Cosmological cosmic rays: Sharpening the primordial lithium problem

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Cosmic structure formation leads to large-scale shocked baryonic flows which are expected to produce a cosmological population of structure-formation cosmic rays (SFCRs). Interactions between SFCRs and ambient baryons will produce lithium isotopes via $\alpha + \alpha \rightarrow {}^{6,7}\mathrm{Li}$. This pre-galactic (but nonprimordial) lithium should contribute to the primordial ^{7}Li measured in halo stars and must be subtracted in order to arrive to the true observed primordial lithium abundance. In this paper we point out that the recent halo star ^{6}Li measurements can be used to place a strong constraint to the level of such contamination, because the exclusive astrophysical production of ^{6}Li is from cosmic-ray interactions. We find that the putative ^{6}Li plateau, if due to pre-galactic cosmic-ray interactions, implies that SFCR-produced lithium represents $\mathrm{Li}_{\mathrm{SFCR}}/\mathrm{Li}_{\mathrm{plateau}} \approx 15\%$ of the observed elemental Li plateau. Taking the remaining plateau Li to be cosmological ^{7}Li, we find a revised (and slightly worsened) discrepancy between the Li observations and big bang nucleosynthesis predictions by a factor of $^7\mathrm{Li}_{\mathrm{BBN}}/^7\mathrm{Li}_{\mathrm{plateau}} \approx 3.7$. Moreover, SFCRs would also contribute to the extragalactic gamma-ray background (EGRB) through neutral pion production. This gamma-ray production is tightly related to the amount of lithium produced by the same cosmic rays; the ^{6}Li plateau limits the pre-galactic (high-redshift) SFCR contribution to be at the level of $I_{\gamma_\pi \mathrm{SFCR}}/I_{\mathrm{EGRB}} \lesssim 5\%$ of the currently observed EGRB.

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I. INTRODUCTION

The observation of the lithium plateau in low-metallicity halo stars [1] indicates pre-galactic lithium production, and has long been understood as a signature of the primordial lithium predicted by the big bang nucleosynthesis (BBN) theory. However, recent *WMAP* results [2] together with the BBN theory predict the primordial lithium abundance $(^7\mathrm{Li}/\mathrm{H})_{\mathrm{BBN}} = 3.82^{+0.73}_{-0.60} \times 10^{-10}$ [3] that is a factor of 3 higher than the observed elemental lithium plateau abundance of $(\mathrm{Li}/\mathrm{H})_{\mathrm{pl}} = 1.23^{+0.34}_{-0.16} \times 10^{-10}$ [4]. Moreover, any nonprimordial but pre-galactic source of lithium would act as a "contaminant" to the plateau lithium abundance and would have to be corrected for in order to obtain the true primordial plateau, which would, consequently, create an even larger discrepancy between theory and observations and result in a even larger lithium problem.

A very well-motivated candidate for such a pre-galactic source of ^{7}Li would be a cosmic-ray population that would originate during the process of cosmological structure formation. Specifically, the particles should be accelerated in the shocks which inevitably arise from the infall of bayronic matter onto dark matter potentials [5]. The composition of these cosmic rays would be primordial, i.e., made only of protons and alpha particles; their interactions with ambient baryons produce lithium isotopes via $\alpha + \alpha \rightarrow {}^{6,7}\mathrm{Li}$ [6]. Besides ^{7}Li, any cosmic-ray population would also produce ^{6}Li. Unlike ^{7}Li, the *only* known astrophysical nucleosynthesis mechanism for ^{6}Li production is in cosmic-ray interactions [7]. Thus, if structure-formation cosmic rays (SFCRs) are an important pre-galactic source of lithium, they should also result in ^{6}Li production [8], and a ^{6}Li plateau should also exist at some level in low-metallicity halo stars.

Recent halo-star observations indeed indicate the existence of a ^{6}Li plateau [9]. These high-sensitivity spectra measure the Li line shape precisely enough to obtain an isotope ratio $^7\mathrm{Li}/^6\mathrm{Li} \approx 0.05$, which corresponds to a plateau of $^6\mathrm{Li}/\mathrm{H} \approx 6 \times 10^{-12}$. This lies far above the standard BBN level of ^{6}Li production [10], and thus has provoked enormous interest. Some scenarios for decaying dark matter can allow for ^{6}Li production (e.g., [11]). It was also suggested that the ^{6}Li may not be pre-galactic but due to *in situ* flare production [12]. In the present discussion, we will work within the assumption that there is a ^{6}Li plateau, which indicates a pre-galactic ^{6}Li component, whose origin is not primordial but astrophysical—i.e., due to accelerated particles.

Since the *ratio* of ^{6}Li and ^{7}Li production in cosmic-ray interactions depends *only* on their cross sections, the existence of the ^{6}Li plateau can be used to determine the possible production of pre-galactic ^{7}Li and constrain the possible "contamination" to the Spite plateau by the SFCR population, or any other pre-galactic cosmic rays [13–15]. Such a correction is in addition to—but a logical extension of—the correction due to Li (and Be and B) synthesis by galactic cosmic rays, which themselves have a small impact on the plateau value [16]. We find below that SFCRs can then make up to 15% of the observed elemental lithium plateau at best. This is in agreement with the findings of

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[14] that analyzed the observed ^{6}Li plateau as a result of cosmic rays that would originate from Population III stars.

Besides lithium, SFCRs would also give rise to the gamma-ray emission from inverse Compton scattering of electrons off photon background and from decay of neutral pions that would result from hadronic interactions $pp \rightarrow \pi^0 \rightarrow 2\gamma$ [17]. This would contribute to the observed extragalactic gamma-ray background [18]. It was shown in [13] that there is a tight connection between pionic gamma rays and lithium that are produced by a given cosmic-ray population. Thus, by using this connection and our constraint on the possible ^{7}Li production by the SFCRs, we can also constrain the level at which this cosmic-ray population could contribute to the observed extragalactic gamma-ray background (EGRB). We find below that the SFCRs can in the upper limit contribute at the level of 5% to the EGRB.

The work of [14] has been along similar lines of argument as those presented here. In their paper [14] (and the follow-up [19]) Rollinde *et al.* account for the observed ^{6}Li plateau by cosmic-ray interactions where they consider cosmic rays that would originate from early Population III stars, as opposed to structure-formation cosmic-ray population discussed here. In this paper we place even stronger constraints, but we also draw attention to how the two scenarios of different cosmic-ray populations could be discriminated against.

II. AN ESTIMATE OF THE ^{7}Li PRODUCTION BY STRUCTURE-FORMATION COSMIC RAYS

The ratio at which ^{7}Li and ^{6}Li are made in cosmic-ray interactions depends only on the ratio of their production reaction rates, which is a ratio of their production cross sections, weighted by the cosmic-ray energy spectrum. In the case of SFCRs, the only relevant production channel is through fusion reaction $\alpha + \alpha \rightarrow {}^{6,7}$Li. With the adopted SFCR spectrum characteristic of strong shocks the ratio at which ^{7}Li and ^{6}Li are produced through this channel is 2:1 [13]. If we assume that the observed ^{6}Li plateau abundance of $^6\mathrm{Li/H} = 6.3 \times 10^{-11}$ [9] is entirely made by SFCRs that originate from strong cosmological shocks, this results in the $\mathrm{Li} = {}^7\mathrm{Li} + {}^6\mathrm{Li}$ production of

$$\left(\frac{\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{SFCR}} = 1.9 \times 10^{-11} \tag{1}$$

$$\frac{\mathrm{Li}_{\mathrm{SFCR}}}{\mathrm{Li}_{\mathrm{plateau}}} = 0.15. \tag{2}$$

With these estimates we can now revise the existing discrepancy between ^{7}Li plateau observations and BBN prediction. We correct the plateau abundance for the possible contamination by SFCRs

$$\frac{{}^7\mathrm{Li}_{\mathrm{BBN}}}{\mathrm{Li}_{\mathrm{plateau}} - {}^7\mathrm{Li}_{\mathrm{SFCR}} - {}^6\mathrm{Li}_{\mathrm{SFCR}}} = 3.7 \tag{3}$$

and find that the magnitude of this discrepancy is enlarged by $\sim$25%. We again emphasize that this revised limit assumes the ^{6}Li is due to SFCRs, but is independent of the details of the SFCR spectra which all give similar $^7\mathrm{Li}/^6\mathrm{Li}$ ratios.

Because ^{6}Li is the more fragile isotope, it is more susceptible to *in situ* stellar depletion effects which one must always consider. Ref. [9] use the pre-main-sequence stellar models of [20] to estimate the possible impact of depletion; the resulting corrected ^{6}Li abundances now show a nonzero rising slope in the ^{6}Li abundance with respect to the metallicity rather than a plateaulike feature. However, for the purpose of our argument such a ^{6}Li-metallicity trend would still constrain the SFCR lithium yield, because SFCRs should still give rise to a ^{6}Li plateau that should resurface below some metallicity. In this case the lowest ^{6}Li abundance represents an upper limit to the ^{6}Li production by SFCRs. This scenario gives somewhat higher estimates of ^{6}Li abundances in low-metallicity halo stars, and the accompanying SFCR ^{7}Li limit would increase to $\mathrm{Li}_{\mathrm{SFCR}}/\mathrm{Li}_{\mathrm{plateau}} \approx 0.24$. This propagates to give a true primordial Li plateau abundance of $^7\mathrm{Li}_{\mathrm{plateau,true}} \approx 9 \times 10^{-11}$ and increases the discrepancy with BBN predictions to the factor of 4.2.

III. AN ESTIMATE OF THE HADRONIC SFCR CONTRIBUTION TO THE EGRB

In [13] we have shown and quantified the tight connection between lithium and hadronic γ-ray production through cosmic-ray interactions. With the assumption that cosmic-ray history in our Galaxy is representative of an average star-forming galaxy, this connection can be expressed as

$$I_{\gamma_\pi}(E > 0) = I_{0,i} \frac{Y_{i,\mathrm{obs}}}{Y_{i,\odot}} \tag{4}$$

where $Y_i \equiv n_i/n_b$ measures the abundance of $i \in {}^6\mathrm{Li}, {}^7\mathrm{Li}$ per baryon. The factor $I_{0,i}$ depends on the assumed helium abundance in cosmic rays and in the local medium and also incorporates the ratio of flux averaged cross sections for $pp \rightarrow \pi^0 \rightarrow 2\gamma$ and $\alpha\alpha \rightarrow {}^{6,7}$Li production reactions. For the adopted cosmic-ray spectrum representative of strong shocks and using ^{6}Li as an indicator, we adopt this prefactor to be $I_{0,6} = 1.86 \times 10^{-5}\ \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ [13]. We note here that $I_{\gamma_\pi}(E > 0, t)$ is the total pionic gamma-ray intensity, i.e., integrated over the entire energy range. Using the solar ^{6}Li abundance from [21] and the observed ^{6}Li plateau abundance of [9] we find that SFCRs can at best produce $I_{\gamma_\pi}(E > 0) = 7.7 \times 10^{-7}\ \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ pionic gamma rays over the entire energy range.

To be able to compare this with observations which have some lower energy limit one would have to assume something about the history of pionic gamma-ray production by SFCRs. Since any such assumption would be quite model dependent we will only try to provide a model-independent upper limit to the SFCR pionic gamma-ray fraction to the EGRB. We will do this by assuming that all of the SFCR pionic gamma rays are created at redshift zero, since higher redshifts would put more weight on the lower energy part of the pionic gamma-ray spectrum. For example, for the pionic gamma-ray spectrum adopted from [22] and a strong-shock cosmic-ray spectrum we find that if all of the pionic gamma rays made by SFCRs are taken to originate from redshift zero, then $I_{\gamma_\pi}(z = 0, E > 0.1\ \mathrm{GeV})/I_{\gamma_\pi}(z = 0, E > 0\ \mathrm{GeV}) = 0.77$, compared to the case where we assume that they all originate from $z = 10$ where we now get $I_{\gamma_\pi}(z = 10, E > 0.1\ \mathrm{GeV})/I_{\gamma_\pi}(z = 10, E > 0\ \mathrm{GeV}) = 0.12$. Thus, if we assume that all of the SFCR pionic gamma rays come from $z = 0$, this gives us the uppermost limit and we find that $I_{\gamma_\pi}(z = 0, E > 0.1\ \mathrm{GeV}) = 5.9 \times 10^{-7}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$, which is $\approx 5\%$ of the observed EGRB $I_{\gamma,\mathrm{obs}}(E > 0.1\ \mathrm{GeV}) = 1.1 \times 10^{-5}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ [18].

It is important to bear in mind the nature of the gamma-ray/lithium connection encoded in Eq. (4). The common cosmic-ray origin of Li isotopes and pionic photons links both observables at any epoch t to the cosmic-ray fluence (integrated flux) *up to that epoch*. This in turn guarantees that the Li abundances at t are proportional to the γ-ray intensity at t. Note, however, that any ^{6}Li plateau abundance must have been produced pre-galactically, i.e., at high redshift. Thus, the pionic γ rays associated with the plateau ^{6}Li are only those produced by SFCRs *at redshifts prior to halo-star formation*. Any additional post-halo-star SFCR activity will contribute (at lower redshifts) to the pionic background, but not to the halo-star ^{6}Li plateau. Hence, our pionic limit is only on the high-redshift EGRB component; a lower redshift SFCR contribution could exist. With this in mind, we note the following. (1) The very existence of any ^{6}Li plateau demands a pre-galactic origin, which if astrophysical would in turn require a rapid and high-redshift particle flux from SFCRs (or Population III supernovae); these particles must contribute to a pionic γ-ray background at some level. (2) Turning the problem around, if a diffuse, redshifted pionic signature can be found in the EGRB, this places an *upper* limit on pre-galactic Li from accelerated particles. If this limit is near the ^{6}Li plateau, one could even hope to use the redshift of the pionic feature as an indicator of the epoch of halo-star formation.

IV. DISCUSSION

In this paper we have placed strong constraints to the level at which a structure-formation population of cosmic rays could contribute to the pre-galactic lithium production and thus ‘‘contaminate’’ halo-star measurements of the lithium plateau which should reflect the primordial ^{7}Li abundance. We find that SFCRs can at most contaminate the Spite plateau at the level of 15%. This in turn makes the discrepancy between BBN predicted primordial ^{7}Li abundance and the observed plateau even larger. The two values differ now by the factor of ≈ 3.7. Thus the cosmological ^{7}Li problem is indeed worsened but only mildly, if pre-galactic cosmic rays are the source of the ^{6}Li plateau. But it is worth emphasizing that in this scenario (1) the cosmological ^{7}Li problem does remain, and (2) any solution to the problem must account for the ^{7}Li discrepancy but *avoid* ^{6}Li production at or above the observed plateau. That is, the mere existence of a ^{6}Li plateau *does* imply pre-galactic production but *does not* necessarily demand a primordial origin for ^{6}Li.

Moreover, we find that SFCR ^{6}Li production is accompanied by a high-redshift pionic gamma-ray flux which would in the upper limit make up 5% of the present observed EGRB. Though this represents only a small fraction to the *currently* observed EGRB, it should certainly leave an imprint on the new observation of the EGRB by *GLAST* [23]. Though no physical feature is at present seen in the EGRB spectrum, greater sensitivity of *GLAST* will allow for many of the currently unresolved sources to become resolved which will result in a lower EGRB (e.g., [24]). Pionic gamma rays made in SFCR interactions represent a true diffuse component of the EGRB and will thus contribute even more to the new reduced EGRB. A spectral feature in such a diffuse component [13] could then potentially be resolved and used to determine the nature of the cosmic-ray population that gave rise to it. Namely, the position and the shape of this pionic gamma-ray feature(s) could discriminate between arising from a SFCR population and/or some other early cosmic-ray population [14] because of different source histories. Unresolved sources are expected to contribute most to the current EGRB at the lower energy end [25]. Resolving these sources will open a window for the signature of SFCR gamma rays to be seen being that larger redshifts of origin of SFCRs will result in larger gamma-ray fluxes at lower energies. Detection of a pionic gamma-ray signature in the EGRB from a given cosmic-ray population would in turn also discriminate between different explanations of the ^{6}Li plateau.

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