

A Markov Chain Monte Carlo technique to sample transport and source parameters of Galactic cosmic rays

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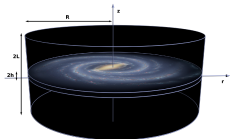
Phenomenology of nuclear cosmic rays

Why study cosmic-ray propagation?

- Study of the standard cosmic-ray astrophysics;
- Indirect search for dark matter.

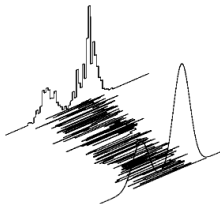
Propagation models:

USINE



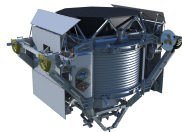
Statistical tools:

MCMC



Experimental data:

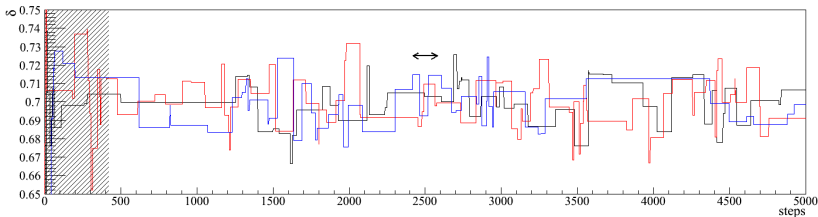
AMS



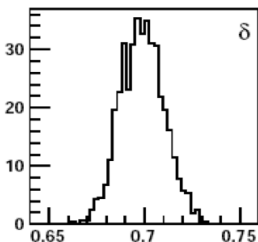
used for the **first time** in the context of cosmic-ray physics [Putze *et al.*, *A&A* (2009–2011)].

Metropolis-Hastings algorithm

Chain spends more time in more probable regions!



Evaluation of the
burn-in and correlation
lengths for independent
sample extraction



Estimation of the
posterior PDF

The USINE propagation code

Slide from D. Maurin

USINE (2)

A – Ingredients common to all models

1. Base ingredients

- Nuclear charts (m , A , Z , β and EC-decay channels)
- Atomic properties (FIP, Ek-shell...)
- Nuclear physics (production, inelastic... X-sections)
- Energy losses (Coulomb, ionisation)

2. Solar modulation (IS to TOA)

3. Database (experimental fluxes)

4. Visualization and fitting tools

- Displays
- Fitting tools

Base package, C++/Root interface

B – Ingredients specific to each model

1. Description (Input variables)

- Geometry
- Sources (spatial distribution, spectra)
- Propagation (transport coefficient, equation)

2. Solution of the transport equation

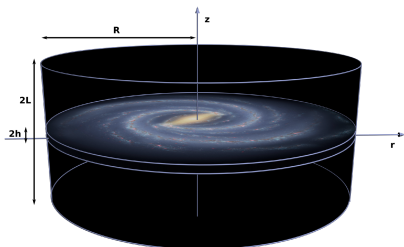
- Standard secondary/primary/tertiary contributions
- Unstable radioactive nuclei (BETA or EC)
- Energy redistributions (energy losses, reacceleration)
- Exotic primary contributions

Models (LB, 1D, 2D const. wind)

Diffusion Model

USINE — semi-analytical propagation code [D. Maurin]

Diffusion model with minimal reacceleration, constant Galactic wind



Galaxy is divided into two zones:

- ① a **thin disk** of size h ;
- ② a **diffusive halo** of size $L \gg h$.

$$K(R) = K_0 \beta^{\eta_T} R^\delta$$

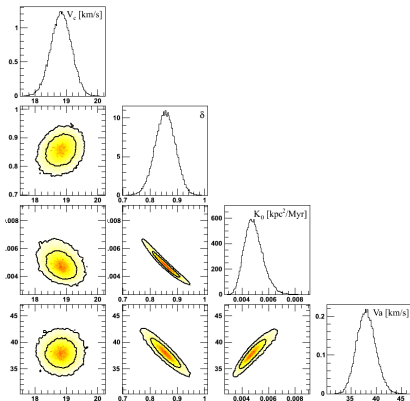
$$Q(R) = q \beta^{\eta_S} R^{-\alpha}$$

$$n_d = n, \quad n_h = 0$$

Free parameters

- 6 transport par.: K_0 [kpc^2/Myr], η_T , δ , V_c and V_a [km/s], L [kpc].
- 3 source par.: q in $(\text{m}^3 \text{s GeV/n})^{-1}$, η_S , α

Stable nuclei: constraining transport parameters – B/C



[Putze *et al.*, A&A 516 (2010), A66]

- Configuration with V_c and V_a preferred:

$L = 4 \text{ kpc}$ fixed

$$V_c = 18.8_{-0.3}^{+0.3} \text{ km/s}$$

$$\delta = 0.86_{-0.04}^{+0.04}$$

$$K_0 = 0.0046_{-0.0006}^{+0.0008} \text{ kpc}^2/\text{Myr}$$

$$V_a = 38_{-2}^{+2} \text{ km/s}$$

- Kolmogorov spectral index ($\delta = 1/3$) disfavoured.

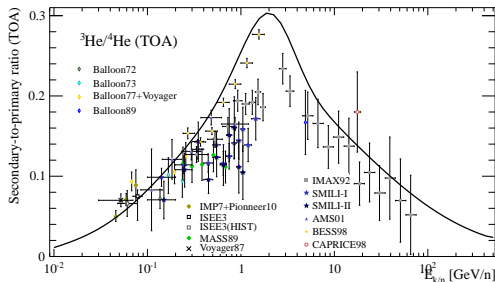
Stable nuclei: constraining transport parameters – $^3\text{He}/^4\text{He}$

B/C:

- abundant;
- elemental separation.

$^3\text{He}/^4\text{He}$:

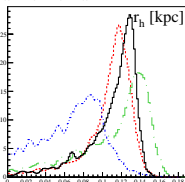
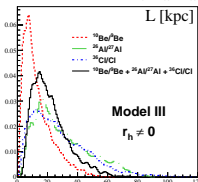
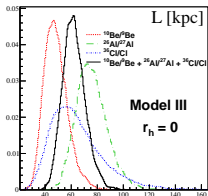
- very abundant;
- isotopic separation.



[Coste et al., in preparation]

Data	V_c (km s^{-1})	δ -	$K_0 \times 10^2$ ($\text{kpc}^2 \text{ Myr}^{-1}$)	V_a (km s^{-1})
$^3\text{He}/^4\text{He}$	$17.3^{+0.3}_{-0.4}$	$0.79^{+0.05}_{-0.04}$	$0.50^{+0.05}_{-0.06}$	40^{+2}_{-3}
B/C	$18.9^{+0.3}_{-0.4}$	$0.86^{+0.04}_{-0.04}$	$0.46^{+0.08}_{-0.06}$	38^{+2}_{-2}

Radioactive secondaries: constraining the halo size L



[Putze *et al.*, A&A 516 (2010), A66]

Results with $^{10}\text{Be}/^9\text{Be}$ data

without local bubble:

$$L = 46_{-8}^{+9} \text{ kpc}$$

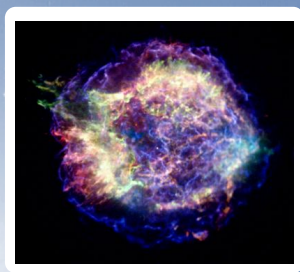
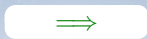
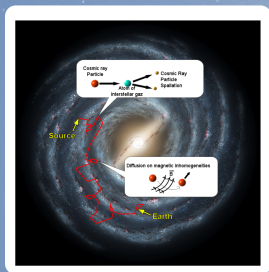
with local bubble:

$$L = 8_{-7}^{+8} \text{ kpc}, r_h = 120_{-20}^{+20} \text{ pc}$$

Local bubble

- underdensity in the LISM modelled as a hole in the disc
- exponential decrease of radioactive fluxes [Donato *et al.*, A&A 381 (2002), 539]

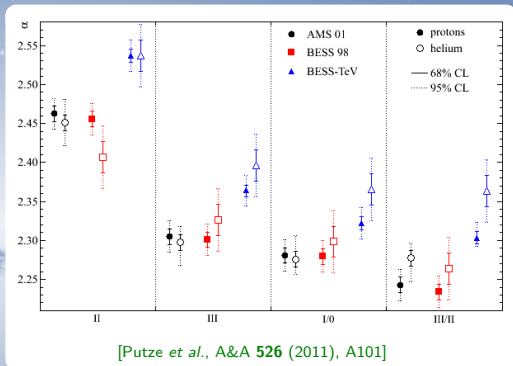
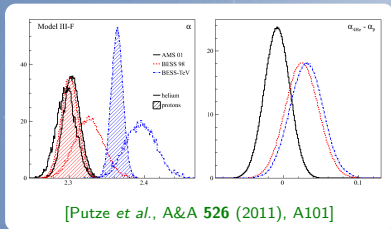
Primary nuclei: constraining source parameters



Model	η_T	$K_0^{\text{best}} \times 10^2$ (kpc ² Myr ⁻¹)	δ^{best}	V_c^{best} (km s ⁻¹)	V_a^{best} (km s ⁻¹)	$\chi^2/\text{d.o.f}$
II	1.	9.76	0.23	0.	73.2	4.73
III	1.	0.48	0.86	18.8	38.0	1.47
I/0	-2.6	2.05	0.61	0.	0.	3.29
III/II	-1.3	3.16	0.51	0.	45.4	2.26

[Maurin *et al.*, A&A 516 (2010), A67]

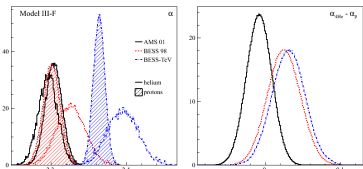
Primary nuclei: p and He



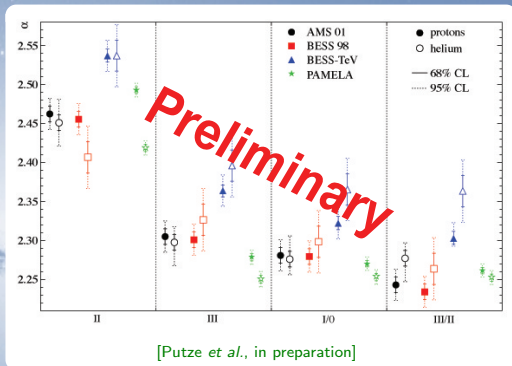
α well constrained between 2.2 and 2.5 (independent of model and data)
asymptotic regime ($\gamma_{\text{asyp}} = \alpha + \delta$) **not reached**

same results for heavier nuclei

Primary nuclei: p and He



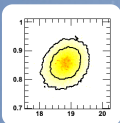
[Putze et al., A&A 526 (2011), A101]



α well constrained between 2.2 and 2.5 (independent of model and data)
asymptotic regime ($\gamma_{asymp} = \alpha + \delta$) **not reached**

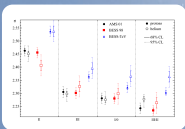
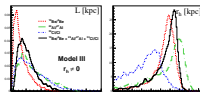
same results for heavier nuclei

Conclusion



Successful posterior PDF extraction of the propagation parameters of the one dimensional diffusion model

First estimation of the Galactic halo size L and the radius r_h of the local bubble



Good constraints of the spectral slope α implicating a universality for primary nuclei

MCMC is a robust tool allowing an excellent parameter estimation in high dimensional parameter spaces.