Cosmic-ray propagation in self-generated turbulence

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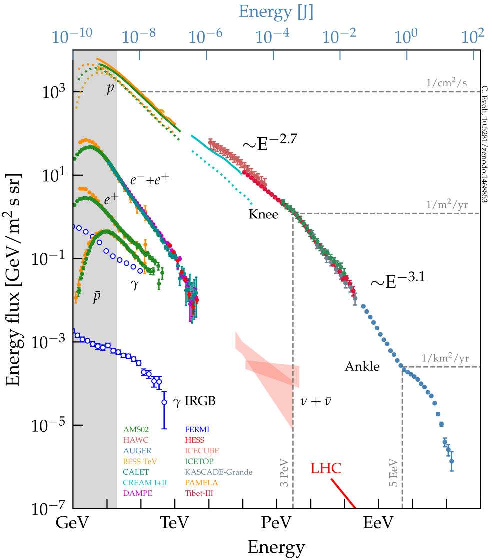
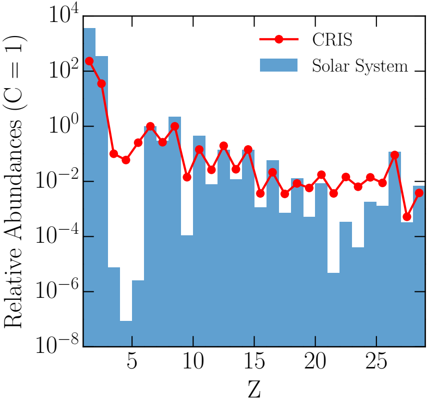
Searching for the sources of Galactic cosmic rays 2018

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 ankle features.
- Spectrum cut-off at $\gtrsim 10^{20}$ eV (GZK?).
- Particles observed at energy higher than any terrestrial laboratory.
- Composition at R∼10 GV:
  - $\sim 99.2\%$ are nuclei
    - $\sim$ 84% protons
    - $\sim$ 15% He
    - $\sim$ 1% heavier nuclei
  - $\sim 0.7\%$ are electrons

What's up with *LiBeB*?



- If we assume that acceleration takes place in the average ISM then this component must be produced during propagation (then the term "secondary").

The grammage pillar

- The grammage, X, is the amount of material that the particle go trough along propagation (a sort of "column density"):

$$X = \int dl \rho(l)$$

- I assume a simple system with one primary species (n_p) and one secondary (n_s) only
- The evolution of primary and secondary along the "grammage" trajectory is given by:

$$\begin{aligned} \frac{dn_p}{dX} &= -\frac{n_p}{\lambda_p} \\ \frac{dn_s}{dX} &= -\frac{n_s}{\lambda_s} + P_{p \to s} \frac{n_p}{\lambda_p} \end{aligned}$$

with i.c. $n_p(0) = n_0$ and $n_s(0) = 0$.

The grammage pillar

- Solving this, I can get n_s/n_p in terms of X, λ_s and λ_p only:

$$\frac{n_s}{n_p} = P_{p\to s}\frac{\lambda_s}{\lambda_s-\lambda_p}\left[\exp\left(-\frac{X}{\lambda_s}+\frac{X}{\lambda_p}\right)-1\right]$$

- I quantify the transport process, X, in terms of something that can be directly measured in CRs (n_s/n_p) or it can be measured in a nuclear physics experiment (λ's, P's).
- For B/C: $\lambda_{\rm C} \sim 6.7$ g/cm^2, $\lambda_{\rm B} \sim 10$ g/cm^2 and the spallation probability is $P_{C\to B} \sim 0.35$:

$$\frac{\rm B}{\rm C} \sim 0.3 \to X = 5~{\rm g/cm^2}$$

The grammage pillar

- Let me assume that the grammage is accumulated in the disk (more than a working hypothesis!)
- At each crossing of the disk ($h \sim 200$ pc):

  $$X_d \sim m_p n_{\rm gas} h \sim 10^{-3}\,{\rm g/cm^2} \ll X_{\rm BC}$$

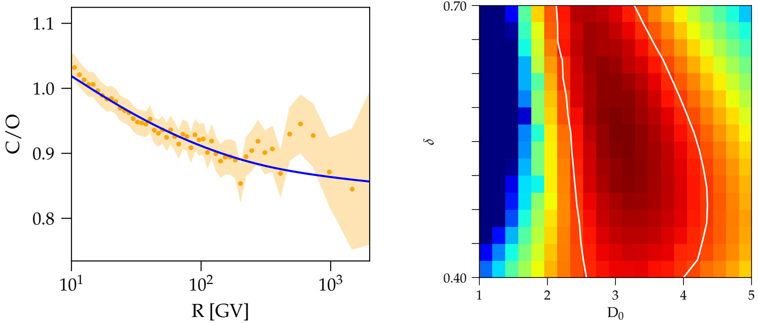
  (for comparison in a molecular cloud, e.g. Ophiuchus, $X_c \sim 0.1$ g / cm^2)
- Therefore the particles have to cross the disk many times. I can estimate what is the minimum time spent in the gas region:

  $$\boxed{t_{\rm prop} \sim \frac{X_{\rm B/C}}{X_{\rm d}} \frac{h}{v} \sim 5 \times 10^6 \text{ years} \ll \frac{R_G}{c}}$$

  (can we hope to measure $t_{\rm prop}$?)
- Finally, we conclude that the particle follows something similar to a Brownian motion in the Galaxy. What can we use to confine these particle in the Galaxy?

A latere: The Galactic grammage from primaries

C. Evoli, et al., *in preparation*



- the primary flux at $z = 0$ including inelastic scattering:

$$f_p(p) = \frac{Q_0(p)}{2 n_d h m_p v} \left[\frac{1}{\chi(p)} + \frac{\sigma_{\rm in}(A)}{m_p} \right]^{-1}$$

- total cross-sections are mass-dependent $\sigma_{\rm in} \propto A^{0.7}$

A latere: Cosmic sources and the energy budget

D. Ter Haar, Reviews of Modern Physics, 1950

The escape time is crucial to identify CR source suspects.

The SNR paradigm is basically this:

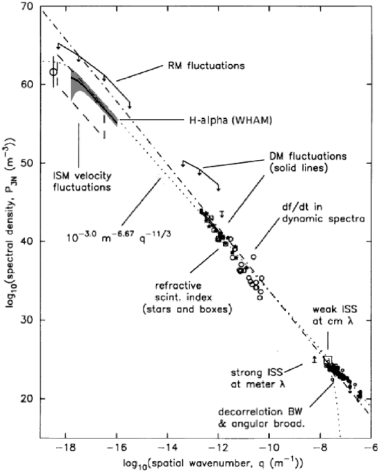
$$L_{\rm CR} = \epsilon_{\rm CR} \frac{V_{\rm MW}}{\tau_{\rm esc}} \sim 0.1 \div 0.5 \, L_{\rm SN}$$

where

- $\epsilon_{\rm CR} \sim 1$ eV/cm^3 CR energy density
- $V_{\rm MW} = \pi R_d^2 H \sim 4 \times 10^{67}$ cm^{-3} Milky Way Volume
- $\tau_{\rm esc} \sim 5 \times 10^6$ yr “escape” time
- $L_{\rm SN} = E_{\rm SN} R_{\rm SN}$ Galactic SNe luminosity

The interstellar turbulence

“The (second) Great Power-Law in the Sky”
(Jokipii)



Electron-density fluctuations in the ISM
[Armstrong et al. 1995, ApJ 443, 209]

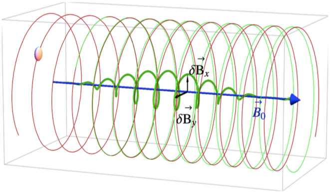
- Turbulence is stirred by Supernovae at a typical scale $L \sim 10 - 100$ pc
- Fluctuations of velocity and magnetic field are Alfvénic
- They have a Kolmogorov $k^{-5/3}$ spectrum (density is a passive tracer so it has the same spectrum: $\delta n_e \sim \delta B^2$):

$$W(k)dk \equiv \frac{\langle \delta B \rangle^2(k)}{B_0^2} = \frac{2}{3}\frac{\eta_B}{k_0}\left(\frac{k}{k_0}\right)^{-5/3}$$

- where $k_0 = L^{-1}$ and the *level of turbulence* is

$$\eta_B = \int_{k_0}^{\infty} dk\, W(k) \sim 0.1 \div 0.01$$

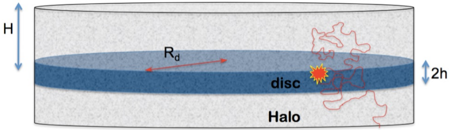
Charged particle in a turbulent field



- The turbulent field amplitude is a small fluctuation with respect to the regular component
- Resonant interaction wave-particle: $k_{\rm res}^{-1} \sim r_L(p)$
- It follows:

$$D_{\rm xx}(p) = \frac{v r_L}{3}\frac{1}{k_{\rm res} W(k_{\rm res})} \sim \overbrace{3 \times 10^{28}\,\text{cm}^2/\text{s}}^{3\times10^{27}/\eta_B\ \text{cm}^2/\text{s}} \left(\frac{p}{\text{GeV/c}}\right)^{1/3}$$

The CR transport equation in the halo model



$$-\frac{\partial}{\partial z}\left(D_{\rm zz}\frac{\partial f_i}{\partial z}\right)+u\frac{\partial f_i}{\partial z}-\frac{du}{dz}\frac{p}{3}\frac{\partial f_i}{\partial p}=Q_{\rm SN}-\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\frac{dp}{dt}f_i\right]+Q_{\rm frag/decay}$$

- Spatial diffusion: $\vec{\nabla}\cdot\vec{J}$
- Advection by Galactic winds/outflows: $u = u_w + v_A \sim v_A$
- Source term proportional to Galactic SN profile
- Energy losses: ionization, Bremsstrahlung, IC, Synchrotron, . . .
- 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:

$$\cancelto{0}{\frac{\partial f}{\partial t}} = Q_0(p)\delta(z) + \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right]$$

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 $Q \propto p^{-\gamma}$):

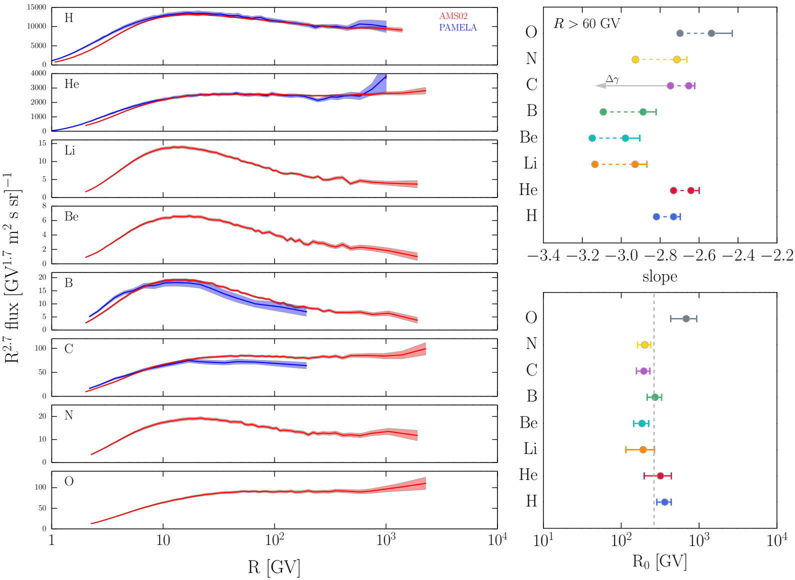
$$f_0(p) = \frac{Q_0(p)}{2A_\mathrm{d}}\frac{H}{D(p)} \sim p^{-\gamma-\delta}$$

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

$$Q_B \sim \bar{n}_\mathrm{ISM} c \sigma_{C\rightarrow B} N_C \;\rightarrow\; \frac{\mathrm{B}}{\mathrm{C}} \sim \frac{H}{D_0}p^{-\delta}$$

where we use $\bar{n}_\mathrm{ISM} = n_\mathrm{disk} h/H$.

Unprecedented data precision: New and exciting discoveries!



Overcome the standard halo model

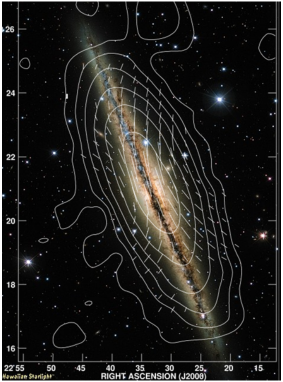
- By solving the transport equation we obtain a featureless (at least up to the knee) propagated spectrum for each primary species, at the odds with observations.
- This result remains true even in more sophisticated approach as GALPROP or DRAGON
- **What is missing in our physical picture?**

The halo size H

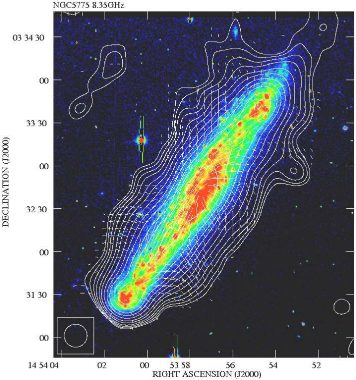
- Assuming $N(z = H) = 0$ reflects the requirement of lack of diffusion (infinite diffusion coefficient)
- May be because $B \to 0$, or because turbulence vanishes (in both cases D cannot be spatially constant!)
- Vanishing turbulence may reflect the lack of sources
- Can be H dependent on p?
- **What is the physical meaning of H?**

The radio halo in external galaxies

Credit: MPIfR Bonn



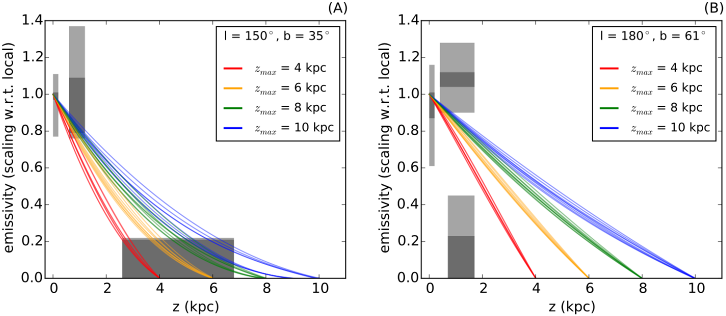
Total radio emission and B-vectors of edge-on galaxy NGC891, observed at 3.6 cm wavelength with the Effelsberg telescope



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

The γ-halo in our Galaxy

Tibaldo et al., 2015, ApJ



- Using high-velocity clouds one can measure the emissivity per atom as a function of z (proportional to N)
- Indication of a halo with $H \sim$ few kpc

Non-linear cosmic ray transport

Skilling71, Wentzel74

- CR energy density is ~ 1 eV/cm^{-3} in equipartition with: starlight, turbulent gas motions and magnetic fields.
- In these conditions, low energy can self-generate the turbulence for their scattering (notice that self-generated waves are $k \sim r_L$)
- Waves are amplified by CRs through streaming instability:

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

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

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

- 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

$$W_{\rm ext}(k_{\rm tr}) = W_{\rm CR}(k_{\rm tr})$$

where $W_{\rm CR}$ corresponds to $\Gamma_{\rm CR} = \Gamma_{\rm NLLD}$

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 $\epsilon \sim 10\%$

$$\boxed{E_{\rm tr} = 228\,\text{GeV} \left(\frac{R_{d,10}^2 H_3^{-1/3}}{\epsilon_{0.1} E_{51} \mathcal{R}_{30}} \right)^{3/2(\gamma_p - 4)} B_{0,\mu}^{(2\gamma_p - 5)/2(\gamma_p - 4)}}$$

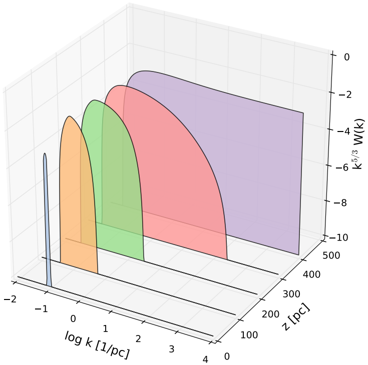
The turbulence evolution equation

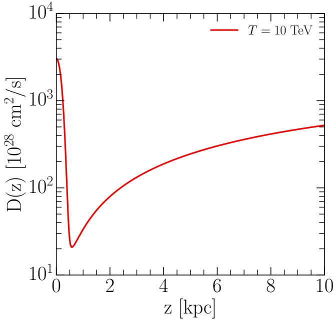
$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right] + \frac{\partial}{\partial z}(v_A W) + \Gamma_{\rm CR} W + Q(k)$$

- 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: $\Gamma_{\rm CR} \propto \partial f / \partial z$
- 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 → the turbulent halo

Evoli, Blasi, Morlino & Aloisio, 2018, PRL





$$\tau_{\rm cascade} = \tau_{\rm adv} \to \frac{k_0^2}{D_{kk}} = \frac{z_{\rm peak}}{v_A} \to z_{\rm peak} \sim \mathcal{O}({\rm kpc})$$

movie

Ad abundantiam: The numerical halo has no impact on local fluxes.

- Assuming now a power-law diffusion coefficient $D(z) = D_0(z/z_c)^\alpha$ for $z > z_c$:

$$-\frac{\partial}{\partial z}\left[D_0\left(\frac{z}{z_c}\right)^\alpha \frac{\partial f}{\partial z}\right] = Q_0(p)\delta(z)$$

- it implies that the density on the disk is:

$$f_0 \propto 1 - \left(\frac{H}{z_c}\right)^{-\alpha+1}$$

- which shows that $f(z=0)$ is weakly dependent on H as long as $\alpha > 1$

Non-linear cosmic ray transport: diffusion coefficient

Evoli, Blasi, Morlino & Aloisio, 2018, PRL

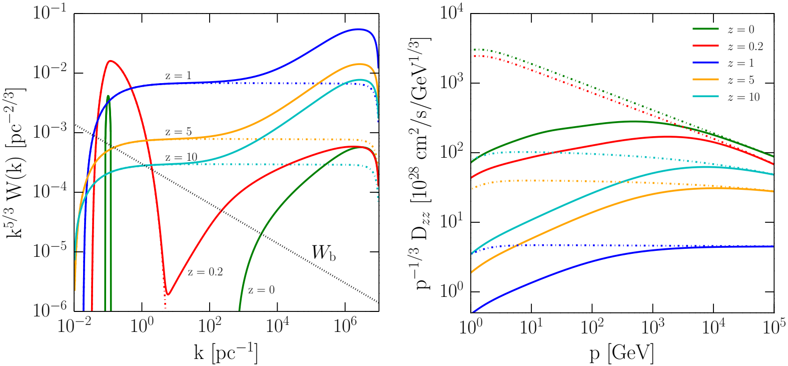


Figure: Turbulence spectrum without (dotted) and with (solid) CR self-generated waves at different distance from the galactic plane.

Non-linear cosmic ray transport: diffusion coefficient

Evoli et al., 2018, PRL

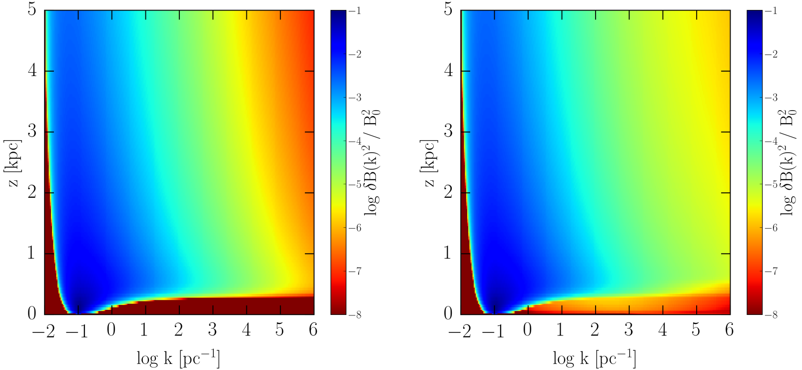
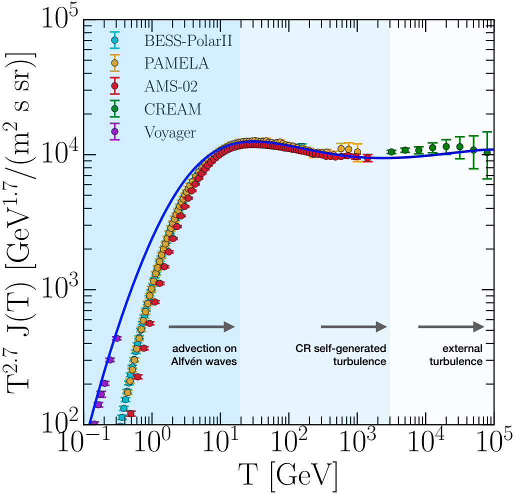


Figure: The normalized turbulent magnetic field $kW(k)$ in the halo without (left) and with (right) CR self-generation.

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 $\epsilon_{\rm w} \sim 10^{-4}$ and b) cosmic-rays with a single power-law and $\epsilon_{\rm CR} \sim 10^{-1}$. The turbulent halo and the change of slope at ∼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.