR driven)

$$D(z, \rho) = \begin{cases} 
    k_0 \beta \rho^\delta & \text{for } |z| < \xi L \ (\text{inner halo}) \\
    k_0 \beta \rho^{\delta + \Delta} & \text{for } |z| > \xi L \ (\text{outer halo})
\end{cases}$$

$\xi \sim 0.1$

$L \sim 5 \text{ kpc}$

Pheno model loosely inspired to arguments raised e.g. in Erlykin & Wolfendale J.Phys. G28 (2002) 2329-2348

Fits well, but no explanation for the values of the parameters
I. PROPAGATION

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Non-linear coupling of CRs with \( D \):

CR below the break diffuse on waves generated by CRs themselves, above the break onto external turbulence.


“Infinite layer”, diffusive halo height \(H\), Galactic-matter disk of infinitesimal thickness, advective wind velocity \(v_c \sim v_A\) outgoing.

\[
- \frac{\partial}{\partial z} \left[ D \frac{\partial f}{\partial z} \right] + v_A \frac{\partial f}{\partial z} - \frac{d v_A}{d z} \frac{p}{3} \frac{\partial f}{\partial p} = q_{CR}(z, p)
\]

Remembering that

\[
D(p) = \frac{1}{3} r_L(p) v(p) \frac{1}{k W(k)} \bigg|_{k=q_B_0/pc} \int_{k_0}^{\infty} dk \, W(k) = \eta_B = \frac{\delta B^2}{B_0^2},
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$$- \frac{\partial}{\partial z} \left[ D \frac{\partial f}{\partial z} \right] + v_A \frac{\partial f}{\partial z} - \frac{dv_A}{dz} \frac{p \partial f}{3 \partial p} = q_{CR}(z, p)$$

Remembering that

$$D(p) = \frac{1}{3} r_L(p) v(p) \frac{1}{k W(k)} \bigg|_{k=qB_0/pc} \int_{k_0}^\infty dk \ W(k) = \eta_B = \frac{\delta B^2}{B_0^2},$$

CR transport eq. solved iteratively with the following one for the waves to which it is coupled

$$\frac{\partial}{\partial k} \left[ D_{kk} \frac{\partial W}{\partial k} \right] + \Gamma_{CR} W = q_W(k).$$

**Non-linear “wave-wave” coupling → cascade**

$$D_{kk} = C_K v_A k^{7/2} W(k)^{1/2}$$

**Streaming instability rate (coupling with CR)**

$$\Gamma_{CR}(k) = \frac{16\pi^2}{3} \frac{v_A}{k W(k) B_0^2} \left[ p^4 v(p) \frac{\partial f}{\partial z} \right]_{p=qB_0/kc}$$

**External power injected** at large scale, e.g. SNRs at $\sim 1/50$ pc

$$q_W \propto \delta (k - k_0)$$
In absence of CR coupling, one finds the Kolmogorov spectrum

\[ W_{\text{ext}}(k) = \left( \frac{2\eta_B}{3k_0} \right) \left( \frac{k}{k_0} \right)^{-5/3} \Theta(k - k_0) \]

the input spectrum of CRs

\[ f_0(p) = A_p \left( \frac{p}{m c} \right)^{-\gamma_p} \]

implies that the NLLD diffusion rate (\( \Gamma_{NL} \sim D_{kk}/k^2 \)) equals the CR instability growth rate (i.e. CR driven waves saturation condition) at

**The right transition energy scale**

\[ E_{\text{tr}} = 228 \text{ GeV} \left( \frac{R_{d,10} H_3^{-1/3}}{\xi_{0.1} E_{51} R_{30}} \right)^{3 \frac{2(\gamma_p - 4)}{2(\gamma_p - 5)}} B_{0,\mu}^{\frac{2(\gamma_p - 5)}{2(\gamma_p - 4)}} \]

indep. of inj. scale \( k_0 \) (depends on level of MDH turbulence, but reasonable \( \eta_B \sim 0.08 \) for \( k_0 \sim 1/50 \text{ pc} \)
SANITY CHECK

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Pheno consequences already worked out
>3 years ago and overall a remarkable agreement with data

R. Aloisio and P. Blasi,
REVISITING THE MODEL

Despite its simplicity & the low number of free parameters, remarkable level of agreement over 6 decades of energy!

(Notably even with the “unmodulated” data at low-E, where transport is essentially advective)

R. Aloisio, P. Blasi and PS,
“Non-linear cosmic ray Galactic transport in the light of AMS-02 and Voyager data,”
II. MAKE Q ≠ POWER-LAW

One can play with acceleration population(s), acceleration mechanisms, or escape. For instance:

- **“Natural” evolution of Mach number, \( M \), within diffusion shock acceleration (DSA)**
  High-E CR accelerated/escape early on when \( M \gg 1 \), spectral index \( \alpha \sim 2 \),
  while low-E later when \( M \) is relatively low, \( \alpha \) steeper, remembering
  \[
  \alpha = 2 \frac{M^2 + 1}{M^2 - 1}
  \]

- **Multiple sources/sites (overlap of “different \( M \)’s”)**
  E.g. harder high-E component involving OB associations -
  Superbubbles, explosion of stars into magnetized winds
  (like Wolf-Rayet), as proposed in the past, e.g.
  T. Stanev, P. L. Biermann & T. K. Gaisser,

- **“Natural” consequence of non-linear diffusive shock acceleration (DSA)**
  Concavity of spectrum resulting from the nonlinear nature of DSA
  (but why reflected in escaping particles? Why universality?)
  V. Ptuskin, V. Zirakashvili, E. S. Seo,

- ...
Low-E comes from average contribution of the Galaxy, hardening due to CR released from local young CR sources

(local contribution can be treated parametrically or from a catalogue)


MNRAS 435, 2532 (2013) [1304.1400]

Till now the assessment of these model only done “qualitatively”: e.g. one typically needs fast diffusion and low supernova rate (in tension with other observations?) but how likely is the hypothesis in itself, given “Galactic variance”?
As another example, it has also been proposed that some local, old source contributes at low-E & overall contribution of young and further away ones dominates at high-E

+ Easily allows for a hadronic origin of the $e^+$ excess
- “breaking” a link, loses predictivity
- Prob. of such a configuration? (Not estimated)

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+ Easily allows for a hadronic origin of the $e^+$ excess
- “breaking” a link, loses predictivity
- Prob. of such a configuration? (Not estimated)

Alternatively, young (~2 Myr) local and steep source at low-E, high-E dominated by average contribution. Also invokes anisotropic diffusion, specific local field configuration and suggest a consistent scenario involving also $\gamma$'s, antimatter.

+ Same event would also explain also anomalous $^{60}$Fe isotopic abundance in deep sea crust sample
- Issue with spectrum of diffuse $\gamma$'s, unless extragalactic component is much smaller than thought
- Prob. of such a configuration? (Not estimated)
A THEORY FOR LOCAL SOURCE EFFECTS

Overall flux coming from N discrete sources

\[ \Psi = \sum_{i=1}^{N} \psi_i \]

does not necessarily match “continuum” average

\[ \langle \Psi \rangle = \frac{q}{2 h \pi R^2} \frac{h L}{K} \]

Actual flux obeys a prob. distribution obtained as convolution of single pdfs

\[ P_N(\Psi) = \int_{\psi_1} \int_{\psi_2} \cdots \int_{\psi_N} p(\psi_1) p(\psi_2) \cdots p(\psi_N) \delta \left( \sum_{i}^{N} \psi_i - \Psi \right) d\psi_1 d\psi_2 \cdots d\psi_N \]

It turns out that the diffusive solution

\[ \psi = \frac{q}{(4\pi K \tau)^{3/2}} \exp \left( -\frac{d^2}{4K \tau} \right) \]

implies power-law pdf \( p(\psi) \) with infinite variance

(Central Limit Theorem does not apply, fat-tail distributions!)

Physically, causality in Special Relativity and/or constraints from “local info” (e.g.: No SN in the Solar System in historical time!) still impose maximal flux, CLT applies…but possibly for a too large N compared with what physically interesting.

One has to deal with fat-tail PDF... “Stable Laws” replace Gaussians for some range of N, \( \Psi \)

A THEORY FOR LOCAL SOURCE EFFECTS

In a range of E and for not to extreme fluctuations, “3D” and “2D” Stable Laws provide a good approximation of the actual distribution obtained by numerical simulations.

**Generic consequence:** with current exp. precision, comparatively high probability to see deviations from average theory predictions, even if the model is correct! But does it explain “CREAM break”? Not very likely!

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What about other models?


It yields  \(8.6 \times 10^{-5}\)

Barring independent evidence for such a close-by, old source, only a two-populations model seems viable

The model in  **M. Kachelrieß, A. Neronov, D.V. Semikoz, PRL 115, 181103 (2015) [1504.06472]**

performs poorly if diffusion is isotropic;

possibly rescued by anisotropic diffusion, then the prob. to evaluate if the one to have a source of the right type along the field direction

<table>
<thead>
<tr>
<th>Models</th>
<th>MIN</th>
<th>MED</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probabilities(Stable law 5/3)</td>
<td>0.0072</td>
<td>0.0012</td>
<td>0.00016</td>
</tr>
<tr>
<td>Probabilities(Gaussian law)</td>
<td>0.06\rangle)</td>
<td>10^{-3}</td>
<td>0</td>
</tr>
</tbody>
</table>
THE “NEWS”
(PART II)
Above O(10) GeV/n, He spectrum ~0.1 harder than the p one


CREAM (filled circles), ATIC-2 (diamonds), CAPRICE94 (upward triangles), CAPRICE98 (downward triangles), LEAP (open circles), JACEE (stars), and RUNJOB (crosses)
Confidence grew stronger after PAMELA. By now, conclusively established:

**Almost uncontroversial, several experiments in agreement!**

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**Figure 11:** Proton/helium flux ratios measured by the present paper.
Confidence grew stronger after PAMELA. By now, conclusively established:

**Almost uncontroversial, several experiments in agreement!**

at high-E, harder He spectrum seems to be shared by heavier nuclei (strong hints e.g. from CREAM, being confirmed by AMS-02?)
THE PUZZLE & POSSIBLE SOLUTIONS

Usual acceleration & diffusive propagation mechanisms respond to rigidity: from EoM, should be composition-blind in the ultra-relativistic regime.

\[
\frac{1}{c} \frac{d\vec{R}}{dt} = \vec{E}(r,t) + \frac{\vec{R} \times \vec{B}(r,t)}{\sqrt{\vec{R}_0^2 + \vec{R}^2}} \quad \vec{R}_0 = A m_p c^2 / Z e
\]

\[
\frac{1}{c} \frac{d\vec{r}}{dt} = \frac{\vec{R}}{\sqrt{\vec{R}_0^2 + \vec{R}^2}} \quad \vec{R} = p c / e Z
\]

Some solutions proposed (and a few challenges!)

- **Non-e.m. effects in propagation (spallation?)**
  Does not seem consistent with parameters for B/C or anti-p
  P. Blasi, E. Amato, JCAP 1201, 010 (2012)

- **Different sources/sites**
  Requires special conditions (e.g. break should be propagation-induced to explain universality, in He/metals accelerators need to suppress p one & vice versa...)

- **Linked to the “natural” evolution of Mach number, \( M \), within DSA:**
  For some reason, He mostly accelerated “early on” (\( M >> 1 \)) p’s “later” (\( M \) is relatively low)
  what is this reason?
PREFERENTIAL “LATE” P ACCELERATION

(Some) possible reasons

• Related to the efficiency of injection in the acceleration cycle

Alfven waves ~ frozen with the shock, dominated by p. At same Vsh, He++ have twice the p gyroradius, more likely to return upstream, more efficiently accelerated. Both p and He efficiency declines with M, but faster decline for p. expected ⇒ softer spectrum


• Variable (ionized) He/p concentration in medium swept by shocks

caused by time-dependent ionization state?

older/weaker shocks propagate in medium where more He is neutral than in strongly ionized environment of young remnant


“just” reflecting the chemical environment in the sources?

e.g. argued to match environment in superbubbles


“spatial” segregation of He vs p

p tend to be in % more abundant “far away” (attained later by the shock)

SOME EXPECTATIONS/GOALS FOR THE NEAR FUTURE

- **Secondary/primaries as diagnostics for break**

- **Spectral dependence vs. primary species** (e.g. C vs O vs Fe...)

- **Antiprotons: a more mature approach to assessing uncertainties** (let’s try not to be surprised of some features which are expected...)

- **Campaign to reduce cross section uncertainties** (e.g. for antiprotons, secondaries...)

- **Aim at establishing a new “reference” scenario to put to test** (the simplest one fails, but too many free parameters in many reasonable alternatives)
Fragile nuclei such as Li, Be, B... present but in traces in stellar astrophysical environments, while in sizable fractions in CRs:

interpreted as result of spallation of “primary” nuclei, accelerated at sources (e.g. SNRs) during the CR diffusive propagation in the ISM.

While CR are sensitive to both acceleration and propagation effects, the ratio of Secondary/Primary species is used to constrain propagation parameters (assumed insensitive to injection)
TOWARD A TEST: SECONDARIES

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While CR are sensitive to both acceleration and propagation effects, the ratio of Secondary/Primary species is used to constrain propagation parameters (assumed insensitive to injection)

If a type of nucleus is not present as primary, but only produced as secondary via collisions (this includes e.g. Boron) then

\[ \Phi_s = Q_s \tau_{\text{diff}} \propto \sigma_{p \rightarrow s} \Phi_p \tau_{\text{diff}} \]

yielding

\[ \frac{\Phi_s}{\Phi_p} \propto \tau_{\text{diff}}(E) \propto D(E)^{-1} \propto E^\delta \]

(typically inferred from B/C)

(customary empirical fitting form)

\[ D(R) \simeq 10^{28} \div 10^{29} \left( \frac{R}{3 \text{ GV}} \right)^{0.5} \text{ cm}^2/\text{s} \]

(modulo uncertainties in the x-section!)

see the ex. at RHS from G. Di Bernardo et al. Astropart. Phys. 34, 274 (2010)
Main diagnostics: from secondaries, notably (but not exclusively!) B/C

In short:

1) Source origin for the break: no feature expected in secondaries/primaries

2) Propagation origin for the break: should reflect in probes of propagation as B/C (i.e. secondary spectra should show a more pronounced break than primary ones)

3) Local models like the “myriad” one may even obtain a softening of sec/primary, since secondaries are ~ sourced by the “unbroken” average spectrum
B/C does not favour local source effects, perhaps still inconclusive for disentangling propagation vs generic source effects

M. Aguilar et al. (AMS Collaboration)


Qualitative hints for propagation effect from AMS preliminary Lithium data?
(Prominent break)

L. Derome [AMS Collaboration]

AMS days @ CERN, 2015 & ICRC 2015
TESTING BREAK MODELS: STATUS

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Need O(10%) precision @ 1 TeV/nuc for firm conclusion!
"Seeing It Coming: "Primary Secondaries""

Physical basis of source/propagation factorization is that characteristic scales are very different.

We may be near the end of that era...

"Secondary" production at sources become a major concern (must be taken into account).

High precision data on secondaries (or sec/prim.) in E~0.1-1 TeV/nuc. needed to test source vs. propagation scenarios.

However, easy to estimate than in the same range we expect sizable "secondary" production at the source

\[ X_{\text{SNR}} \approx 1.4 r_s m_p n_{\text{ISM}} c T_{\text{SNR}} \approx 0.17 \text{ g cm}^{-2} \frac{n_{\text{ISM}}}{\text{cm}^{-3}} \frac{T_{\text{SNR}}}{2 \times 10^4 \text{yr}} \]


This is a generic conclusion on "theoretical" limitation in extracting propagation parameters from B/C

“PRIMARY” PBAR SOURCES LIKELY!

Just as B/C at high-E could be significantly affected by production at sources, so could anti-p!

Already noted in the past (well before any suspect of anomaly in p-bar was even raised!)

“The good news is that the high-energy range of the antip. spectrum may reveal important constraints on the physics of the CR acceleration sites. The bad news is that it is not straightforward to infer from high energy antip/p-data the propagation parameters […] our results may change dramatically the perspectives for the detection of DM. An “excess” in the high-energy range of antip/p could not be interpreted anymore uniquely as manifestation of new physics […]”

P. Blasi and PS, “High-energy antiprotons from old supernova remnants,” PRL 103, 081103 (2009) [0904.0871]

Should an antiproton anomaly of this type be measured… don’t be so surprised, then!
One important diagnostics is the dependence of the feature on the nuclei. Are the spectra of the “metals” the same as He and among themselves?

**Good News:** AMS should provide some new data soon.

**Bad News:** Problem may be related to understanding of relative abundances of species of different chemical composition, either poorly understood aspects of injection or of source astrophysics may be involved.

**Do not despair, yet! Keep hoping in the future...**

**Example of futuristic handle:** inferring and comparing the “grammage at source” experienced by protons & nuclei (e.g. antiprotons wrt secondary nuclei) could indicate if the main culprit is some environmental condition at accelerator site (as opposed to injection).
The observational improvements have shown the first cracks in the simplest model for cosmic ray production/propagation.

κῦδος to our experimental colleagues for their successful efforts!
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Many ‘natural’ ideas for what is causing these cracks, but currently there is “no standard model” for CRs fitting all observables. Most of these depend on a number of unknown parameters and some may be “accidental” (e.g. specific position and time of the Galaxy we happen to live at)

Remember my list:

- Drop $D$ homogeneity (and possibly isotropy)
- Drop power-law behaviour in $D$
- Drop power-law behaviour in $Q$
- Drop homogeneity (and possibly stationarity, isotropy…) in $Q$
- ...

More data & more precision (e.g. sec./prim.) will help to understand the main class of solution for spectral breaks (e.g. source vs. propagation), but cannot be expected to shed light on the new picture alone.

Improvement in the precision of data probably not enough. We need **theoretical progress** + meaningful combined pheno approaches.

Extra tools (multimess. aspects, non-local observables) probably can help but bear in mind the risk of uncontrolled multiplication of parameters.

Simply not enough information in

\[ \Phi(E, r) \]

\[ D_{ij}(E, r) \]

\[ Q(E, r) \]

... to reconstruct all the “free functions” entering the problem, such as possibly time-dependences, superpositions of multiple populations, etc.

Must hope that (at least) **some observables**, at the desired level of accuracy, are only controlled by a **limited** number of “generic/statistically meaningful” **parameters**.
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Current challenge: identify new reference model (if it exists!) satisfying Golden Rule

\# observables > \# relevant parameters – \# theory relations