Cosmic ray propagation models with 3D and inhomogeneous interstellar medium

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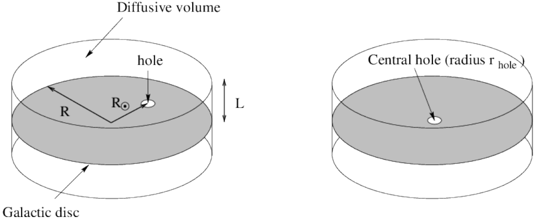
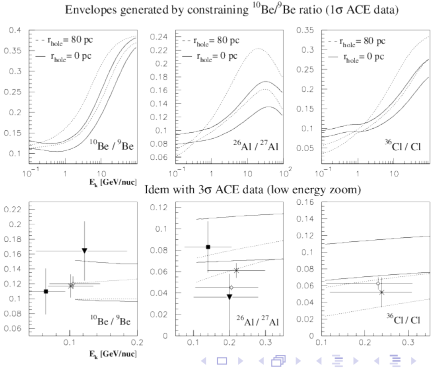
Cosmic Rays with Homogeneous ISM

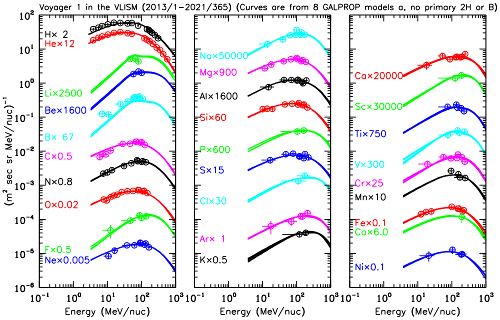
- Leaky box model: path-length distribution based on mean gas density.
- Variants of diffusion model: almost all using either some average gas density over disc, or 2D gas model coming from GALPROP.
- Kind-of justification: energy losses on gas not fast enough at low energies for structure of ISM to strongly influence spectra.
- Early attempt to account for inhomogeneous gas distribution → introduce 'hole' to approximate underdensity over Local Bubble.
- Some indication of sensitivity to it in CR isotope ratios.

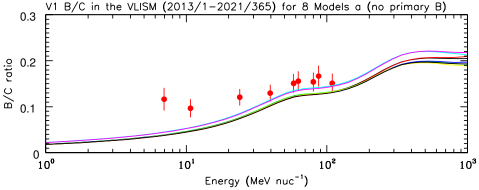




New Voyager Measurements

- New Voyager measurements for $Z \leq 28$ down to $\lesssim$10–10s MeV/nucleon.
- Taken after transition to interstellar space.
- Interpretation using 2D diffusion models possible evidence for primary B and ^{2}H (see Igor's talk).
- Low-energy $\rightarrow$ direct probe of the 'local' interstellar medium, e.g., effects of Local Bubble, cloud complexes.
- Model using 3D with more realistic ISM structure.
- Latest GALPROP can efficiently calculate down to $\lesssim$10 pc scales $\rightarrow$ allows numerical solutions at scales of the ISM descriptions now available (gas and dust, ISRF).

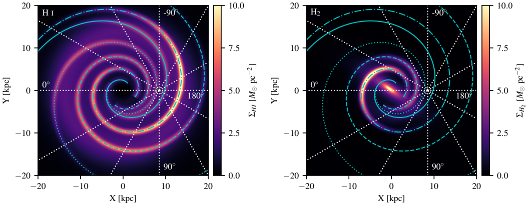




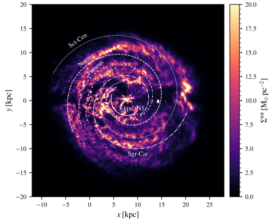
See Igor's talk.

Method

- Use GALPROP together with 3D interstellar gas models from reconstruction of HI and CO line survey data $\rightarrow$ both gas models have similar total masses.
- Assume best-fit diffusion model without primary B and ^{2}H.
- Solve in 3D with sufficient spatial resolution resolving features for both gas models for all nuclei Z$\leq$28.
- Use 2D model as proxy for data $\rightarrow$ high energies reproduce GALPROP-HelMod derived LIS (Boschini+ 2020).
- Obtain parameters (diffusion coefficient, source spectra) by adjusting to reproduce the 2D model solution for same 4 kpc halo size.



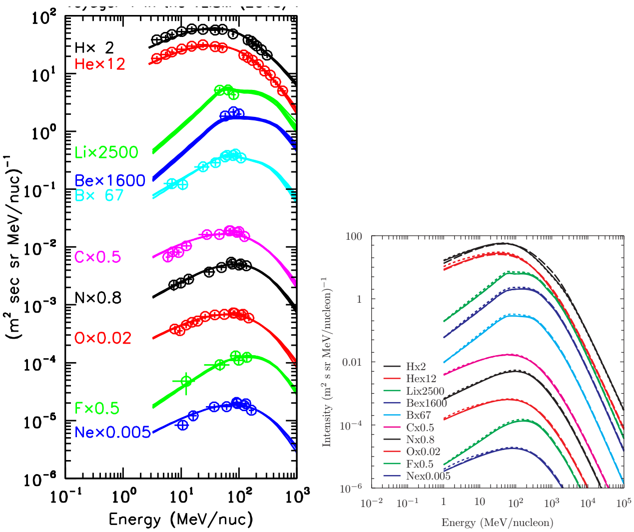
Jóhannesson et al. (2018) – J18.



Söding et al. (2025) – S25.

Nuclei Spectra

- Consistent solutions obtained for both 3D gas models with only simple adjustments.
- Diffusion coefficient is lower.
- Source spectra are modified:
  - J18 protons/heavies, same spectra different rigidity breaks.
  - S25 protons/He/heavies, same spectra different break rigidity breaks.
- Expect a lower diffusion constant simply 2D $\rightarrow$ 3D if everything else same, but changing to either 3D gas model lowers further.

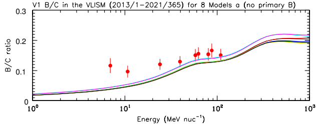


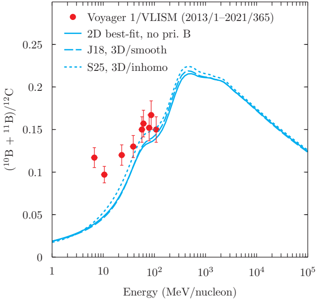
Left: V1 data and model. Right: solid line, 2D; long-dashed J18-tuned; short-dashed, S25-tuned.

Stable Secondary/Primary Fraction

- B/C is most often used for determining the scaling for halo size and diffusion constant.
- Both 3D models can be the adjusted to reproduce the 2D best-fit, no primary B model at high energies.
- For $\lesssim$1 GeV/nuc. small differences $\rightarrow$ additional fine tuning but not necessary.
- Overall the 3D models agree as well with the data as the 2D model.
- Evidence for the primary B (Igor's talk) unaffected by changing to more realistic gas distributions.

V1 VLISM data with 8 2D GALPROP models.

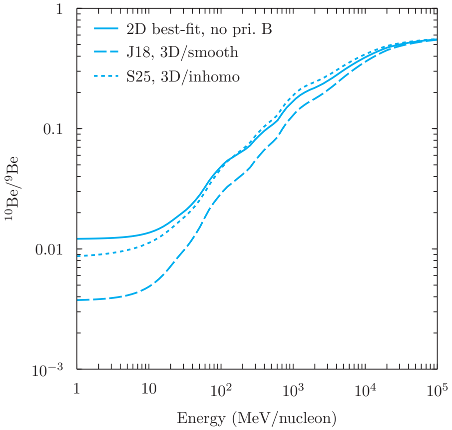




B/C for 2D best-fit, J18 and S25 gas models adjusted to reproduce nuclei spectra.

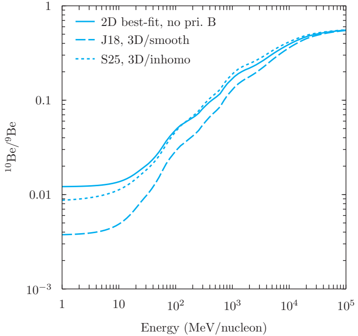
Radioisotope ratios: ^{10}Be

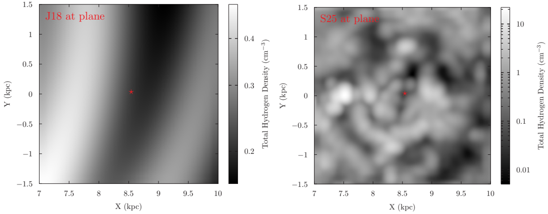
- With equivalent models from elemental spectra and stable S/P can predict radioisotopes → investigate effect of ISM spatial structure.
- Using ^{10}Be predictions shown for the 2D model, J18 and S25 models.
- Marked difference between smooth 3D (J18) and smooth 2D.
- Puzzling similarity between inhomogeneous 3D (S25) and 2D.



Radioisotope ratios: ^{10}Be

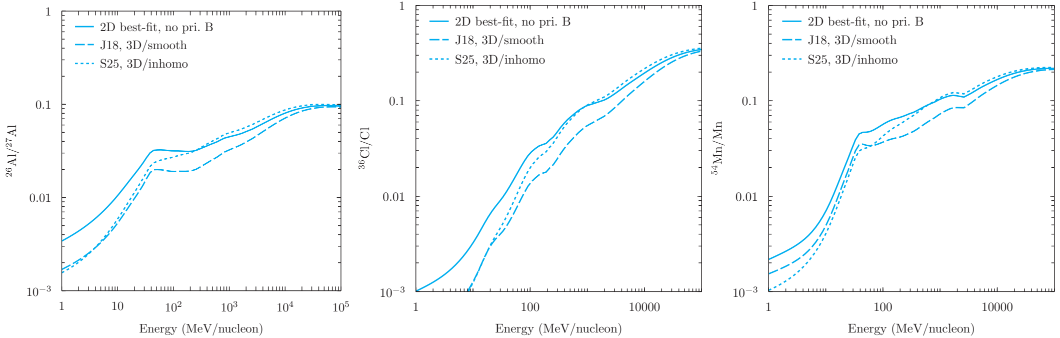
- Why?
- Consider 'nearby' distributions of gas for both 3D models.
- J18 model has gas mainly located in arms within several kpc of SS $\rightarrow$ SS is located fairly far from concentrations of gas with this model.
- S25 model has many more clumpy structures, but there appears more gas nearer to the SS.
- Even though the S25 model has a low-density region about the SS, still get more fragmentation/production for secondaries.





J18/S25 total hydrogen density at plane.

Radioisotopes: ^{26}Al, ^{36}Cl, ^{54}Mn



- Other ratios may provide some clues.
- Density/size PDFs for gas distributions are different.
- May manifest as "A-Z" dependent effect $\rightarrow$ increased cross sections for heavier nuclei may give enhanced production when densities are higher, and energy losses.

Summary

- Investigated effect of 3D and inhomogeneous ISM distributions on production of nuclei in 'nearby' region of MW.
- Both gas models based on reconstructions of essentially same data, but produce different outcomes for secondary species.
- Early investigations suggesting LB size significant effect for radioisotope chronometers not so clear for ISM with significant density fluctuations.
- The new features to enable these calculations included in next GALPROP release $\rightarrow$ revisions of the gas reconstruction become available can easily include (also dust).

Other GALPROP-related Contributions

- "GALPROP framework for propagation of Galactic cosmic rays and associated diffuse emissions" Moskalenko et al.
- "Voyager 1 Observations of Galactic Cosmic Ray Isotopes in the Very Local Interstellar Medium: Evidence for Primary 2H and B" Moskalenko et al.
- "Cosmic ray ionisation rate and Beryllium-10 modelling with inhomogeneous interstellar medium and time-dependent cosmic ray sources" Porter et al.
- "Modelling Galactic CRs and the Diffuse Gamma-Ray Emission" Marinos et al.
- "Modelling the cosmic-ray/radio/infrared/gamma-ray correlation at sub-galactic scales for the Milky Way and starforming galaxies" Porter et al.
- "Modelling the interstellar radiation field of the Milky Way at parsec scale resolution" Porter et al.
- "Diffuse Neutrino Emission from the Milky Way" Marinos et al.