Galactic Cosmic-Rays after AMS02

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The cosmic-ray spectrum

- **Non-thermal:** Almost a perfect power-law over more than 11 energy decades.
- Evidence of departures from a perfect power-law: the **knee** and the **ankle** features.
- Spectrum cut-off at $\gtrsim 10^{20}$ eV.
- Particles observed at energy higher than any terrestrial laboratory.
- Composition at $R \sim 10$ GV:
  - $\sim 99.2\%$ are nuclei
  - $\sim 84\%$ protons
  - $\sim 15\%$ He
  - $\sim 1\%$ heavier nuclei
  - $\sim 0.7\%$ are electrons
The classical questions in CR physics

Gabici+, arXiv tomorrow(?)

- Which classes of sources contribute to the CR flux in different energy ranges?
- Which are the relevant processes responsible for CR confinement in the Galaxy?
- Are CR nuclei and electrons accelerated by the same sources?
- What is the origin of CR anti-matter?
- What is the role of CRs in the ISM? (e.g., for star formation)

Figure: The TOA proton flux as measured by AMS02 at different times.
LiBeB as cosmic-ray clocks

If we assume that acceleration takes place in the average interstellar medium then this component must be produced during propagation (from that the term secondary).
The grammage pillar

From this plot it follows the more robust evidence of diffusion so far:

\[ \frac{B}{C} \sim \frac{X}{\bar{n}_{\text{ISM}}/\sigma_{C\to B}} \]

following:

\[ \tau_{\text{esc}}(10 \text{ GV}) \sim \frac{X(R)}{\bar{n}_{\text{ISM}}/\mu v} \sim 90 \text{ Myr} \]

while

\[ \tau_{\text{ball}} \sim R_G/\nu \sim 3 \times 10^4 \text{ yr} \]

The escape time is energy dependent and (roughly) scales like \( R^{-1/3} \).

Figure: Secondary-over-primary ratios from AMS02.
Galactic cosmic-ray factories

- Galactic SN Remnants provide the right energetics ($\sim 10\%$ efficiency)
- Diffusive shock acceleration (DSA) predicts $q \propto E^{-2}$ for strong shocks, independent on microphysics
- maybe softer because of non-linear effects
- Pure rigidity dependent acceleration (universality) with a single power-law in momentum.
The interstellar turbulence

Turbulence is stirred by Supernovae at a typical scale \( L \sim 10^{-100} \) pc

- Fluctuations of velocity and magnetic field are Alfvénic
- They have a Kolmogorov \( \alpha \sim -5/3 \) spectrum (density is a passive tracer so it has the same spectrum: \( \delta n_e \sim \delta B^2 \)):

\[
W(k)dk \equiv \frac{\langle \delta B \rangle^2(k)}{B_0^2} = \frac{2}{3} \frac{\eta_B}{k_0} \left( \frac{k}{k_0} \right)^{-\alpha}
\]

where \( k_0 = L^{-1} \) and the level of turbulence is

\[
\eta_B = \int_{k_0}^{\infty} dk \; W(k) \sim 0.1 \div 0.01
\]

Electron-density fluctuations in the ISM
[Armstrong+, ApJ 1995 – Chepurnov & Lazarian, ApJ 2010 – Lee & Lee, Nature Astr. 2019]
Charged particle in a turbulent field

Jokipii, ApJ 1966

- The turbulent field produces a small fluctuation with respect to the regular component

\[ \langle \delta B^2 \rangle (k) \ll B_0^2 \text{ for } k \gg k_0 \]

- The particle interacts resonantly with the waves, when the condition \( k_{\text{res}}^{-1} \sim r_L(p) \) is met

- The diffusion coefficient becomes:

\[
D_{\text{QLT}}(p) = \frac{\nu r_L}{3} \frac{1}{k_{\text{res}} W(k_{\text{res}})} \sim \frac{3 \times 10^{27}}{\eta_B} \left( \frac{p}{\text{GeV/c}} \right)^{2-\alpha}
\]

- \( \lambda \sim \text{kpc for } k_{\text{res}} W(k_{\text{res}}) \sim 10^{-6} \) at scales \( \sim \text{A.U.} \).

- that is just another example of the problem: little things affect big things
The CR transport equation in the halo model

\[-\frac{\partial}{\partial z} \left( D_z \frac{\partial f_\alpha}{\partial z} \right) + u \frac{\partial f_\alpha}{\partial z} - \frac{du}{dz} p \frac{\partial f_\alpha}{\partial p} = q_{SN} - \frac{1}{p^2} \frac{\partial}{\partial p} \left[ p^2 \dot{f}_\alpha \right] - \frac{f_\alpha}{\tau_\alpha^{\text{in}}} + \sum_{\alpha' > \alpha} b_{\alpha' \alpha} \frac{f_{\alpha'}}{\tau_{\alpha'}^{\text{in}}}\]

Spatial diffusion: \( \vec{\nabla} \cdot \vec{J} \)
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- Spatial diffusion: $\vec{\nabla} \cdot \vec{J}$
- Advection by Galactic winds/outflows: $u = u_w + v_A \sim v_A$
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- **Spatial diffusion:** \( \vec{\nabla} \cdot \vec{J} \)
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- **Source term proportional to Galactic SN profile**
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- Production/destruction of nuclei due to inelastic scattering (or decay)
Predictions of the standard picture

For a primary CR species (e.g., H, C, O) at high energy we can ignore energy gain/losses, and the transport equation can be simplified as:

\[ \frac{\partial f}{\partial t} = Q_0(p)\delta(z) + \frac{\partial}{\partial z} \left[ D \frac{\partial f}{\partial z} \right] \]

For \( z \neq 0 \) one has:

\[ D \frac{\partial f}{\partial z} = \text{constant} \rightarrow f(z) = f_0 \left( 1 - \frac{z}{H} \right) \]

where we used the definition of a halo: \( f(z = \pm H) = 0 \).

The typical solution gives (assuming injection \( Q \propto p^{-\gamma} \)):

\[ f_0(p) = \frac{Q_0(p)}{2A_d} \frac{H}{D(p)} \sim p^{-\gamma-\delta} \]

For a secondary (e.g., Li, Be, B) the source term is proportional to the primary density:

\[ Q_B \sim \tilde{n}_{\text{ISM}} c\sigma_{C \rightarrow B} N_C \rightarrow \frac{B}{C} \sim \frac{H}{D_0} p^{-\delta} \]

where we use \( \tilde{n}_{\text{ISM}} = n_{\text{disk}} h/H \).
Unprecedented data precision: The rigidity break
Adriani+, Science 2011 - Aguilar+, PRLs 2013 and so on

C. Evoli
GSSI
GCRs after AMS02
We conclude from the data that the observed spectral hardening at $\sim 300$ GV is due to a change of regime in particle diffusion.

Similar conclusion from a Bayesian analysis in [Genolini+, PRL 2018].

Physical mechanisms able to explain the break are presented in [Blasi, Amato & Serpico, PRL 2012 - Tomassetti, ApJL 752 (2012) 13].
Fitting the nuclei heavier than He

Modelling $D$ with a smooth break:

$$D(R) = \beta D_0 \frac{(R/GV)^\delta}{[1 + (R/R_b)\Delta \delta/s]^s},$$

we find $\delta = 0.64$, $D_0/H = 0.25 \times 10^{28}$ cm/s$^2$, $\Delta \delta = 0.2$, $u = 7$ km/s and $\gamma = 4.26$

$B/C$ and $C/O$ as grammage indicators are severely limited by our knowledge of cross-sections.
The problem with cross-sections: need for new measurements
Genolini+, PRC 2018 - Reinert & Winkler, JCAP 2018 - Evoli+, JCAP 2018

Figure: Cross-sections for Boron production by CNO spallation on Hydrogen target as a function of kinetic energy per nucleon. Data are taken from GALPROP and from EXFOR database.
The injection drama

- H is softer than nuclei, while He is harder.
- At odds with what one would expect in the case of pure rigidity dependent acceleration [Serpico, ICRC 2015].
- Problematic even for models of the difference between H and He injection based on the different A/Z at shocks [Hanusch+, ApJ 2019].
Grammage at the source

To provide a better fit of high-energy B/C we account for an additional contribution to the grammage traversed by CRs.

The grammage due to confinement inside a SNR can be easily estimated as [Aloisio, Blasi & Serpico, A&A 2015]

\[ X_{SNR} \sim 0.2 \text{ g/cm}^{-2} \]

It is important at high-energy since the harder spectrum.

B/C can constrain \( X_s \lesssim 0.7 \text{ gr/cm}^2 \).

However the injection problem for He gets worse!
A new scenario for cosmic-ray propagation in the halo

- By solving the transport equation we obtain a featureless (at least up to the knee) propagated spectrum for each primary species, differently than what is observed.
- This result remains true even in more sophisticated approaches as GALPROP or DRAGON
- What is missing in our physical picture?
The halo size $H$

- Assuming $f(z = H) = 0$ reflects the requirement of lack of diffusion (infinite diffusion coefficient)
- May be because $B \rightarrow 0$, or because turbulence vanishes (in both cases $D$ cannot be spatially constant!)
- Vanishing turbulence may reflect the lack of sources
- Can be $H$ dependent on $p$? (remember $B/C \sim H/D$!)
- What is the physical meaning of $H$?
The radio halo in external galaxies

Credit: MPIfR Bonn

Total radio emission and B-vectors of edge-on galaxy NGC891, observed at 3.6 cm wavelength with the Effelsberg telescope.

Total radio intensity and B-vectors of edge-on galaxy NGC 5775, combined from observations at 3.6 cm wavelength with the VLA and Effelsberg telescopes.
Using high-velocity clouds one can measure the emissivity per atom as a function of $z$ (proportional to $f$)

Indication of a halo with $H \sim$ few kpc
Non-linear cosmic ray transport

Skilling71, Wentzel74

- The net effect of spatial diffusion is to reduce the momentum of the particles forcing them, eventually, to move at the same speed as the waves $\sim v_A$

- If CR stream faster than the waves, the net effect of diffusion is to make waves grow and make CR diffusive motion slow down: this process is known as **self-generation of waves** (notice that self-generated waves are $k \sim r_L$)

- Waves are amplified by CRs through streaming instability:

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

and are damped by wave-wave interactions that lead the development of a turbulent cascade (NLLD):

$$\Gamma_{NLLD} = (2c_k)^{-3/2} k v_A (kW)^{1/2}$$

- What is the typical scale/energy up to which self-generated turbulence is dominant?
Non-linear cosmic ray transport
Blasi, Amato & Serpico, PRL, 2012

Transition occurs at scale where external turbulence (e.g., from SNe) equals in energy density the self-generated turbulence

\[ W_{\text{ext}}(k_{\text{tr}}) = W_{\text{CR}}(k_{\text{tr}}) \]

where \( W_{\text{CR}} \) corresponds to \( \Gamma_{\text{CR}} = \Gamma_{\text{NLLD}} \)

Assumptions:

- Quasi-linear theory applies
- The external turbulence has a Kolmogorov spectrum
- Main source of damping is non-linear damping
- Diffusion in external turbulence explains high-energy flux with SNR efficiency of \( \epsilon \sim 10\% \)

\[ E_{\text{tr}} = 228 \text{ GeV} \left( \frac{R_{d,10}^2H_3^{-1/3}}{\epsilon_0.1E_{51}R_{30}} \right)^{3/2(\gamma_p-4)} B_{0,\mu}^{(2\gamma_p-5)/2(\gamma_p-4)} \]
The turbulence evolution equation
Eilek, ApJ 1979

\[
\frac{\partial W}{\partial t} = \frac{\partial}{\partial k} \left[ D_{kk} \frac{\partial W}{\partial k} \right] + \frac{\partial}{\partial z} (v_A W) + \Gamma_{CR} W + Q(k)
\]

- Diffusion in $k$-space damping: $D_{kk} = c_k |v_A| k^{7/2} W^{1/2}$
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- **Diffusion in \( k \)-space damping:**  \( D_{kk} = c_k |v_A| k^{7/2} W^{1/2} \)
- **Advection of the Alfvén waves**
- **Waves growth due to cosmic-ray streaming:**  \( \Gamma_{CR} \propto \partial f/\partial z \)
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- Waves growth due to cosmic-ray streaming: $\Gamma_{CR} \propto \partial f / \partial z$
- External (e.g., SNe) source term $Q \sim \delta(z) \delta(k - k_0)$
- In the absence of the instability, it returns a kolmogorov spectrum: $W(k) \sim k^{-5/3}$
Wave advection $\rightarrow$ the turbulent halo

Evoli, Blasi, Morlino & Aloisio, 2018, PRL

\[ \tau_{\text{cascade}} = \tau_{\text{adv}} \rightarrow \frac{k_0^2}{D_{kk}} = \frac{z_{\text{peak}}}{v_A} \rightarrow z_{\text{peak}} \sim \mathcal{O}(\text{kpc}) \]
Non-linear cosmic ray transport: diffusion coefficient
Evoli, Blasi, Morlino & Aloisio, 2018, PRL

Figure: Turbulence spectrum without (dotted) and with (solid) CR self-generated waves at different distance from the galactic plane.
Non-linear cosmic ray transport: a global picture

Evoli, Blasi, Morlino & Aloisio, 2018, PRL

- Pre-existing waves (Kolmogorov) dominates above the break
- Self-generated turbulence between 1-100 GeV
- Voyager data are reproduced with no additional breaks, but due to advection with self-generated waves (single injection slope)
- \( H \) is not predetermined here.
- None of these effects were included in the numerical simulations of CR transport before.
Conclusions

▶ Recent findings by PAMELA and AMS-02 (breaks in the spectra of primaries, B/C à la Kolmogorov, flat anti-protons, rising positron fraction) are challenging the standard scenario of CR propagation.

▶ Non-linearities might play an essential role for propagation (as they do for acceleration). They allow to reproduce local observables (primary spectra) without ad hoc breaks.

▶ We present a non-linear model in which SNRs inject: a) turbulence at a given scale with efficiency $\epsilon_w \sim 10^{-4}$ and b) cosmic-rays with a single power-law and $\epsilon_{CR} \sim 10^{-1}$. The turbulent halo and the change of slope at $\sim 300$ GV are obtained self-consistently.

▶ As a bonus, these models enable us a deeper understanding of the interplay between CR, magnetic turbulence and ISM in our Galaxy.