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Can solar ^{6}Li abundance really be explained by Galactic cosmic rays?

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Abstract: Cosmic-ray interactions are the only known source of the rare isotope ^{6}Li. The standard picture is that the observed solar ^{6}Li is produced by galactic cosmic rays accelerated in supernova remnants. Thus lithium-6 is a unique probe of the local Galactic (hadronic) cosmic-ray history. On the other hand, extragalactic gamma-ray background is a measure of cosmic-ray fluence but for the average star-forming galaxy. Using the connection between production of lithium and hadronic gamma-rays in cosmic-ray interactions we tested this assumption and came to a surprising andalarming result: extragalactic gamma-ray background allows for only $\sim 50\%$ of solar lithium-6 abundance to be produced by Galactic Cosmic Rays. Although extreme assumptions yield a consistent picture, more realistic ones indicate that solar ^{6}Li cannot be produced by standard GCRs alone without overproducing the hadronic gamma rays.

Introduction

It is a standard picture that cosmic-ray nucleosinthesis is the only known process for the ^{6}Li production [1, 2] and thus Galactic cosmic-ray (GCR) interactions are believed to be the source of the observed solar ^{6}Li abundance. Besides ^{6}Li production, GCR interactions in the normal galaxies will also inevitably produce gamma rays and thus contribute [3] to the observed [4] extragalactic gamma-ray background (EGRB). The common origin of ^{6}Li and hadronic gamma rays in cosmic-ray interactions results in a tight connection between them [5]. We exploit this connection and use the observed EGBR to test the maximal allowed ^{6}Li abundance produced by GCR interactions. In a detailed analysis we found that the observed solar ^{6}Li abundance, if made entirely through GCR nucleosynthesis, demands ~ 2 times as large EGRB than observed, i.e., that the observed EGRB allows at best $\sim 50\%$ of solar ^{6}Li to be produced by GCRs [5, 6]. Our result strongly suggests that a new source of ^{6}Li must be present, which, along with recent suggestions such as dark matter and low-energy cosmic-rays in the light of the new ^{6}Li measurements, casts an even darker shadow on the standard picture for the ^{6}Li origin. New gamma-ray observations by *GLAST* will help resolve this matter by placing better constraints (or determining!) on the hadronic gamma-ray component of the EGRB.

Lithium–Gamma-Ray Connection

The rare isotope ^{6}Li is only produced in cosmic-ray interactions with the interstellar medium where the dominant production channel is the $\alpha + \alpha \rightarrow {}^6\text{Li}$ reaction [7]. On the other hand, hadronic gamma rays are produced in interactions of cosmic-ray protons where neutral pions are created which then decay into two gamma-ray photons $p + p \rightarrow \pi^0 \rightarrow 2\gamma$. We call these "pionic" gamma rays. Due to the fact that both ^{6}Li and pionic gamma rays result from cosmic-ray interactions, there is a simple and model independent connection between them which we found to be [5]:

$$\frac{I_{\gamma_\pi}(t)}{{}^6\text{Li}(\vec{x},t)} = \frac{n_\text{b} c}{4\pi y_{\alpha,\text{cr}} y_{\alpha,\text{ism}}} \frac{\sigma_\gamma}{\sigma_6} \frac{F_\text{avg}(t)}{F_\text{MW}(t)} \quad (1)$$

Namely, the ratio of the "pionic" γ-ray intensity I_{γ_π} (integrated over the entire energy spectrum) and ^{6}Li abundance (baryon or mole fraction $^6\text{Li} \equiv$

$Y_6 \equiv n_6/n_{\rm baryon}$) produced in fusion reactions with the ISM essentially comes down to the ratio of their reaction rates. Here $n_{\rm b} = 2.52 \times 10^{-7}$ cm^{-3} is the comoving baryon number density, while abundances are taken to be $y_\alpha^{\rm cr} = y_\alpha^{\rm ism} = 0.1$ ($y_i \equiv n_i/n_H$). The flux-averaged pionic γ-ray production cross-section is $\sigma_\gamma \equiv 2\xi_\alpha\zeta_\pi\sigma_{\pi^0}$ where the factor of 2 counts the number of photons per pion decay, σ_{π^0} is the cross section, ζ_π is the pion multiplicity, and the factor $\xi_\alpha = 1.45$ accounts for $p\alpha$ and $\alpha\alpha$ reactions [8]. For the lithium production cross section $\sigma_{\alpha\alpha}^{\rm Li}$ we have used a recent result of [9]. Finally, the ratio $F_{\rm avg}/F_{\rm MW}$ is the ratio of the line-of-sight baryon-averaged fluence to the local fluence, which compares the cumulative cosmic-ray activity of our Galaxy to that of an average star-forming galaxy. In our work we have taken this ratio to be ≈ 1, i.e. we have assumed that the Milky Way is an average star-forming galaxy with a CR flux that is approximated to the cosmic mean over the history.

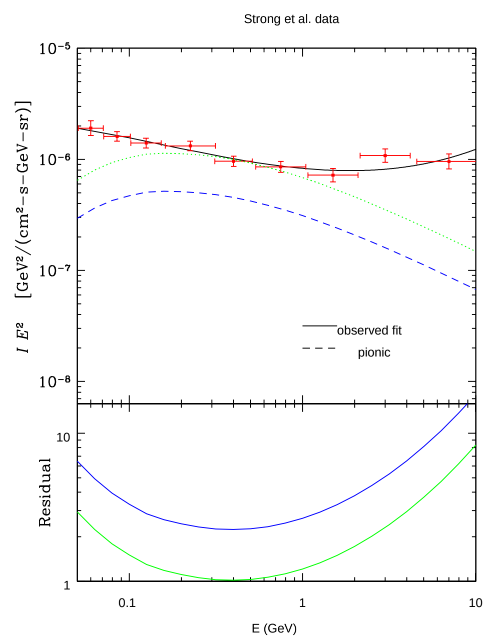

Figure 1: In the upper panel of this figure, we plot the pionic spectrum (dotted green line - maximized, dashed blue line - normalized to the Milky Way), compared to the observed EGRB spectrum (solid line, fit to data); we use the [4] data points, which are given in red crosses. The bottom panel represents the residual function, that is, $\log[(IE^2)_{\rm obs}/(IE^2)_\pi] = \log(I_{\rm obs}/I_\pi)$.

Pionic Gamma-Ray Spectrum

In order to obtain the pionic gamma-ray spectrum we have calculated a carefully propagated cosmic-ray spectrum for a leaky box model [10], where for the source spectrum we have assumed a standard power-law in momentum (e.g. [11]). This results in a spectrum which is more realistic at lower energies where threshold for lithium production is, than the standardly assumed single power-law spectrum in total energy with spectral index of 2.75 [5, 6].

The pionic γ-ray spectrum was numerically calculated in full detail, by adopting the isobar+scaling model [8] and the same cosmic-ray spectrum as the ^{6}Li production [6].

Since I_{γ_π} is the result of cosmic-ray interactions over the history we have integrated over the history of the sources using the cosmic star-formation rate [5, 12], which sets the shape of the pionic contribution to the EGRB, but normalization needs to be adopted. The use of maximal normalization, such that the pionic gamma-ray curve stays below the observed EGRB (the observed data points are taken from [4]), though not realistic, produces a pionic gamma-ray spectrum presented in Fig. 1 as a dotted green (top) line. A more realistic approach would be through a normalization to the Milky Way [3] where pionic gamma-ray spectrum should now reflect the contribution from the normal galaxies to the EGRB. This is shown on Fig 1. as a dashed green (bottom) curve [6].

Galactic Cosmic-Ray Production of ^{6}Li

Still assuming that the Milky Way cosmic-ray fluence is equal to the cosmic mean ($F_{\rm MW}/F_{\rm MW} =$ 1), and with the pionic gamma-ray spectrum representative of normal galaxies (normalized to the Milky Way), we can now use equation (1) to determine the GCR-produced ^{6}Li abundance that is allowed by EGRB observations. Though the use of maximal possible pionic contribution to the EGRB (dotted curve on the Fig.1) would require GCR production of $^6\mathrm{Li}$ that is consistent with the observed solar $^6\mathrm{Li}$ abundance, such pionic gamma-ray component would leave little or no room for other guaranteed components of the EGRB, such as unresolved blasars [3], and we will not consider it further. To obtain the most realistic $^6\mathrm{Li}$ abundance produced by GCRs, we also include contribution from other production channels, i.e. spallation reactions $\mathrm{p}, \alpha + \mathrm{CNO} \rightarrow {}^6\mathrm{Li}$ (both forward and inverse kinematics included). For the CNO abundances we adopt 1/2 of the solar values for the average abundance over the history $(\mathrm{O/H})_{\mathrm{eq}} = 0.5\ (\mathrm{O/H})_{\odot}$. Two-step spallation reactions like $\mathrm{O} + \mathrm{H} \rightarrow^{11} \mathrm{B} + \mathrm{H} \rightarrow {}^6\mathrm{Li}$ [13] have also been included. As a final adjustment we have to correct the observed solar $^6\mathrm{Li}$ abundance for the astrated fraction. Namely, due to its very fragile nature some of $^6\mathrm{Li}$ was destroyed in stars, and thus $^6\mathrm{Li}_{\odot}$ is just a lower bound on the total $^6\mathrm{Li}$ that was supposed to be produced in GCR interactions. Deuterium is similarly fragile and has the only important source in the Big Bang Nucleosynthesis [14, 15] resulting in the abundance that should be strictly decreasing over the history. Thus, by using deuterium as an indicator of the level of astration, we find that $\sim 25\%$ was processed in stars up to that moment and thus solar $^6\mathrm{Li}$ abundance is just $\sim 75\%$ of the total $^6\mathrm{Li}$ produced [6]. With all this taken into account we finally find that EGRB observations allow for only

$$^6\mathrm{Li}_{\mathrm{GCR}} = 0.59\, {}^6\mathrm{Li}_{\odot} = \approx 0.45 {}^6\mathrm{Li}_{\mathrm{tot}} \qquad (2)$$

of lithium to be produced by GCR interactions [6], contrary to the standard the belief. That is, if one would to demand that entire solar $^6\mathrm{Li}$ abundance was produced by GCRs, that would require pionic gamma-ray component that would overshoot the observed EGRB.

Conclusions

Cosmic-ray interactions with the interstellar medium are the source of the $^6\mathrm{Li}$ production but they will also inevitably result in a certain pionic gamma-ray flux. It then follows that there is a tight connection between GCR produce $^6\mathrm{Li}$ and pionic gamma rays. This connection is given in Eq. (1) [5] and can be used to test the origin of the solar $^6\mathrm{Li}$ which is standardly assumed to be in the GCR interactions. Surprisingly, this simple and model independent connection in a detailed analysis allows for only $\sim 60\%$ of the solar $^6\mathrm{Li}$ to be produced by GCRs so that the acompanying pionic gamma-ray contribution from the normal galaxies does not overshoot the available EGRB.

This result therefore indicates either the need for another important source of $^6\mathrm{Li}$, or suggests that the Milky Way is not a typical star-forming galaxy. New pre-Galactic sources of $^6\mathrm{Li}$ are favorable in the light of new observations in metal-poor halo stars where a $^6\mathrm{Li}$ plateau was reported [16]. Though the $^6\mathrm{Li}$ plateau is only at the $\lesssim 10\%$ level of the $^6\mathrm{Li}_{\odot}$ and thus the source responsible for it will not be able to account for the missing $\sim 50\%$ that we have found [6], the two effects would indicate that any non-standard source that could explain both, would become important only at metallicities close to solar. Another solution might be found in demanding that the Milky Way had at some point gone through an important phase where the CR flux was greatly enhanced, which in turn could point to a more vigorous star-formation. In such case we could no longer assume that $F_{\mathrm{MW}}/F_{\mathrm{avg}} = 1$ in Eq. (1). However, such solution would have important consequences for the Milky Way star-formation history. One other thing to consider would be the possible presence of a low-energy ($\lesssim 100$ MeV) cosmic-ray component in the Milky Way, which would, due to a lower threshold for the $^6\mathrm{Li}$ production, allow for more $^6\mathrm{Li}$ to be produced without demanding too much of the observed EGRB. Though there are constraints that come from energetics considerations [17] and LiBeB ratios [18], the existence of such CR component is supported by H_3^+ observations in molecular clouds [19].

Finally, we have to note that important piece, namely the signature of the pionic gamma-ray contribution from the normal galaxies to the EGRB, is still missing, which will be better constrained and possibly even resolved by the upcoming *GLAST* observations. Detection of such signature, would certainly be crucial in resolving this new issue.

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