Modelling spectrally-resolved primary and secondary cosmic ray nuclei in the life MHD stratified-box simulations of interstellar medium

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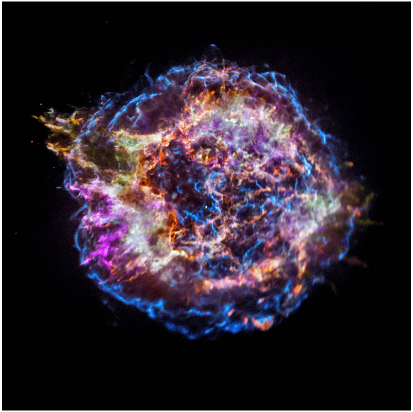
Primary CR nuclei (^{12}C, ^{14}N, ^{16}O, etc) accelerated in Supernovae (SN) remnants:



Cassiopeia A, Chandra observatory

Secondary CR nuclei (^{7}Li, Be, B, etc) created by spallation of primary CRs with the ISM protons:

$$
\begin{aligned}
(^{12}C,^{14}O,^{16}O) + p_{ISM} &\rightarrow \ ^{7}Li + p_{ISM} \\
(^{12}C,^{14}O,^{16}O) + p_{ISM} &\rightarrow (^{9}Be,^{10}Be) + p_{ISM} \\
(^{12}C,^{14}O,^{16}O) + p_{ISM} &\rightarrow (^{10}B,^{11}B) + p_{ISM}
\end{aligned}
$$

Why focus on CR nuclei?

Primary CR nuclei generate secondary particles (spallation, etc)
Observables: B/C and ${}^{10}Be/{}^{9}Be$

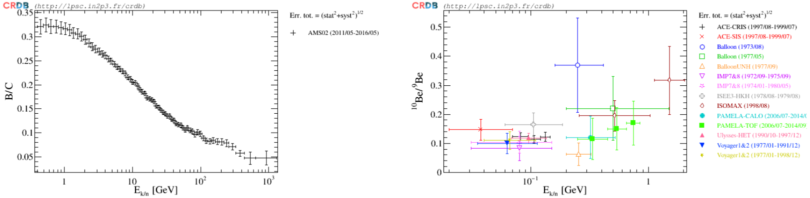


Figure: Cosmic Ray DataBase (CRDB) (Maurin et al, 2014)

Flux ratios inform about the propagation and diffusion of CR particles

GALPROP & similar codes : (Strong Moskalenko, 1998) dynamical and spectral CR, but **static** environment and laminar magnetic fields

- Leptonic and Nuclei species
- Radiative processes
- Secondary production

PIERNIK & similar codes : (Hanasz et al, 2010) Self-consistent CR resolution in a MHD environment, interaction with thermal gas and magnetic field (See Michal Hanasz and Nicolas Peschken talks).

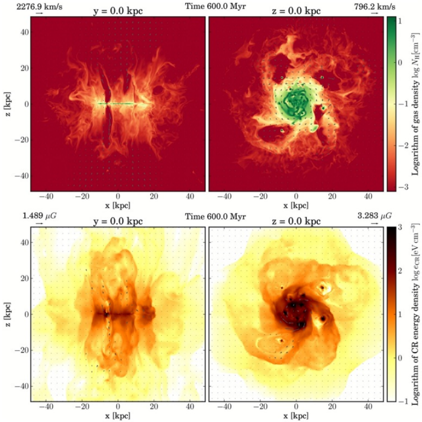
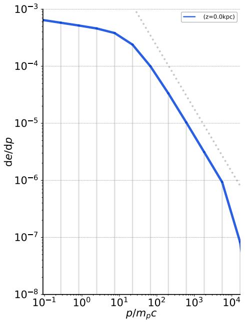


Figure: Hanasz et al, 2013

Spectral approach and CRESP algorithm :

- Cosmic Ray Energy SPectrum (CRESP) (Ogrodnik et al, 2021 based on Miniati, COSMOCR algorithm, 2001) purposes to study cosmic rays propagation with their spectral evolution in the momentum space (Girichids et al, 2020, Ogrodnik et al, 2021, Hopkins et al, 2022)
- Done for primary electrons. Next step : hadrons (C, Be, Li, N)



Initial CR ^{12}C energy density spectrum from test simulation

Fokker planck equation resolved independently for :

- primary CR : proton, ^{12}C, ^{14}N, ^{16}O
- secondary CR : ^{7}Li, ^{11}B and ^{10}B, ^{9}Be and ^{10}Be (^{10}Be radioactive)

,

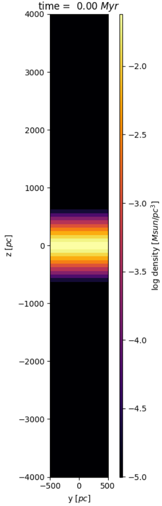
Piecewise power-law distribution function: 16 momentum bins to cover a few decades of the CR energy spectrum (see Michal Hanasz talk):

$$f^a(p) = f^a_{i-\frac{1}{2}} \left(\frac{p}{p_{i-\frac{1}{2}}} \right)^{-q_i}, \tag{1}$$

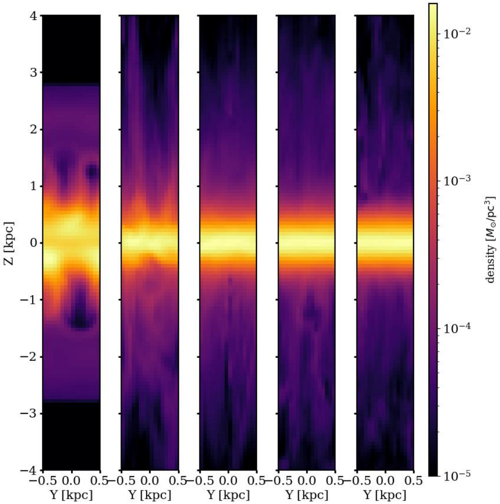
$f^a_{i-\frac{1}{2}}$ – distribution function amplitudes.

Two-moment approach: The algorithm evolves number and energy spectral densities of CR particles n_i and e_i.

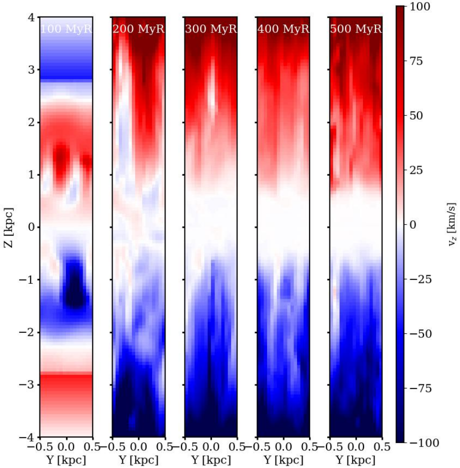
- Gravity-stratified box: eulerian grid of dimensions $L_x \times L_y \times L_z = 0.5\ \mathrm{kpc} \times 1\ \mathrm{kpc} \times 8\ \mathrm{kpc}$, $\Delta x = \Delta y = \Delta z = 62.5\mathrm{pc}$
- Conditions of local neighborhood of the sun : radius from galactic center $\approx 8.5\ \mathrm{Kpc}$, $n_{\mathrm{ISM}} = 1\ \mathrm{cm}^{-3}$ (Ferrière, 1998)
- CR protons in the grey/single bin approximation coupled to gas
- CR transport: advection ($\boldsymbol{v}.\nabla f^a$) and anisotropic rigidity-dependant diffusion: $D_{||}, D_{\perp} \propto D_{||}^0 R^{\delta}$, $, D_{\perp}(R) = 1\ \%$ of $D_{||}(R)$ (Strong et al, review of 2007)



Initial condition of gas density



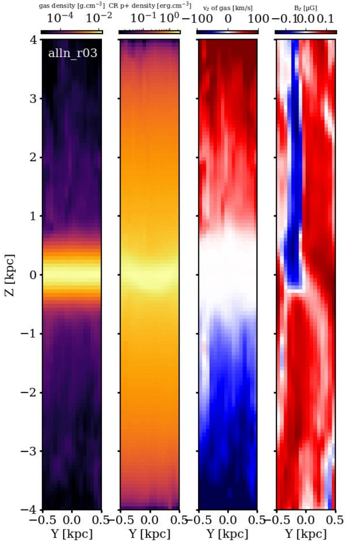
Gas density evolution: Parker loops (left slice) evolves to gas outflows



Vertical velocity evolution: Parker loops (left slice) evolves to gas outflows

Stratified box simulations

- From left to right: Gas density, CR protons, velocity and Magnetic Field (MF) after 500Myr evolution
- Outflows from Parker loop are visible in the MF



Example of spectrum:

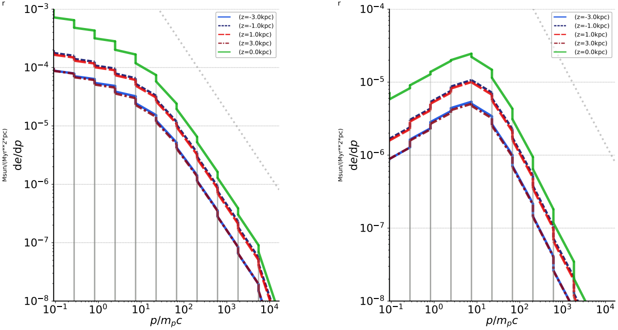


Figure: Energy density spectrum of primary ^{12}C (left) and secondary ^{11}B (right) at different altitudes in the box.

High energy CR diffusion changes the spectrum

Influence of SN rate: 20 $\mathrm{Kpc}^{-2}\mathrm{Myr}^{-1}$ (left) vs 80 $\mathrm{Kpc}^{-2}\mathrm{Myr}^{-1}$ (right)

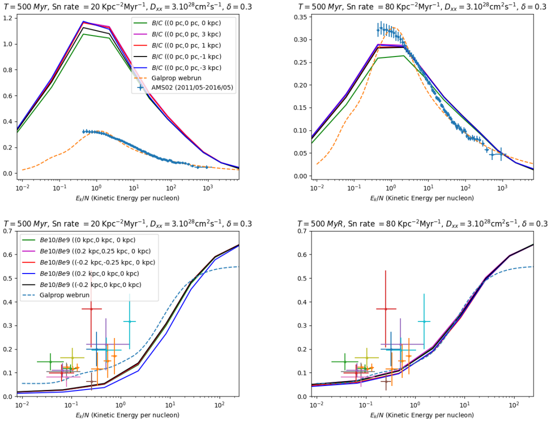


Figure: B/C and ${}^{10}Be/{}^{9}Be$ from Piernik - CRESP, $D_{||} = 3.10^{28}\mathrm{cm}^2\mathrm{s}^{-1}$, $\delta = 0.3$

Comparison with observationnal data and Galprop Webrun (Vladimirov et al, 2011): Left model is excluded!

Influence of diffusion coefficient $D_{\|}$: $3.10^{28}\mathrm{cm}^2\mathrm{s}^{-1}$ (left) vs $6.10^{28}\mathrm{cm}^2\mathrm{s}^{-1}$ (right)

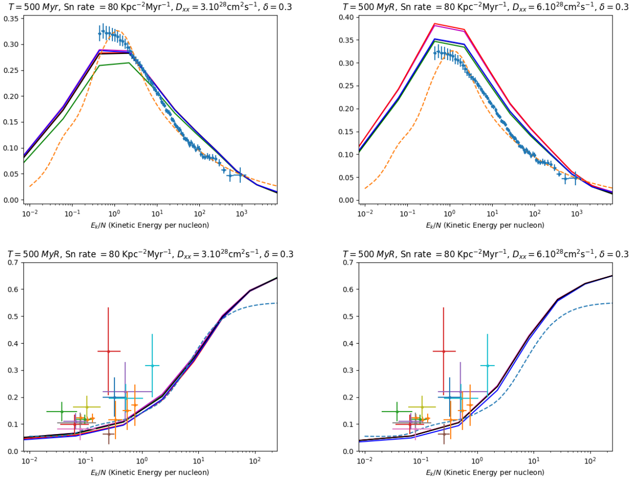


Figure: Sn rate $= 80\ \mathrm{Kpc}^{-2}\mathrm{Myr}^{-1}$, $\delta = 0.3$

Influence of diffusion power index: $D_{\|} \propto R^{\delta}$, 0.3 (left) vs 0.5 (right)

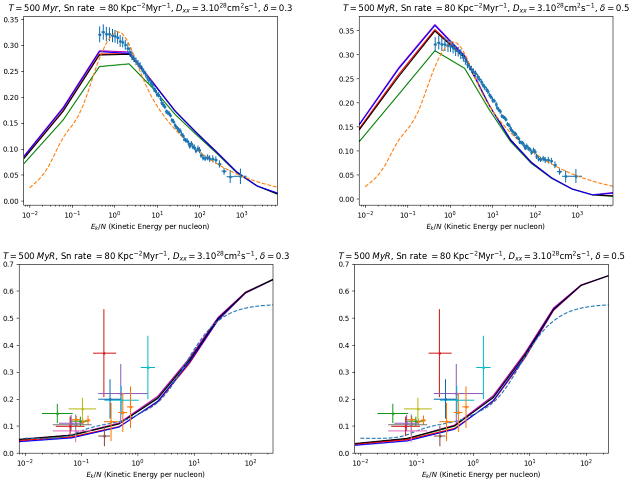
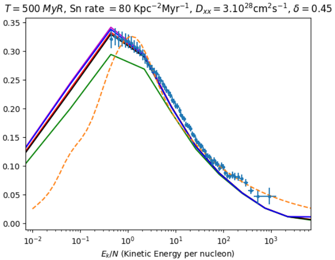
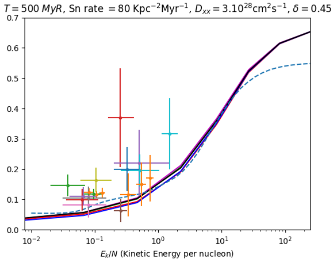


Figure: $D_{\|} = 3.10^{28}\mathrm{cm}^2\mathrm{s}^{-1}$, Sn rate $= 80\ \mathrm{Kpc}^{-2}\mathrm{Myr}$

Best fitting case: $D_{\|} = 3.10^{28}\mathrm{cm}^2\mathrm{s}^{-1}$, Sn rate $= 80\ \mathrm{Kpc}^{-2}\mathrm{Myr}$, $\delta = 0.45$





- CR transport parameters can be constrained with MHD self consistent models
- Note: this is a stratified box, not a whole galactic disc, a galactic-scale geometry/topology may influence the results

Summary and prospects:

- We built a self-consistent model for spectrally resolved CR nuclei propagation in stratified boxes representing the nearby galactic environment in the framework of Piernik-CRESP
- Using spectrally resolved self-consistent CRMHD models, we can predict CR observables (then transport parameters) ratio and fit the observational and numerical data from GALPROP.
- The current geometry of the setup can influence the results, extrapolation to galactic discs and thermal feedback is needed
- Further studies will be conducted with gamma rays and spectral protons