

Voyager 1 Observations of Galactic Cosmic Ray Isotopes in the Very Local Interstellar Medium: Evidence for Primary ^2H and B

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We present the first measurements of the energy spectra of the isotopes of Galactic cosmic rays (GCRs) with nuclear charge $Z=1-14$ in the very local interstellar medium (VLISM). The observations are from the Cosmic Ray Subsystem (CRS) on the Voyager 1 (V1) spacecraft and cover the Z -dependent energy range from $\sim 3-661$ MeV/nucleon. The data are fit to eight models using the GCR propagation code GALPROP, and provide a new set of GCR elemental source abundances. The models all have injection spectra as power laws in rigidity, all with the same power-law index, and fit exclusively to the V1 data. The eight models differ in the relative abundances and by having two options for production cross sections and four options for total fragmentation cross sections. The VLISM energy spectra generated by all eight models agree reasonably well with the observed VLISM energy spectra for the isotopes with Z from 1–14. However, in all models it was necessary to add contributions from a primary source of ^2H and B.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland



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1. Introduction

In the forthcoming full paper [1], we employ a new method to account for background in the V1 observations of the isotopes of H and He, and present for the first time their energy spectra for a period when V1 was in the VLISM. We also present energy spectra of the isotopes of Li through Si from V1 for the same time period, using a somewhat different method than was used in prior studies of these isotopes from Voyager data in the heliosphere. Besides, we present energy spectra of elements H through Ni that were originally given in [2], updated for slightly different analysis techniques and for the much longer time period in the VLISM, 1/1/2013 through 12/31/2021. We compare our observations with GALPROP-based plain diffusion models of their origin and transport in the Galaxy and conclude that there is a primary component of the GCR ^2H energy spectrum. The GALPROP calculations lead to a new set of Voyager-GALPROP GCR elemental source abundances and require a small contribution of primary B to properly fit the data.

Here we present an abridged version of our analysis and interpretation.

2. GALPROP Models

In our calculations we use the GALPROP¹ framework [3–6]. We restrict ourselves to using only V1 data and to using a plain diffusion model with the minimal number of free parameters. The justification for such an approach is straightforward. First, the V1 data are taken in the VLISM and, therefore, they represent the cleanest sample of the GCRs not affected by solar modulation. Second, the ionization losses of low-energy GCR nuclei are fast. Therefore, slow processes, such as convection and diffusive reacceleration, cannot affect the low-energy species, which are mostly coming from our local Galactic neighborhood. Besides, local sources contributing to low-energy GCRs could have peculiar properties and adding more free parameters to our analysis, while providing formally a better fit, will simply make the overall picture less clear.

We set eight models, which cover available options in the isotopic production and fragmentation cross sections. The models are marked as X0YY, where X=1...4 denotes the total inelastic cross section option, and YY=12, 22 denotes the isotopic production option. The propagation model is plain diffusion with a single power-law index δ in the diffusion coefficient $\propto D_0\rho^\delta$, where D_0 is the normalization at 4 GV, and ρ is the rigidity. The injection spectrum is chosen in the form of a power-law with a break, where the lower rigidity index γ_0 is fit to the V1 data, while the index $\gamma_1 = 2.35$ above the break at $\rho_0 = 3$ GV is fixed, and the smoothing parameter is $s_0 = 0.25$. *The same values of γ_0, ρ_0, s_0 are used for all GCR species and depend only on the cross section options used (aka models). For all models, the same fixed value of the index γ_1 is selected with an aim to reproduce the GALPROP-HelMod-derived VLISM spectra at higher energies (hereafter GALPROP-HelMod VLISM spectra) [7]. Other free parameters are the source abundances of the GCR species.*

For the source density distribution we use a pulsar distribution from [8], their C-model. For the molecular H_2 , atomic H I , and ionized gas H II , we use the standard 2D distributions. For the conversion factor X_{CO} , we use an exponential fit to a table derived from the EGRET data [9]: $X_{\text{CO}}(R) = 10^{-0.4+0.066R} \times 10^{20} \text{ mol. cm}^{-2}(\text{K km s}^{-1})^{-1}$, where R is the distance from the Galactic

¹<https://galprop.stanford.edu>

center, and X_{CO} is set a constant value above $R = 15$ kpc. For all models, the Galactic radius and the halo size are fixed at 20 kpc and 4 kpc, respectively.

For each model described above, we made two runs, i.e. sixteen runs in total. In one run (labeled “X0YYa”) we allow source abundances of all isotopes to be free except ^2H , ^3He , and isotopes of Li, Be, B are set to 0 according to the conventional assumption that ^2H , ^3He , Li, Be, and B are almost entirely secondary. In another run (labeled “X0YYc”) we also allow free source abundances for ^2H and isotopes of B, while keeping ^3He , Li, and Be abundances set to 0.

3. Primary ^2H and B

The energy spectra for isotopes of H through Si are shown in Fig. 1. The injection spectrum is the same for *all primary* components, but differs for each model. The fits made in “a” models with purely secondary ^2H and B were unable to satisfactorily reproduce the spectra of ^2H and B (Figs. 1, 2), while spectra of other species are well reproduced. Attempts to add more weight to the spectrum of B in the fits, by arbitrarily decreasing the uncertainties, led to an increasingly worsening situation with the spectrum of C. Even the most dramatic 100-fold increase of the weight of the B data points did not result in satisfactory reproduction of the B spectrum, while making an unacceptable situation with the C spectrum.

In an attempt to cure the situation with ^2H and B without the introduction of primary components, we made an extensive analysis and updates of the production cross sections of all involved isotopes. The updates of the ^2H and ^3He production and inelastic cross sections are described in [5]. In addition, we updated production cross sections of the most important stable, long-lived, and some short-lived isotopes of Li through Na and Ca through Mn [1, 6]. While it adds confidence to our results, the updates did not cure the need for primary ^2H and B components in any of the considered models.

This was our motivation to introduce “c” models, which include primary contributions to ^2H and to ^{10}B and ^{11}B . Fig. 2 shows calculations with (model 4022c, solid lines) and without (model 4022a, dotted lines) primary ^2H and B components. The dashed lines represents the propagated primary ^2H and B components that would be needed to reasonably reproduce the observations. *This is the first time that observations indicate the need for primary ^2H and B components at low energies, the latter could significantly affect our understanding of the origin of GCRs.*

Below we discuss two of the most prominent systematic uncertainties. Due to significant ionization energy losses, the variations of other parameters have little effect on propagation of low-energy GCRs given that their spectra are tuned to the same data.

(i) *The accuracy of the production and fragmentation cross sections.* The main progenitor of ^2H is ^4He with some fraction of ^2H coming from fragmentation of ^3He and fusion reaction $pp \rightarrow d + \pi^+$. The fusion reaction (Fig. 14 in [5]) and cross sections $\alpha + p \rightarrow d + X$ and $^3\text{He} + p \rightarrow d + X$ (Figs. 12, 13 in [5]) are well measured in the energy range of interest and up to ~ 1 GeV nuc^{-1} . The observed excess of ^2H is by a factor of ~ 3 at ~ 16 MeV nuc^{-1} , and even larger at lower energies (Figs. 1, 2). The available cross section data does not allow such a significant increase to match the V1 data. The fragmentation cross sections of ^2H , $^3,^4\text{He}$ are also well measured in the energy range of 20–50 MeV nuc^{-1} (Fig. 10 in [5]), where the excess is observed. Therefore, it is unlikely that errors in the cross sections are responsible for the observed excess in ^2H .

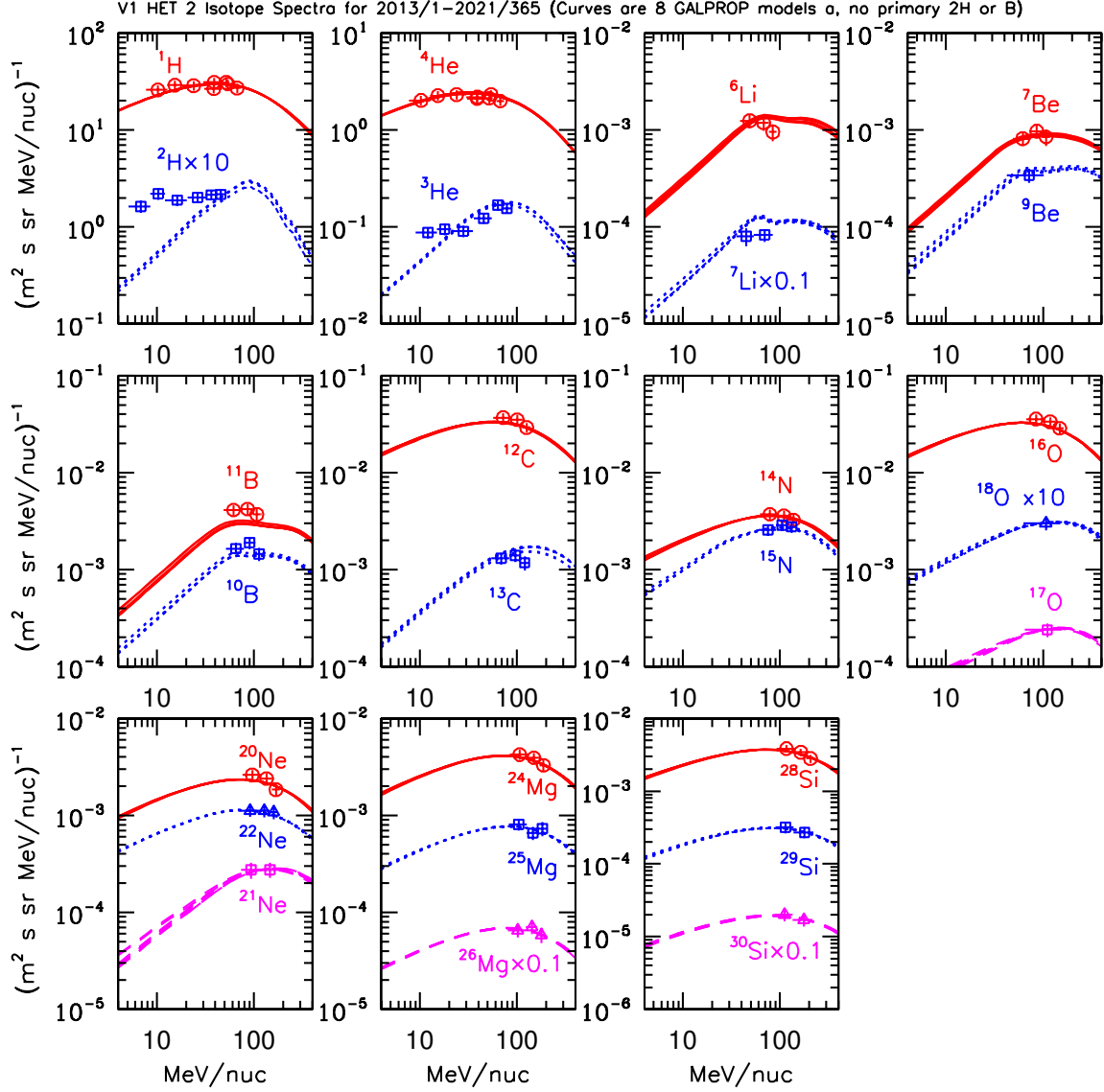


Figure 1: Energy spectra of 26 isotopes involving 11 elements from the V1 CRS instrument for the period 2013/1–2021/365. The lines are calculated energy spectra from the GALPROP models “a”, which do not include primary components from ^2H , ^{10}B , and ^{11}B .

In the case of B, the excess is $\sim 30\%$ at energies from $50\text{--}100\text{ MeV nuc}^{-1}$ and is mostly due to the excess in ^{11}B isotope. At lower energies, the excess is larger, being by a factor of 2.6 at 7 MeV nuc^{-1} (Fig. 2). ^{11}B is produced directly and through the decay of short lived ^{11}Be and ^{11}C isotopes, where the cross section for production of ^{11}Be is very small. Evaluation of the contribution of various production channels at 10 GeV nuc^{-1} [10, 11] shows that ^{12}C and ^{16}O are the main progenitors to the production of ^{11}B with other species contributing less than 2% each. ^{12}C and ^{16}O remain the main contributors to the production of B also at lower energies. The available isobaric cross sections [12] for the main progenitors, ^{12}C , ^{14}N , $^{16}\text{O} + p \rightarrow ^{11}\text{A}$, are essentially the cumulative production cross sections for ^{11}B , and cover the energy range of interest from $\sim 20\text{ MeV}$

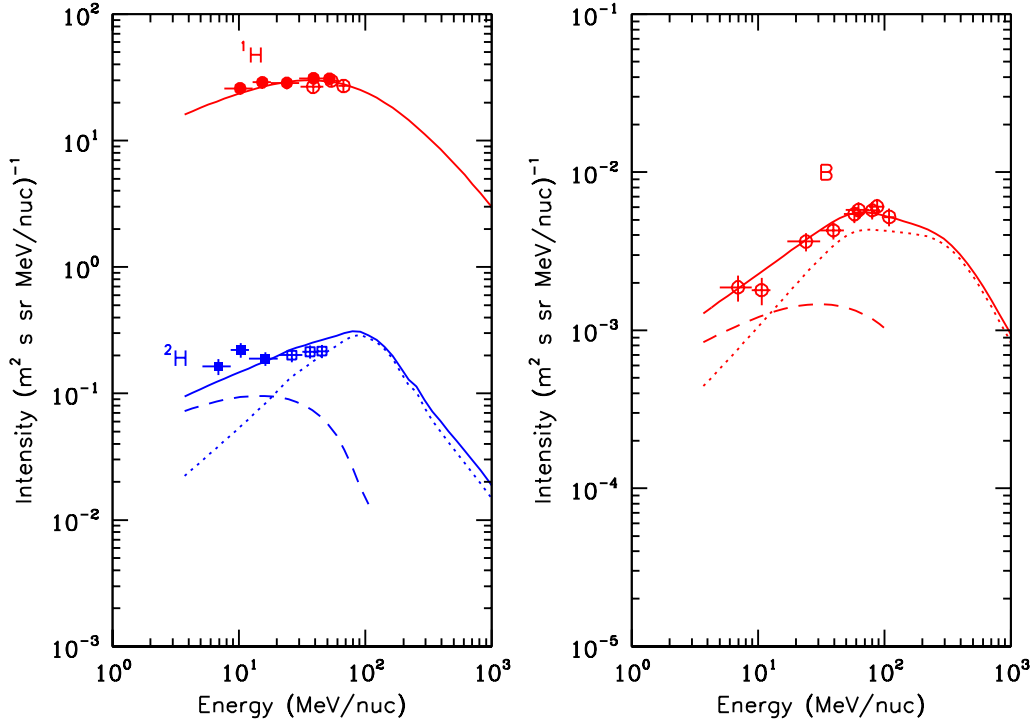


Figure 2: V1 GCR energy spectra of ^1H , ^2H , and B for the period 2013/1-2021/365. The curves show the energy spectra from the GALPROP models with (model 4022c, solid lines) and without (model 4022a, dotted lines) primary ^2H and B components. The dotted lines show only the secondary ^2H and B components, which result from nuclear interactions in the interstellar medium. The dashed lines show the resulting energy spectra of primary ^2H and B after the propagation. Their injection spectra have the same shape as other primaries.

nuc^{-1} to a few GeV nuc^{-1} . The cross section data for production of ^{11}C are abundant, which allows for consistency checks.

For ^{12}C progenitor, the cross section errors are $\sim 20\%$, while for ^{16}O progenitor, they are $\sim 10\%$. The total fragmentation cross section for ^{11}B , ^{12}C , and ^{16}O are well measured in the energy range from $10\text{--}20 \text{ MeV nuc}^{-1}$ to 50 MeV nuc^{-1} . Increasing the production cross sections of ^{11}B by 40% can improve the agreement with ^{11}B data points at 62 and 86 MeV nuc^{-1} , but such increase would not be able to compensate for the excess in elemental B at lower energies, i.e. excesses by a factor of 1.6 and 2.6 at 24 MeV nuc^{-1} and at 7 MeV nuc^{-1} , respectively.

(ii) *The production of secondary ^2H and B in nuclear interactions of GCRs with the material covering the V1 telescope aperture.* As we already mentioned above, below 60 MeV nuc^{-1} the primary progenitor of ^2H and ^3He in GCR interactions with H gas is ^4He . We expect the same to be true for interactions of GCRs with the window/thermal blanket material above the telescope aperture. We can compare the energy spectra of H, He, as well as of ^2H , and ^3He for two observational periods (Fig. 3). One is for the period in the VLISM (2013/1-2021/365) and the other is for a period in the heliosheath (2006/1-2011/365) when the anomalous components of cosmic rays (ACRs) cause the intensity levels of H and He to be much higher below $\sim 60 \text{ MeV}$ than those of GCR H and He in the VLISM. Yet the observed intensities of ^2H and ^3He in the heliosheath at these energies are lower.

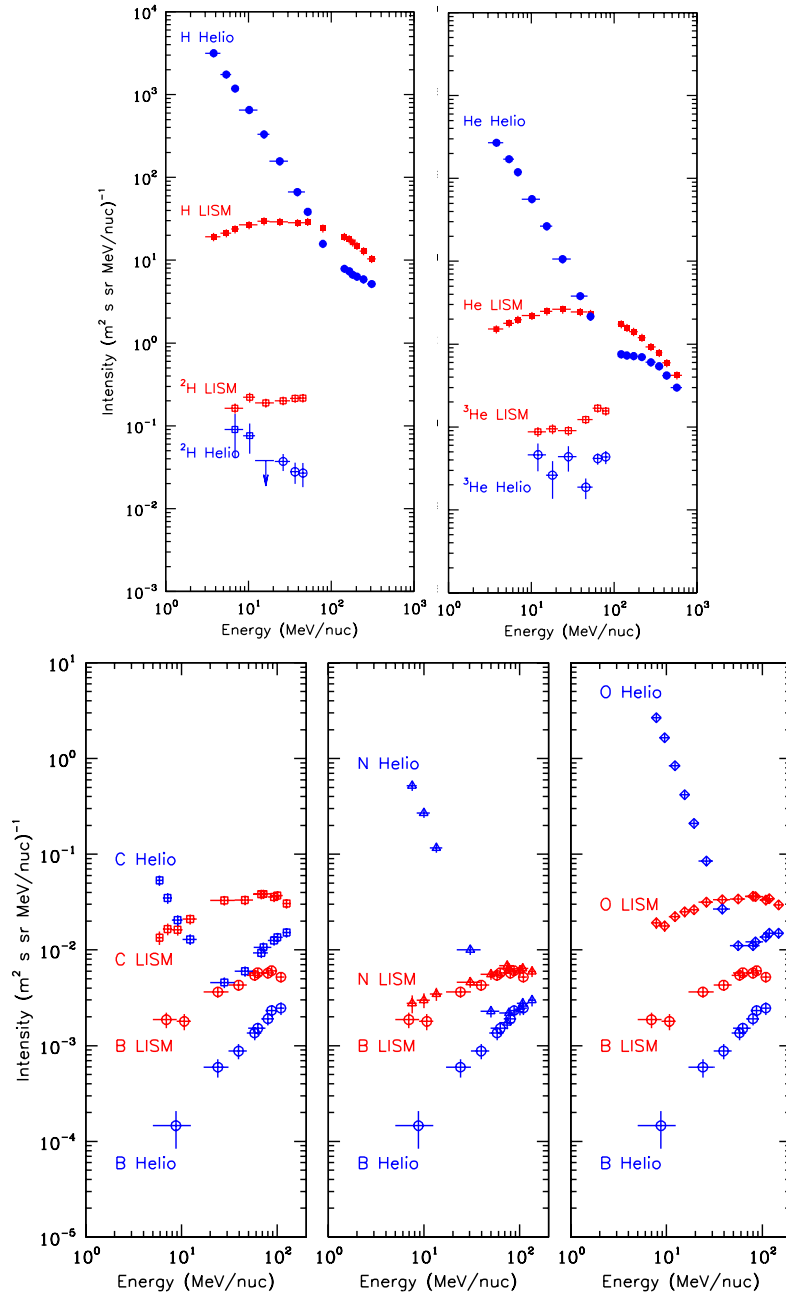


Figure 3: *Top:* V1 GCR energy spectra of H, ^2H , He, and ^3He for two time periods. In red are the energy spectra for the period 2013/1-2021/365 when V1 was in the VLISM. In blue are the energy spectra for a time period when V1 was in the heliosheath, 2006/1-2011/365. At low energies in the heliosheath the ACR H and He components dominate the GCR component. Since He is the main progenitor of ^2H and ^3He , the fact that the ^2H and ^3He intensities are lower in the heliosheath than in the VLISM suggests that ^2H and ^3He produced by nuclear interactions in the instrument are not significant. *Bottom:* V1 GCR energy spectra of B, C, N, O for two time periods. In red are the energy spectra for the period 2013/1-2021/365 when V1 was in the VLISM. In blue are the energy spectra for a time period when V1 was in the heliosheath, 2006/1-2011/365. At low energies in the heliosheath the ACR C, N, O components have much larger intensities than in the VLISM. Since C and O are the main progenitors of B, the fact that the B intensity is lower in the heliosheath than in the VLISM suggests that B produced by nuclear interactions in the instrument is not significant.

Similarly, one can look at the V1 GCR energy spectra of B, C, N, O for the same two time periods (Fig. 3). At low energies in the heliosheath the ACR C, and especially N and O components have much larger intensities than in the VLISM. Since C and O are the main progenitors of B, the fact that the B intensity is lower in the heliosheath than in the VLISM suggests that B produced by interactions in the instrument is not significant. Besides, if the observed B contribution would come from interactions in the material of the telescope, a similar contribution should be observed also in the spectra of (secondary) Li and Be. However, the spectra of Li and Be are in a good agreement with model calculations assuming no Li and Be in the source.

4. Conclusion

This is the first time that observations indicate the need for primary ^2H and B components at low energies. It is entirely connected with the unexplored energy range that was unreachable for instruments inside the heliosphere due to solar modulation. The discovery of these primary components may imply a contribution from new types of GCR sources or a new phenomenon, and has a profound impact on our understanding of the propagation of GCRs. The latter relies on the paradigm that B in GCRs is fully secondary and the B/C ratio measures the effective grammage that GCRs traverse in the ISM before coming to our instruments. If some fraction of B is primary, it would require a re-evaluation of *all* previous results.

Acknowledgments

Edward Stone would have been a co-author on this paper, but he passed away on 9 June 2024. He was a long time friend and colleague to us and will be greatly missed. ACC and BCH acknowledge Voyager data analysis support from NASA award number 80NM0018F0577. IVM and TAP acknowledge support from NASA Grants No. 80NSSC23K0169, 80NSSC22K0718, and 80NSSC22K0477.

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