Propagation of Light Elements in the Galaxy

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Abstract

The origin and evolution of isotopes of the lightest elements H^2, He^3, Li, Be, B in the universe is a key problem in such fields as astrophysics of CR, Galactic evolution, non-thermal nucleosynthesis, and cosmological studies. One of the major sources of these species is spallation by CR nuclei in the interstellar medium. On the other hand, it is the B/C ratio in CR and Be^{10} abundance which are used to fix the propagation parameters and thus the spallation rate. We study the production and Galactic propagation of isotopes of elements $Z \leq 5$ using the numerical propagation code GALPROP and updated production cross sections.

1. Introduction

It has been shown recently [9] that accurate measurements of the antiproton flux made during the last solar minimum [12] pose a challenge to conventional CR propagation models. A solution has been proposed [10] that the observed CR may contain a fresh, local, "unprocessed" component at low energies (LE), perhaps associated with the Local Bubble (LB). This component reduces the production of B at LE allowing to fit the B/C ratio and antiproton flux simultaneously. For more discussion see [11].

Isotopes of the lightest elements H^2, He^3, Li, Be, B in CR are almost all secondary, being produced in spallations of heavier nuclei on interstellar gas Galaxy-wide. Their abundances and isotopic composition, therefore, might help to distinguish between the propagation models. In this study we calculate abundances and isotopic composition of H, He, Li, Be, B in two models, a conventional reacceleration model [9], and a model with a local component [10].

2. The Model

In our calculations we use the propagation model GALPROP (2D option) as described elsewhere [9,14]. The nucleon injection spectrum of the Galactic CR

Table 1. Propagation Parameter Sets

| Model | Injection index, γ | Diffusion coeff. at 3GV | | Alfvén speed v_A, km s^{-1} | Source abundances |
		D_0, cm^2 s^{-1}	Index, δ		
$\mathcal{A}$	1.94/2.42	6.25×10^{28}	0.33	36	LE=HE
$\mathcal{B}$	1.69/2.28	3.30×10^{28}	0.47	23	LB$\neq$Galactic CR

is taken as a modified power law in rigidity [6], for the injected particle density. The LB spectrum is taken as a power law in rigidity with exponential cut off. The Galactic halo size is fixed at 4 kpc. To reduce possible errors due to the cross sections we use our own fits to the data on reactions $p + \mathrm{He}, \mathrm{C}, \mathrm{N}, \mathrm{O} \rightarrow \mathrm{H}^2, \mathrm{He}^{3,4}$ and $p + \mathrm{C}, \mathrm{N}, \mathrm{O} \rightarrow \mathrm{Li}, \mathrm{Be}, \mathrm{B}$ that produce most of these elements [8]. The heliospheric modulation is treated using the force-field approximation; here we use $\Phi = 500$ MV for all plots.

In the case of a conventional reacceleration model (model $\mathcal{A}$) we use our standard methodologies: the propagation parameters were derived from the fit to the B/C ratio, while source abundances were tuned to ACE data [15] and HEAO-3 data [4] at high energies (HE). No special tuning was done for antiprotons.

In the case of the model with a local component (model $\mathcal{B}$) we use the following procedure. The HE part of the B/C ratio *plus* antiproton flux measurements are used to restrict the value of the diffusion coefficient and its energy dependence, while the LE part of the B/C ratio is used to fix the reacceleration level and define the parameters of the LB component. In this way the model provides the best fit to all data at the cost of extra free parameters.

Model parameters are given in Table 1; model $\mathcal{A}$ is similar to models DR/DRB as defined in [9], and model $\mathcal{B}$ is similar to model DR II as defined in [10]. To better match the He spectrum (Fig. 1), a major contributor to H^2 and He^3 production, in both models we introduced a break (at 14 GV in $\mathcal{A}$, and at 10 GV in $\mathcal{B}$) in He^4 (only) power-law injection spectrum.

3.   Results

Fig. 2 shows the $\mathrm{H}^2/\mathrm{He}^4$ ratio. The measured ratio [2] is a factor of $\sim$1.8 larger than expected. While there are important hints that this may be caused by systematic effects, the analysis is still in progress (D. Vasilas private comm.).

Fig. 3 shows other ratios. Both models are consistent with data on isotopic ratios of Li, Be, and B given the large error bars. $\mathrm{He}^3/\mathrm{He}^4$ ratio is more sensitive. Both models agree well with the data, however to match the $\mathrm{He}^3/\mathrm{He}^4$ ratio *and* He spectrum, model $\mathcal{B}$ requires a factor of $\sim$2 larger LB abundance of He^4. The HE CR source abundance in both models He/Si $\approx$ 100, while the LB abundance in model $\mathcal{B}$ is 220 (cf. solar system value 2400). Taking into account that He and
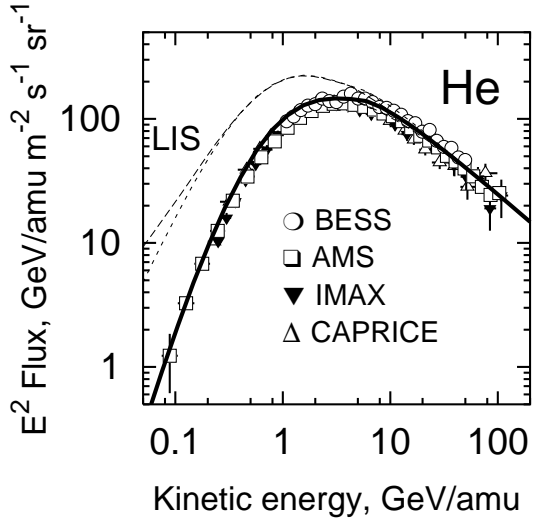
Fig. 1. He spectrum. Calculations: $\cdots$ – model $\mathcal{A}$, $---$ – $\mathcal{B}$. Solid line – modulated ($\mathcal{A}$ & $\mathcal{B}$), thin lines – interstellar (LIS). Data: for references see [9].
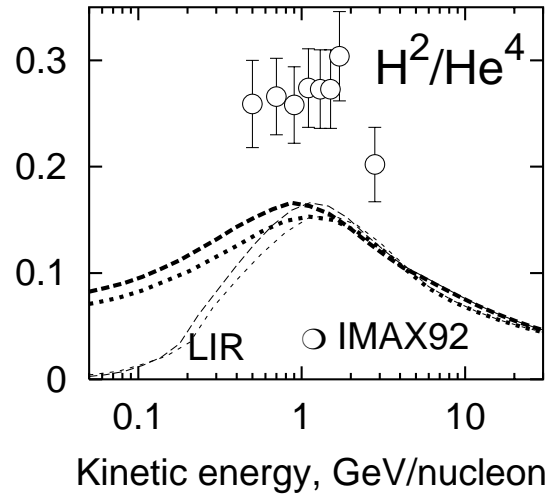
Fig. 2. H^2/He^4 ratio. Calculations: $\cdots$ – model $\mathcal{A}$, $---$ – model $\mathcal{B}$. Bold lines – modulated, thin lines – local interstellar ratio (LIR). Data: IMAX92 [2].

Si are abundant elements a factor of 2 difference is significant. Contributions of C^{12} and O^{16} to He^3 and He^4 production appear to be non-negligible.

The smaller proportion of He compared to heavier elements in Galactic CR sources supports the idea that HE CR are accelerated in shocks from fresh SN ejecta. The higher proportion of He compared to heavier elements in model $\mathcal{B}$ at LE implies that the material was diluted before acceleration. This is in line with the view described in [10] that the LB component may be accelerated by an ensemble of weak shock waves out of the interstellar medium. If the model $\mathcal{B}$ is correct it may indicate that the LE part of the He and proton Galactic spectra is flatter than thought with corresponding consequences for the diffuse Galactic γ-ray emission and Galactic chemical evolution.

4. References

1. Connell J.J. 1998, ApJ 501, L59
2. de Nolfo G.A. et al. 2000, in Proc. ACE-2000 Symp., ed. Mewaldt R.A. et al. (AIP: NY), AIP 528, 425
3. de Nolfo G.A. et al. 2001, in Proc. 27th ICRC (Hamburg), 1667
4. Engelmann J.J. et al. 1990, A&A 233, 96
5. Göbel H. et al. 2001, in Proc. 27th ICRC (Hamburg), 1663
6. Jones F.C., Lukasiak A., Ptuskin V., Webber W. 2001, ApJ 546, 264
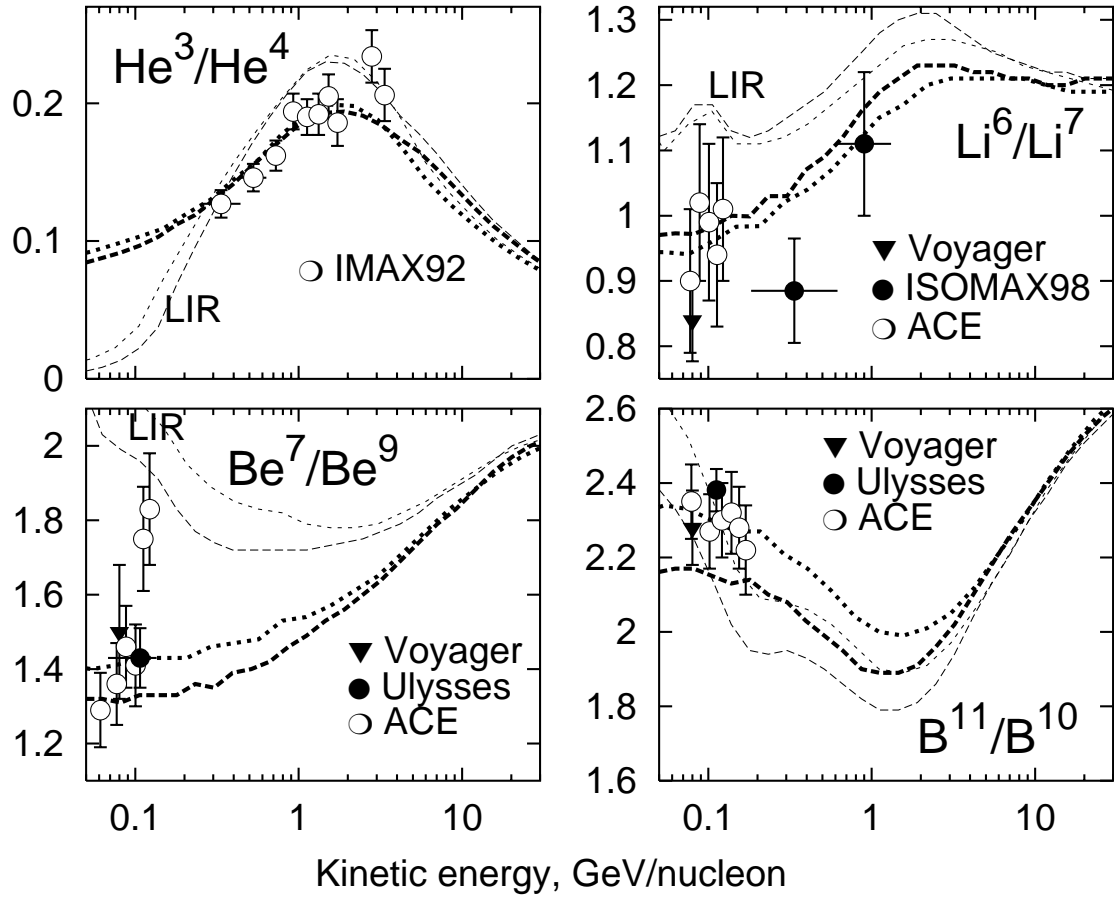
Fig. 3. Isotopic ratios as calculated in two propagation models. Lines are coded as in Fig. 2. Data: IMAX92 [13], ISOMAX98 [5] (with statistical errors only), Voyager [7], Ulysses [1], ACE [3].

7. Lukasiak A., McDonald F.B., Webber W.R. 1999, in Proc. 26th ICRC (Salt Lake City), 3, 41
8. Moskalenko I.V., Mashnik S.G. 2003, these Proc.
9. Moskalenko I.V., Strong A.W., Ormes J.F., Potgieter M.S. 2002, ApJ 565, 280
10. Moskalenko I.V., Strong A.W., Mashnik S.G., Ormes J.F. 2003, ApJ 586, 1050
11. Moskalenko I.V., Strong A.W., Mashnik S.G., Ormes J.F. 2003, these Proc.
12. Orito S. et al. 2000, Phys. Rev. Lett. 84, 1078
13. Reimer O. et al. 1998, ApJ 496, 490
14. Strong A.W., Moskalenko I.V. 1998, ApJ 509, 212
15. Wiedenbeck M.E. et al. 2001, Spa. Sci. Rev. 99, 15