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STRUCTURE FORMATION COSMIC RAYS: IDENTIFYING OBSERVATIONAL CONSTRAINTS

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SUMMARY: Shocks that arise from baryonic in-fall and merger events during the structure formation are believed to be a source of cosmic rays. These "structure formation cosmic rays" (SFCRs) would essentially be primordial in composition, namely, mostly made of protons and alpha particles. However, very little is known about this population of cosmic rays. One way to test the level of its presence is to look at the products of hadronic reactions between SFCRs and the ISM. A perfect probe of these reactions would be ^6Li. The rare isotope ^6Li is produced only by cosmic rays, dominantly in $\alpha\alpha \rightarrow {}^6Li$ fusion reactions with the ISM helium. Consequently, this nuclide provides a unique diagnostic of the history of cosmic rays. Exactly because of this unique property is ^6Li affected most by the presence of an additional cosmic ray population. In turn, this could have profound consequences for the Big-Bang nucleosynthesis: cosmic rays created during cosmic structure formation would lead to pre-Galactic Li production, which would act as a "contaminant" to the primordial ^7Li content of metal-poor halo stars. Given the already existing problem of establishing the concordance between ^7Li observed in halo stars and primordial ^7Li as predicted by the $WMAP$, it is crucial to set limits to the level of this "contamination". However, the history of SFCRs is not very well known. Thus we propose a few model-independent ways of testing the SFCR species and their history, as well as the existing lithium problem: 1) we establish the connection between gamma-ray and ^6Li production, which enables us to place constraints on the SFCR-made lithium by using the observed Extragalactic Gamma-Ray Background (EGRB); 2) we propose a new site for testing the primordial and SFCR-made lithium, namely, low-metalicity High-Velocity Clouds (HVCs), which retain the pre-Galactic composition without any significant depletion. Although using one method alone may not give us strong constraints, using them in concert will shed a new light on the SFCR population and possibly give some answers about the pressing lithium problem.

Key words. cosmic rays – Gamma rays: theory – Gamma rays: observations – Nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

A number of recent cosmological hydrodynamic simulations have shown that the baryonic in-fall and merger events during the growth of large-scale structures give rise to cosmological shocks (see e.g. Miniati et al. 2000, Ryu et al. 2003). Accretion of gas onto sheets, filaments and knots produces very strong external, large-scale accretion shocks, with

Mach numbers up to $\sim$ 100 (Ryu et al. 2003) or even higher (Miniati et al. 2000). On the other hand, collisions between substructures inside clusters produce merger shocks, which together with accretion shocks that propagate through the intracluster medium, form very complex "flow shocks" that are continuously fueled by the inflow of gas through filaments and sheets. These internal shocks are somewhat weaker but still with Mach numbers up to 10 (Miniati et al. 2000).

Because of their vastness, longevity and high velocities, structure formation shocks are potentially very important sites for cosmic-ray acceleration, provided that there is at least a modest magnetic field[1]. Due to their high shock velocities and higher preshock gas densities, internal shocks[2] are responsible for about $\sim$ 90% of cosmic-ray acceleration, and moreover, a significant fraction of energy of these collisionless shocks can be converted into cosmic rays via diffusive shock acceleration mechanism (Ryu et al. 2003). Thus, "structure forming" cosmic rays (hereafter SFCRs) population might be quite substantial, which could have numerous consequences. It was proposed by Loeb and Waxman (2000) that SFCR-electrons could significantly contribute to the extragalactic gamma-ray background (hereafter EGRB), by Inverse Compton scattering (IC) off of cosmic microwave background (CMB) photons. On the other hand, accumulating population of SFCR-protons could have profound consequences on the cosmology if cosmic-ray pressure was ever comparable to the thermal pressure (Ensslin et al. 1997). However, our main interest revolves around possible consequences for the Big Bang nucleosynthesis.

For decades Big Bang Nucleosynthesis (hereafter BBN) has stood the test of time by successfully predicting primordial abundances of the light elements, which agreed with observational constraints (see e.g. Olive et al. 2000). Although the recent Wilkinson Microwave Anisotropy Probe (hereafter *WMAP*) results (Spergel et al. 2003) together with the BBN showed excellent agreement with helium and deuterium abundances, they also showed primordial ^7Li abundance to be at least 2 times greater than the lithium measured in low-metallicity halo stars (Cyburt et al. 2003). There are several possible causes for this discrepancy– observational systematics, stellar destruction, BBN uncertainties and even possible presence of a new physics (see e.g. Cyburt et al. 2004 and references therein). Although the solution in the form of the new physics is maybe the least likely one of all, it is also the one with the most severe consequences. Therefore, it is crucial that we fully understand this discrepancy and its level.

Observations of Li in low-metallicity stars show flatness with respect to the metallicity ("Spite plateau"; Spite and Spite 1982), indicating that what we see is apparently the primordial ^7Li abundance. However, lithium is also produced in cosmic-ray interactions, mainly through the fusion process $\alpha + \alpha \rightarrow {}^{6,7}Li$ (Steigman and Walker 1992). Thus, what is observed in halo stars is, in fact, the *pre-Galactic* Li abundance since $\mathrm{Li_{halo}} = \mathrm{Li_{BBN}} + \mathrm{Li_{GCR}}$ (Ryan et al. 2000). Although ^7Li in the early Galaxy is dominated by its primordial value (e.g. Cyburt et al. 2003 and references therein), the observed halo star Li should be corrected for the GCR component in order to get to the primordial abundance. However, the primordial ^7Li inferred from halo stars is substantially lower than the value predicted by BBN+ *WMAP*, which represents a serious problem. This problem becomes even more severe as soon as one realizes that there is yet another pre-Galactic source of lithium, namely structure formation shocks, which has to be accounted for in order to obtain the primordial value. Although the SFCR population is bound to contribute to the halo star lithium ($\mathrm{Li_{halo}} = \mathrm{Li_{BBN}} + \mathrm{Li_{GCR}} + \mathrm{Li_{SFCR}}$), it is unknown to which level. Thus it is not clear how much worse the lithium problem truly is.

We will try to constrain this SFCR-Li component and see how large it can be compared to the primordial value. One way to do this is to realize that there is a connection between gamma-rays and lithium produced by any cosmic-ray population. As already stated, both Li isotopes are produced by cosmic rays, but ^7Li is dominated by its primordial value. On the other hand, ^6Li is produced *only* by comic rays, which makes it a perfect diagnostic tool of cosmic rays. Besides lithium, cosmic rays also inevitably produce γ-rays (pp $\rightarrow \pi^0 \rightarrow 2\gamma$), which are seen as pronounced emission from the Galactic plane (Hunter et al. 1997), but cosmic-ray populations in and between external galaxies also contribute to a diffuse EGRB. Thus, at some level, there is a "structure formation" component to the EGRB. We establish the model-independent γ-ray–Li connection and then use the observed EGRB to place constraints on the pre-Galactic lithium component that could have been produced by SFCRs. Unfortunately, we find that uncertainties are large enough so that our constraints, based on this method, are too weak to exclude large SFCR-Li contribution to the halo star lithium (Fields and Prodanović 2005). These method and constraints that follow from it are discussed in Section 2.

Another way to test the lithium problem and the pre-Galactic lithium component is to measure lithium abundances in other low-metallicity sites. To this date halo stars are the only low-metallicity sites where lithium was observed, but abundance measurements are plagued with systematic uncertainties

[1]Magnetic fields inside intracluster medium of galaxy clusters have been observed to have strengths of the order $\sim 0.1\ \mu$G (see e.g. Fusco-Femiano et al. 1999), while new upper limits of $\lesssim 1\ \mu$G along cosmic structures have also been claimed (Ryu et al. 1998).

[2]Ryu et al. (2003) classified cosmological shocks into two groups: *external* – form when never-shocked, low-density, void gas accretes onto sheets, filaments and knots- and *internal* – inside the regions bounded by external shocks where the preshock gas was previously shocked.

due to modeling of stellar atmospheres and convection. We propose a new site – high-velocity clouds (hereafter HVCs). Some of the HVCs falling into our Galaxy were observed to have metallicities as low as 1/10 of solar, which, together with the fact that they are free from all the systematic problems that halo-star measurements suffer from, makes them attractive sites for testing the primordial lithium. We predict elemental lithium abundance that these low-metallicity HVCs should have, and demonstrate that such measurement would be possible given the present technology. With this measurement in hand one would be able to test the existing lithium problem. Measuring Li abundance to be at or above the predicted limit would be consistent with the *WMAP* result, implying that the discrepancy with halo stars arises from stellar-modeling problems. On the other hand, measuring lithium in the HVCs would also test the level to which SFCR-Li component is present and the level of its contamination to the observed halo star lithium. This method is discussed in Section 3.

Even if these two separate methods for constraining the SFCR-made lithium abundance are not powerful enough to rule out (or in!) a significant contribution to lithium measured in halo stars, using them in concert could provide stronger constraints and also give us valuable insight into this additional cosmic-ray population. This and future work are discussed in Section 4.

2. LITHIUM-6 AND GAMMA-RAY CONSTRAINTS ON COSMIC RAY HISTORY

The rare isotope ^6Li is made only by cosmic rays, dominantly in $\alpha\alpha \to {}^6Li$ fusion reactions with the ISM helium. Consequently, this nuclide provides a unique diagnostic of the history of cosmic rays in our Galaxy. The same hadronic cosmic-ray interactions also produce high-energy γ-rays (mostly via $pp \to \pi^0 \to \gamma\gamma$). Thus, hadronic γ-rays and ^6Li are intimately linked. In Fields and Prodanović (2005) we examine this link and show how ^6Li and γ-rays can be used together to place important model-independent limits on the cosmic-ray history of our Galaxy and the universe.

The most recent high-energy (roughly, in the 30 MeV – 30 GeV range) γ-ray observations are those of the EGRET experiment on the Compton Gamma-Ray Observatory, where the EGRET team found the evidence for an extragalactic γ-ray background (Sreekumar et al. 1998). The intensity, energy spectrum, and even the very existence of an extragalactic γ-ray background (EGRB) are not trivial to measure, as this information only arises as the residual after subtracting the dominant Galactic foreground from the observed γ-ray sky. The procedure for foreground subtraction is thus crucial, and different procedures starting with the same EGRET data have arrived at an EGRB with a lower intensity and different spectrum (Strong et al. 2004a), or have even failed to find evidence for an EGRB at all (Keshet et al. 2004). Despite these uncertainties, we will see that the EGRB (or limits to it) and Li abundances are mutually very constraining.

Whether or not an EGRB has yet been detected, at some level it certainly should exist. EGRET detections of individual active galactic nuclei (blazars) as well as the Milky Way and the LMC together guarantee that unresolved blazars (e.g. Stecker and Salamon 1996, Mukherjee and Chiang 1999), and to a lesser extent normal galaxies (Pavlidou and Fields 2002), will generate a signal at or near the levels claimed for the EGRB. Many other EGRB sources have been proposed, but one of the promising has been a subject of intense interest recently: namely, γ-rays originating from SFCRs. The most recent semi-analytical and numerical calculations (Gabici and Blasi 2003, Miniati 2002) suggest that this "structure forming" component to the EGRB is likely below the blazar contribution, but the observational and theoretical uncertainties here remain large; upcoming γ-ray observations by GLAST (Gehrels and Michelson 1999) will shed welcome new light on this problem.

In Fields and Prodanović (2005) we constrain Li production using recent determinations of the EGRB. First we place limits on γ-ray production from ordinary galactic cosmic rays (GCRs) by using the local ^6Li abundance (Section 2.3.1.). On the other hand, by using the EGRB we also place an upper limit to the Li production via SFCRs. This is done by first determining the maximal fraction of the EGRB that can come from pion decay (Prodanović and Fields 2004a), where we then assume that all of those pions were produced by SFCRs (Section 2.3.2.). However, we cannot rule out (or in!) SFCRs as an important source of pre-Galactic Li, but we will constrain it using the observed EGRB.

2.1 Formalism

In this Section we are going to perform a simple, back of the envelope analysis in order to demonstrate the straightforward connection between gamma-rays and lithium.

We know that low-energy ($\sim 10-100$ MeV/nucleon), hadronic cosmic rays produce lithium through $\alpha\alpha \to {}^{6,7}Li + \cdots$. However, higher-energy (>280 MeV/nucleon) cosmic rays also produce γ-rays via neutral pion decay: $pp \to \pi^0 \to \gamma\gamma$. Because they share a common origin in hadronic cosmic-ray interactions, we can directly relate cosmic-ray lithium production to "pionic" gamma-rays. The cosmic-ray production rate of ^6Li per unit volume is $q(^6Li) = \sigma_{\alpha\alpha\to{}^6\mathrm{Li}}\Phi_\alpha n_\alpha$, where Φ_α is the net cosmic ray He flux, n_α is the interstellar He number density, and $\sigma_{\alpha\alpha\to{}^6\mathrm{Li}}$ is the cross section for ^6Li production, appropriately averaged over the cosmic-ray energy spectrum (detailed definitions and normalization conventions are given in Appendix A.1.). Thus, the ^6Li mole fraction $Y_6 = n_6/n_\mathrm{b}$ is just $Y(^6Li) \sim \int \frac{dt}{n_\mathrm{b}} q_{6_{Li}} \sim y_{\alpha,\mathrm{cr}} Y_{\alpha,\mathrm{ism}} \sigma_{\alpha\alpha\to{}^6\mathrm{Li}} \Phi_p t_0$, where $y_{\alpha,\mathrm{cr}} = \Phi_\alpha/\Phi_p \approx (\mathrm{He/H})_\mathrm{ism}$.

On the other hand, the cosmic-ray production rate of pionic γ-rays is just the pion production rate times a factor of 2, that is, $q_{\gamma,\pi^0} = 2\sigma_{pp\to\pi^0}\Phi_{p,\rm cr}n_{p,\rm ism}$. Integrated over a line of sight towards the cosmic particle horizon, this gives a EGRB intensity $I_{\gamma,\pi^0} \sim c\int dt q_{\gamma,\pi^0}/4\pi \sim 2\sigma_{pp\to\pi^0}\Phi_p t_0 n_{\rm b}c/(4\pi)$. Thus we see that both the ^6Li abundance and the γ-ray intensity have a common factor of the (time-integrated) cosmic-ray flux, and so we can eliminate this factor and express each observable in terms of the other:

$$I_{\gamma,\pi^0} \sim \frac{n_b c}{2\pi y_{\alpha,\rm cr}} Y_{\alpha,\rm gas}\frac{\sigma_{\pi^0}^{pp}}{\sigma_{^6Li}^{\alpha\alpha}} Y_{^6Li}, \tag{1}$$

From Eq. (1) we see that the connection between cosmic-ray lithium production and pionic gamma-ray flux is straightforward: $I_{\gamma,\pi^0} \propto Y_{^6Li}$.

This rough argument shows the intimacy of the connection between ^6Li and pionic γ-rays. However, this simplistic treatment does not account for the expansion of the universe, nor for time-variations in the cosmic-ray flux, nor for the inhomogeneous distribution of sources within the universe. A detailed derivation, which includes these effects in a more rigorous treatment (Appendix A.2.), demonstrates that, indeed, the lithium abundance and the pionic γ-ray intensity arise from very similar integrals, which we can express via the ratio

$$\frac{I_{\gamma,\pi^0}(t)}{Y_i(\vec{x},t)} = \frac{n_{\rm b}c}{4\pi y_{\alpha,\rm cr}y_{\alpha,\rm ism}}\ \frac{\sigma_\gamma}{\sigma_{\alpha\alpha}^i}\ \frac{F_p(t)}{F_p(\vec{x},t)}, \tag{2}$$

where i denotes ^6Li or ^7Li. The flux-averaged pionic γ-ray production cross section is $\sigma_\gamma \equiv 2\xi_\alpha\zeta_\pi\sigma_{\pi^0}$ where the factor 2 accounts for the number of photons per pion decay, σ_{π^0} is the cross section for pion production, ζ_π is the pion multiplicity, while the factor $\xi_\alpha = 1.45$ accounts for $p\alpha$ and $\alpha\alpha$ reactions (Dermer 1986). The mean value of the cosmic-ray *fluence* (time-integrated flux) along the line of sight is given as

$$F_p(t) = \int_0^t dt\ \mu(\vec{s})\ \frac{n_{\rm b}^{\rm com}(\vec{s})}{n_{\rm b,0}}\ \Phi_p^{\rm cr}(\vec{s}), \tag{3}$$

where the average is weighted by the baryonic gas fraction and the ratio $n_{\rm b}^{\rm com}(\vec{s})/n_{\rm b,0}$ of the local baryon density along the photon path. On the other hand, the local proton fluence, weighted by the gas fraction $\mu = n_{\rm b,gas}/n_{\rm b}$ is given as $F_p(\vec{x},t) = \int_0^t dt'\ \mu(\vec{x},t')\ \Phi_p^{\rm cr}(\vec{x},t')$. Note that this "γ-to-lithium" ratio has its only significant space and time dependence via the ratio $F_p(t)/F_p(\vec{x},t)$ of the line-of-sight baryon-averaged fluence to the local fluence.[3]

One further technical note: $I_{\gamma,\pi^0} \equiv I_{\gamma,\pi^0}(>0) = \int_0^\infty d\epsilon_\gamma I_{\gamma,\pi^0}(\epsilon_\gamma)$ represents the total pionic γ-ray flux, integrated over *all* photon energies. While this quantity is well-defined theoretically, real observations have some energy cutoff, and thus report $I_\gamma(>\epsilon_0) = \int_{\epsilon_0}^\infty d\epsilon_\gamma I_\gamma(\epsilon_\gamma)$, typically with $\epsilon_0 = 100$ MeV. But the spectrum of pionic γ-rays will be shifted towards lower energies if they originate from a nonzero redshift. Thus it is clear that γ-ray intensity I_γ, integrated above some energy $\epsilon_0 \neq 0$, will be redshift-dependent. A way to eliminate this z-dependence is to include *all* pionic γ-rays, that is to take $I_\gamma \equiv I_\gamma(>0$ GeV), i.e., to take $\epsilon_0 = 0$. The ^6Li-γ proportionality is only exact for $I_\gamma(>0)$, as this quantity removes photon redshifting effects which spoil the proportionality for $\epsilon_0 \neq 0$. Thus we will have to use information on the pionic spectrum to translate between $I_\gamma(>\epsilon_0)$ and $I_\gamma(>0)$; these issues are discussed further in Section 2.2.

The relationship expressed by Eq. (2) is the main result of Fields and Prodanović (2005) paper, and we will bring this tool to bear on Li and γ-ray observations, using each to constrain the other. To do this, it will be convenient to write eq. (2) in the form

$$I_{\gamma,\pi^0}(t) = I_{0,i}\frac{Y_i(\vec{x},t)}{Y_{i,\odot}}\frac{F_p(t)}{F_p(\vec{x},t)}, \tag{4}$$

where the scaling factor

$$I_{0,i} = \frac{n_{\rm b}c}{4\pi y_{\alpha,\rm cr}y_{\alpha,\rm ism}}\ \frac{\sigma_\gamma}{\sigma_{\alpha\alpha}^i}\ Y_{i,\odot}, \tag{5}$$

is independent of time and space, and only depends, via the ratio of cross sections, on the shape of the cosmic-ray population considered. Table 1. presents the values of $I_{0,i}$ for different spectra that will be considered in the following Sections. Values of the scaling factor were obtained by using baryon number density $n_{\rm b} = 2.52\times10^{-7}$ cm^{-3}, cosmic-ray and the ISM helium abundances $y_\alpha^{\rm cr} = y_\alpha^{\rm ism} = 0.1$ and solar abundances $y_{^6Li_\odot} = 1.53\times10^{-10}$ and $y_{^7Li_\odot} = 1.89\times10^{-9}$ (Anders and Grevesse 1986). For the π^0 and lithium production cross-sections, we used the fits taken from Dermer (1986) and Mercer et al. (2001), and from that we obtained the ratios of flux-averaged cross-sections for different spectra, and these are also presented in Table 1.

We use two different cosmic-ray spectra. On the one hand, we adopt a GCR spectrum that is a power law in *total* energy, $\phi_p(E) \propto (m_p+E)^{-2.75}$, a commonly used approximation to the locally observed (i.e., *propagated*) spectrum. In contrast, the SFCR flux is taken to be the standard result for diffusive acceleration due to a strong shock, namely, a power law in momentum $\phi(E) \propto p(E)^{-2.2}$.

[3]In fact, the ratio also depends on the shape of the cosmic-ray spectrum (assumed universal), which determines the ratio of cross sections. We will take this into account below when we consider different cosmic-ray populations.

Table 1. Lithium and γ-ray Scalings and Production Ratios.

Cosmic-Ray Population	$I_{0,6}$ $[\mathrm{cm}^{-2}s^{-1}sr^{-1}]$	$I_{0.7}$	$\sigma^{\alpha\alpha}_{^6Li}/\sigma^{pp}_{\pi}$	$\sigma^{\alpha\alpha}_{^7Li}/\sigma^{pp}_{\pi}$	$^7Li/^6Li$
GCR	9.06×10^{-5}	8.36×10^{-4}	0.21	0.28	1.3
SFCR	1.86×10^{-5}	1.15×10^{-4}	1.02	2.03	2.0

2.2 Limits to "Pionic" Gamma-Rays

It Prodanović and Fields (2004a) we showed that a model-independent limit on the fraction of the observed gamma-ray intensity that is of pionic origin (gamma rays that originate from π^0 decay) can be placed. This limit comes from the notion that the observed gamma-ray spectrum shows no strong evidence of the pionic γ-ray spectral peak at $m_{\pi^0}/2$, the "pion bump"[4]. This is true for both the observed Galactic gamma-ray spectrum and the EGRB. Thus, by comparing the shapes of the observed EGRB and theoretical pionic gamma-ray spectra, we were able to maximize the pionic flux so that it stays below the observed one. This procedure allowed us to place constraints on the maximal fraction of the EGRB that can be of pionic origin.

We use a convenient semi-analytic fit to the pionic γ-ray source-function that was recently presented by Pfrommer and Ensslin (2004). They use Dermer's model (Dermer 1986) for the production cross section, and arrive at the formula:

$$\Gamma(\epsilon_\gamma) = \mathcal{N}\varphi[\epsilon(1+z)],$$
$$= \mathcal{N}\left[\left(\frac{2\epsilon_\gamma(1+z)}{m_{\pi^0}}\right)^{\delta_\gamma} + \left(\frac{2\epsilon_\gamma(1+z)}{m_{\pi^0}}\right)^{-\delta_\gamma}\right]^{-\alpha_\gamma/\delta_\gamma} \quad (6)$$

where ϵ_γ is the observed energy, and redshift z accounts for the distribution of sources. The spectral index α_γ determines the shape parameter $\delta_\gamma = 0.14\alpha_\gamma^{-1.6}+0.44$. In Dermer's model, the γ-ray spectral index α_γ is equivalent to the cosmic-ray spectral index, i.e. $\alpha_\gamma = \alpha_p$ (Dermer 1986). We adopt the value $\alpha_\gamma = 2.2$ for pionic extragalactic γ-rays, which is consistent with blazars and structure forming cosmic rays as their origin, and $\alpha_\gamma = 2.75$ for GCR-produced pionic gamma-rays. This source function peaks at half the pion rest energy. In our analysis, to obtain an uppermost limit to the "pionic" gamma-ray flux, we need only the energy-dependent part of Eq. (6), that is, everything that does not depend on energy we absorb in the normalization $\mathcal{N}$. Eventually, we set the normalization $\mathcal{N}$ so that "pionic" gamma-ray spectrum is maximal, but below the observed EGRB.

Due to the lack of a full model for the redshift history of SFCR sources, we assume that all of the SFCR-made pionic γ-rays originate at a single redshift. On the other hand, in the case of the contribution to the EGRB from normal galaxies we have better understanding for the redshift history of sources. Thus, in the GCR case, we follow Pavlidou and Fields (2002) to calculate the pionic differential gamma-ray intensity for some range of energies

$$I_{\gamma_{\pi,\epsilon}} = \mathcal{N}\int_0^{z_*} dz\frac{\dot\rho_\star(z)\varphi[(1+z)\epsilon]}{\sqrt{\Omega_\Lambda+\Omega_M(1+z)^3}} \quad (7)$$
$$\times\left[\frac{1}{\mu_{0,\mathrm{MW}}} - \left(\frac{1}{\mu_{0,\mathrm{MW}}}-1\right)\frac{\int_{z_*}^{z} dz(dt/dz)\dot\rho_\star(z)}{\int_{z_*}^{0} dz(dt/dz)\dot\rho_\star(z)}\right]$$

where $\mathcal{N}$ is again the normalization that is to be determined so that the pionic γ-ray flux is maximal. The present day Milky Way gas mass fraction is denoted by $\mu_{0,\mathrm{MW}}$, the cosmic star-formation rate is $\dot\rho_\star(z)$, and the cosmology is parameterized by Ω_Λ and Ω_m. We integrated up to z_*, the assumed starting redshift for star formation. In Fields and Prodanovć (2005) we adopted the following values: $\mu_{0,\mathrm{MW}} = 0.14$, $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$ and $z_* = 5$. For the cosmic star-formation rate we use the dust-corrected analytic fit from Cole et al. (2001).

For the observed EGRB we use Strong et al. (2004a) data which we fit. In order to set the normalization of Eq. (6) that maximizes the "pionic" contribution to the EGRB, we match the slope of the "pionic" source function to the slope of the fit to the EGRB data. This guarantees that the pionic EGRB will be maximal and always below the total observed one. Maximized pionic spectra are presented in Fig. 1. Because of the single-redshift approximation in the SFCR case, we perform this procedure for a range of redshifts, where results for two most extreme redshifts $z = 0$ and $z = 10$ for SFCR spectrum are plotted on the left. In the GCR case, we use the differential pionic gamma-ray intensity that was calculated from Eq. (8) for a range of energies, we then fit it, and finally through the same slope-matching procedure with the Strong et al. (2004a) data, we maximize the GCR-made pionic flux. This is presented on the right panel of Fig. 1.

[4]As described in detail by Stecker (1970), the gamma-ray spectrum that originates from pion decay $\pi^0 \to 2\gamma$ is symmetric around the peak at $m_{\pi^0}/2$ at the pion rest frame. We refer to this peak as the "pion bump".

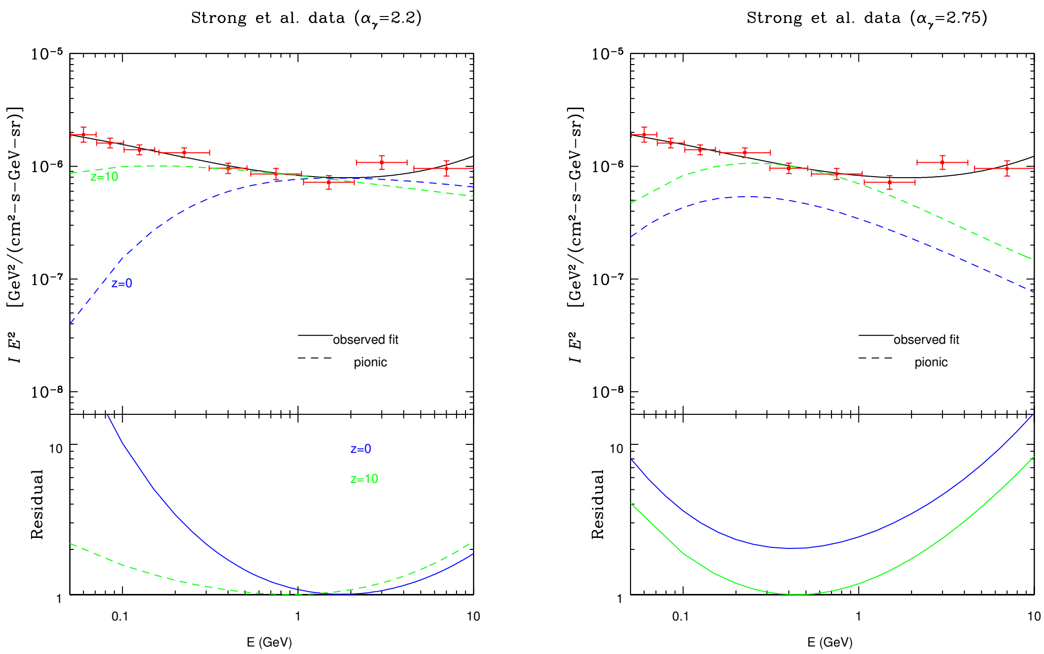

Fig. 1. *Left: maximal SFCR-pionic contribution to the EGRB, computed by assuming that pionic γ-rays originated at a single redshift, namely at $z_* = 0$ (dashed blue) and $z_* = 10$ (dashed green). Right: GCR-pionic contribution to the EGRB; dashed green- maximized, blue- normalized to the Milky Way. Solid line is the observed EGRB spectrum (fit to data) for Strong et al. (2004a) data (red crosses). Bottom panels present the residual function, that is,* $\log[(IE^2)_{\rm obs}/(IE^2)_\pi] = \log(I_{\rm obs}/I_\pi)$.[5]

However, to be able to connect the pionic γ-ray intensity I_{γ,π^0} with lithium mole fraction Y_i, as shown in Eq. (2), I_{γ,π^0} must include all of the pionic γ-rays, that is, the spectrum has to be integrated from energy $\epsilon_0 = 0$. The upper limit to the pionic γ-ray intensity above energy ϵ_0 for a given redshift can be written as

$$\begin{aligned} I_{\gamma,\pi^0}(>\epsilon_0) &= f_\pi(>\epsilon_0, z) I_\gamma^{\rm obs}(>\epsilon_0), \\ &= \mathcal{N}_{\max} \int_{\epsilon_0} \varphi[\epsilon(1+z)] d\epsilon, \end{aligned} \tag{8}$$

where $f_\pi(>\epsilon_0, z)$ is the upper limit to the fraction of pionic γ-rays (Fields and Prodanović 2005), $I_\gamma^{\rm obs}(>\epsilon_0)$ is the observed intensity above some energy, while $\mathcal{N}_{\max}$ is maximizing normalization from Eq. (6). An upper limit to the pionic γ-ray intensity that covers all energies $I_{\gamma,\pi^0}(>0, z)$, follows immediately from the above equations:

$$I_{\gamma,\pi^0}(>0, z) = f_\pi(>\epsilon_0, z) I_\gamma^{\rm obs}(>\epsilon_0) \frac{\int_0 \varphi[\epsilon(1+z)] d\epsilon}{\int_{\epsilon_0} \varphi[\epsilon(1+z)] d\epsilon}, \tag{9}$$

Now, this is something that is semi-observational and can be easily obtained from γ-ray intensity observed above some energy, and from Pfrommer and Ensslin (2004) results.

2.3. Results

2.3.1. Solar ^6Li and GCR-made Gamma-Rays

We have shown that ^6Li abundances and extragalactic γ-rays are linked because both sample cosmic-ray fluence. Now we apply this formalism to γ-ray and ^6Li data. In this section we turn to the hadronic products of Galactic cosmic rays, which are believed to be the dominant source of ^6Li, but have a sub-dominant contribution to the EGRB (Pavlidou and Fileds 2002). By using the formalism established in earlier sections we can test this standard point of view.

In Fields and Prodanović (2005) we use the solar ^6Li abundance to determine the fraction of the observed EGRB that is required if we assume that the entire solar ^6Li was made by GCRs. To be able to find $I_{\gamma,\pi^0}/Y_{^6{\rm Li}}$ from eq. (2) we assume that ratio of cosmic-ray fluence along the line of sight (weighted by gas fraction) to the local cosmic-ray fluence is $F_p(t)/F_p(\vec{x}, t) \approx 1$. That is, we assume that the Milky Way fluence is typical of star forming galaxies, i.e., that the γ-luminosities are comparable: $L_{\rm MW} \approx \langle L \rangle_{\rm gal}$. Note that in the most simple case of a uniform approximation (cosmic-ray flux and gas fraction the same in all galaxies), the two fluences would indeed be exactly equal.

[5]The figure in full colors are available on WEB site `http://saj.matf.bg.ac.yu`.

Taking the solar ^6Li abundance and $\langle\sigma^{\alpha\alpha}_{^6Li}\rangle/\langle\sigma^{pp}_{\pi}\rangle = 0.21$ for the ratio of GCR flux averaged cross-sections, we can now use eq. (4) to say that $I_{\gamma,\pi^0}(\epsilon > 0) = 9.06 \times 10^{-5}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$ is the hadronic γ-ray intensity that is required if all of the solar ^{6}Li is made via Galactic cosmic rays.

We wish to compare this ^6Li-based pionic γ-ray flux to the observed EGRB intensity $I^{\rm obs}_{\gamma}(\epsilon > \epsilon_0)$. However, eq. (4) gives the hadronic γ-ray intensity integrated over all energies, whereas the observed one is above some finite energy. Therefore, as explained in Section 2.2., we have to compute

$$
\begin{aligned}
I_{\gamma,\pi^0}(\epsilon > \epsilon_0) &= I_{\gamma,\pi^0}(\epsilon > 0)\frac{\int_{\epsilon_0} d\epsilon I_{\epsilon,\pi}}{\int_0 d\epsilon I_{\epsilon,\pi}} \\
&= 9.06 \times 10^{-5}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\frac{\int_{\epsilon_0} d\epsilon I_{\epsilon,\pi}}{\int_0 d\epsilon I_{\epsilon,\pi}}. \qquad (10)
\end{aligned}
$$

Following Pavlidou and Fields (2002), we use the specific form of $I_{\epsilon,\pi}$ as expressed in Eq. (8), noticing that, in Eq. (10), we have the ratio of two integrals where integrands are identical, thus normalizations and constants will cancel out. Finally, we find

$$
I_{\gamma,\pi^0}(\epsilon > 0.1\mathrm{GeV}) = 3.22 \times 10^{-5}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}, \qquad (11)
$$

which we can now compare to the observed Strong et al. (2004a) EGRB value of $I^{\rm obs}_{\gamma}(\epsilon > 0.1\mathrm{GeV}) = 1.11 \times 10^{-5}$. As one can see, our *pionic* EGRB gamma-ray intensity is about 3 times larger than the *entire* observed value!

We thus conclude that the solar ^6Li abundance, if made by GCRs as is usually assumed, seems to demand an enormous diffuse pionic γ-ray contribution, far above the entire EGRB level. We also note that if the astration (destruction in stars) of ^6Li is taken into consideration, one might use ^6Li abundance larger than solar. In that case one would find that the accompanying *pionic* EGRB gamma-ray intensity is more than 3 times greater than the observed EGRB.

How might this discrepancy be resolved? One explanation follows by dropping our assumption that $F(\vec{x}_{\rm MW}, t_0) = F_{\rm avg}(t_0)$, i.e., that the baryon-weighted Milky Way GCR fluence is the same as the cosmic mean for star-forming galaxies. Note that we have $F = \int dt\mu\Phi \propto \int dt\,\langle\psi M_{\rm gas}\rangle$, where ψ is the global galactic star formation rate (assuming $\Phi \propto \psi$), and $M_{\rm gas}$ the galactic gas content. If our Galaxy has an above-average star formation rate and/or gas mass, this shall increase the local ^6Li production relative to the average over all galactic populations, and thus lead to an overestimate of the EGRB. A more unconventional view would be that ^6Li is in fact primarily made by SFCRs themselves, rather than by GCRs. However, as we will see in Section 4.1., there is indication that this problem will be resolved with a more careful analysis in our future work.

2.3.2. ^6Li and SFCR-made Gamma-Rays

In Fields and Prodanović (2005) we exploit the γ-ray-Li connection to constrain the structure-formation Li contamination. However, only the fraction of lithium that was made by SFCR *prior* to the birth of halo stars will end up being a contaminant to the primordial halo star lithium. Unfortunately, we currently lack a detailed understanding of the amount and time-history of SFCRs (and resulting γ-rays and Li). Thus, we shall make the conservative assumption that *all* SFCRs, and the resulting γs and Li, are generated prior to *any* halo stars. Furthermore, as the history of SFCR sources is not very well known, we shall assume that all of the SFCR-pionic γ-rays originate at a single redshift. Finally, we will assume that the pionic contribution to the EGRB is *entirely* due to SFCRs. This allows us to relate observational limits on the pionic EGRB to pre-Galactic Li. We again take the ratio of cosmic-ray fluence along the line of sight (weighted by gas fraction) to the local cosmic-ray fluence to be $F_p(t)/F_p(\vec{x}, t) \approx 1$.

With these assumptions and SFCR composition $\Phi^{\rm cr}_{\alpha}/\Phi^{\rm cr}_{p} \approx y^{\rm cr}_{\alpha} = 0.1$, we can now use the appropriate scaling factor from Table 1. to rewrite Eq. (2)

$$
\begin{aligned}
I_{\gamma,\pi^0}(\epsilon > 0, z) &= \frac{\xi_\gamma\zeta_\alpha}{4\pi y^{\rm cr}_{\alpha} y^{\rm ism}_{\alpha}}\frac{\zeta\sigma_{\pi^0}}{\sigma^{\alpha\alpha}_{^6Li}}\left(\frac{^6Li}{\mathrm{H}}\right)n_{\rm b}c, \\
&= 1.86 \times 10^{-5}\left(\frac{^6Li}{^6Li_{\odot}}\right)\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}, \qquad (12)
\end{aligned}
$$

or

$$
\left(\frac{^6Li}{^6Li_{\odot}}\right) = 0.538\left(\frac{I_{\gamma,\pi^0}(>0)}{10^{-5}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}}\right), \qquad (13)
$$

where we used the solar lithium mole fraction $Y(^6Li)_{\odot} = 1.09 \times 10^{-10}$. As mentioned previously, the method used in subtraction of the Galactic foreground is crucial for obtaining the EGRB spectrum. Moreover, the EGRB spectrum is an important input parameter in our estimates of the maximal pionic gamma-ray flux that we use. In Fields and Prodanović (2005) we have considered three different spectra: Sreekumar et al. (1998), Strong et al. (2004a), and Keshet et al. (2004) limit to the EGRB. However, here we present our results for Strong et al. (2004a) spectra only. The results depend on the choice of the EGRB spectrum as well as the redshift of origin of cosmic rays according to the single-redshift approximation used to obtain the maximal pionic EGRB fraction. Note that we considered only two of the most extreme redshifts to illustrate the results. In the Table 2, z is the redshift, $I_{\gamma,\pi}(>0)$ is the upper limit for the pionic γ-ray intensity above 0 energy determined from Eq. (9) as explained in Section 2.2. $\mathrm{Li}^{\rm theo}_{p}$ and $\mathrm{Li}^{\rm obs}_{p}$ are the theoretical, that is, "CMB"-based (Cyburt et al. 2003) primordial, and observational, that is pre-Galactic (Ryan et al. 2000), lithium abundances respectively

$$
\left(\frac{^7Li}{\mathrm{H}}\right)_{\rm BBN,thy} = (3.82^{+0.73}_{-0.60}) \times 10^{-10}, \qquad (14)
$$

$$
\left(\frac{\mathrm{Li}}{\mathrm{H}}\right)_{\rm pre-Gal,obs} = (1.23^{+0.34}_{-0.16}) \times 10^{-10}, \qquad (15)
$$

Table 2. Upper limits on Li of SFCR origin.

EGRB [$\mathrm{cm^{-2}s^{-1}sr^{-1}}$]	z	$I_{\gamma,\pi}(>0)$	$(\mathrm{Li/H})^{\max}_{\mathrm{SFCR}}$	$\frac{\mathrm{Li}^{\max}_{\mathrm{SFCR}}}{\mathrm{Li}^{\mathrm{theo}}_{p}}$	$\frac{\mathrm{Li}^{\max}_{\mathrm{SFCR}}}{\mathrm{Li}^{\mathrm{obs}}_{p}}$
Strong et al. (2004a)	0	4.59×10^{-6}	1.14×10^{-10}	0.30	0.93
$I_{\gamma,\mathrm{obs}}(>0.1)=1.11\times10^{-5}$	10	6.27×10^{-5}	1.56×10^{-9}	4.09	12.69

To find the total halo star contribution we must also include ^7Li, which is, in fact, produced more than ^6Li in $\alpha\alpha$ fusion: as seen in Table , $(^7\mathrm{Li}/^6Li)_{\mathrm{SFCR}} = \langle\sigma^{\alpha\alpha}_{^7Li}\rangle/\langle\sigma^{\alpha\alpha}_{^6Li}\rangle \approx 2$. The total SFCR elemental Li $\equiv$ $^6Li + {}^7Li$ production appears in Table 2, both in terms of the absolute $(\mathrm{Li/H})^{\max}_{\mathrm{SFCR}}$ abundance and its ratio to the different measures of the primordial Li.

From Table 2. we see that the maximal possible SFCR contribution to halo star lithium could be quite substantial. If the pre-Galactic SFCR component is dominantly produced at high redshift (i.e., as in the $z\sim10$ case) then the maximal allowed Li production can exceed the primordial Li production (however it is estimated), in some cases by a factor of 12! The situation is somewhat better if the pre-Galactic SFCR production is at low redshift, but here it is hard to understand how this would preceed the halo star component of our Galaxy. The high-redshift result is, thus, the more likely one, but also somewhat troubling in that the limit is not constraining.

We caution that the lack of a strong constraint on SFCR Li production is not the same as positive evidence that the production was large. Recall that we have made several assumptions which purposely maximize the SFCR contribution; to the extent that these assumptions fail, the contribution falls, perhaps drastically. A more detailed theoretical and observational understanding of the SFCR history, and of the EGRB, will help to clarify this situation. Moreover, given that the halo star Li is already found to be below the CMB-based ^7Li BBN results, we are already strongly biased to believe that the pre-Galactic SFCR component is *not* very large.

3. HIGH-VELOCITY CLOUDS: AN INSIGHT INTO SFCRs AND Li

The primordial lithium abundance currently presents a pressing cosmological conundrum. The recent *WMAP* determination of the cosmic baryon density (Spergel et al. 2003), combined with big bang nucleosynthesis theory, tightly predicts the primordial ^7Li abundance (Cyburt et al. 2003), but Li measurements in halo stars give values lower than this by factors $\gtrsim 2$. The Li problem becomes even worse when one realizes that there is likely to be an *additional pre-Galactic source of lithium*, namely SFCR population. To date, halo stars are the only site suitable for observations of pre-Galactic Li, and have proven a very powerful tool for studies both of cosmology and of cosmic rays. But given that the observations are dominated by systematic errors (Ryan et al. 2000, Bonifacio et al. 2002), it is critical to identify other independent sites in which pre-Galactic Li can be measured.

In Prodanović and Fields (2004b) we propose a way to independently test the pre-Galactic Li abundance – to look at high-velocity clouds (HVCs). These consist of gas which falls onto our Galaxy, and the lowest metallicity clouds have a metallicity of about 10% of solar. These low-metallicity HVCs thus should have a mostly pre-Galactic composition, with a small contamination from the Galaxy. Moreover, these cold clouds are free of the possibility of thermonuclear depletion, which complicates the interpretation of halo star Li abundances.

Thus measuring Li in HVCs would provide an important test of the Li problem: if the measurement is consistent with the *WMAP*+BBN Li abundance (i.e., at that level or above), it would indicate that low Li measured in halo stars is a convection problem, or if measurement is below the *WMAP* result it would indicate that Li problem is more severe and requires more radical solutions. Also, measurement of Li in HVCs would test the significance of SFCR contribution to Li production.

3.1. Expectations

We expect the HVC lithium to consist of at least two components: (1) primordial ^7Li, plus (2) some amount of ^6Li and ^7Li from Galactic processes; it is also likely that there is a third component due to SFCRs. The Galactic Li sources are Galactic cosmic rays (which produce ^7Li and are the only Galactic source of ^6Li ; see Steigman and Walker 1992, Vangioni-Flam et al. 1999, Fields and Olive 1999), and other sources of ^7Li: the supernova neutrino process (e.g. Woosley et al. 1990) and low-mass giant stars (Sackmann and Boothroyd 1999). In models of the Galactic chemical evolution of Li, both the Galactic cosmic-ray Li components and the supernova component scale linearly with metallicity (Ryan et al. 2000). The evolution of stellar Li is more complex (Romano et al. 2001) but is only important at the highest metallicities ($\gtrsim 10^{-0.8}$ solar), and to a rough approximation also scales linearly with metallicity. Of course, it is unclear whether the Galactic contribution to HVC Li should be taken as a diluted form of the solar component, or as the predicted value at the HVC metallicity, but as long as the Galactic component scales linearly with metal content, these two results should be the same.

Thus the total (pre-Galactic plus Galactic) Li content in an HVC would depend on the cloud metallicity, and the pre-Galactic component should be more dominant the lower the metallicity. As shown in Prodanović and Fields (2004b), one would thus expect to find

$$\mathrm{Li_{HVC}} \gtrsim {}^7Li_\mathrm{p} + \frac{Z}{Z_\odot}\left[\left({}^7Li_\odot - {}^7Li_\mathrm{p}\right) + {}^6Li_\odot\right],$$
$$\gtrsim 7\times10^{-10}, \tag{16}$$

where the notation $\mathrm{Li} \equiv \mathrm{Li/H} = n_\mathrm{Li}/n_\mathrm{H}$ represents the lithium abundance. The primordial lithium abundance is given as ${}^7Li_\mathrm{p}$ (Cyburt et al. 2003), while the solar abundances were taken from Anders and Grevesse (1989). The final, numerical value is that appropriate for the HVC Complex C (Sembach et al. 2004), which has $Z = Z_\odot/6$ as determined from the oxygen abundance.

3.2. Observing Li in HVC

As we demonstrate in Prodanović and Fields (2004b), measuring lithium in the HVCs would resemble the ISM measurements in the sense that both systems contain diffuse, gas-phase Li. However, the observed HI column in, e.g. the HVC Complex C (towards the QSO PG 1259+593) is $N(\mathrm{HI}) \approx 10^{20}$ cm^{-2} (Sembach et al. 2004). This indicates that the Li column can be $\gtrsim 10^{10}$ cm^{-2}; indeed, Eq. (16) gives $N(\mathrm{Li}) = 7\times10^{10}$ cm^{-2}. Thus, with respect to the column density, HVCs are more favorable sites for measuring Li than the ISM. On the other hand, local ISM Li measurements can exploit nearby bright stars, while for HVC measurements one would have to observe toward an extragalactic object. In that case the brightest candidates are QSOs, the brightest of which are $m_V \sim 15$, about 10^4 times dimmer than stars used in the ISM measurements. Finally, one would have to worry about the presence of dust in the high-velocity clouds, but Tripp et al. (2003) found elemental abundances which imply that Complex C contains little or no dust. On the other hand, depletion onto dust is a significant effect for the ISM Li measurement. This is the main reason why expected Li column in HVC Complex C ($\sim 10^{10}$ cm^{-2}) is so much bigger than the ones reported by Knauth et al. (2003) for the ISM Li measurement ($\sim 10^9$ cm^{-2}).

To be more specific and get the sense of the observability of elemental Li, consider the Knauth et al. (2003) observations of the ISM lithium, where *isotopic* lithium abundances were successfully measured and resolved. For example, Li column density towards the Per X star ($m_{\mathrm{v},*} \approx 6$), is $N(\mathrm{Li}) \sim 5\times10^9$ cm^{-2}, which is about 10 times lower then the expected column of the elemental Li in the Complex C towards QSO PG 1259+593 ($m_{\mathrm{v,QSO}} \approx 15$). However, the star used in the ISM Li measurement has about 4000 times larger flux than the quasar that could be used in the HVC Li measurement. Thus, for the same exposure time and spectral resolution that was used in Knauth et al. (2003) ISM measurement of ${}^6Li$, HVC Li observability would be about 300 times lower; that is, a similar *isotopic* measurement would require that many times larger exposure time. However, Knauth et al. (2003) used a 2.7 m telescope for their ISM-Li observation. Thus if one were to use a 10 m telescope to observe Li in HVC Complex C, the HVC Li exposure time would now be about 20 times higher compared to Knauth et al. (2003) ISM-Li measurement toward Per X. It is important to note that Knauth et al. (2003) measurement was made with an impressive spectral resolution. On the other hand, much lower spectral resolution would be quite sufficient for measuring the *elemental* lithium abundance. Thus, by having a spectral resolution that is about a factor of 6 lower than the one obtained by Knauth et al. (2003), the exposure time needed for elemental lithium measurement in the Complex C would be about 300 ksec (Prodanović and Fields 2004b).

Thus, although observing Li in a HVC is more challenging than in the ISM, we believe that *elemental* Li can successfully be measured using a low-dispersion spectrum in a suitable HVC like Complex C toward QSO PG 1259+593.

3.3 Implications

In Eq. (16) of Section 3.1, we predict a lower limit to the lithium abundance that is expected to be observed in low-metallicity HVC Complex C toward the QSO PG 1259+593 (Prodanović and Fields 2004b). Measuring at or above this limit would be consistent with BBN prediction of primordial Li abundance and would, thus, indicate that the solution to the lithium problem should be found in the stellar modeling. Moreover, this measurement would also be a valuable test of additional sources of pre-Galactic lithium, like SFCRs. Since the Galactic contribution in Eq. (16) is about the same as the primordial one, a measurement above this level would indicate the presence of an additional source of Li (from the presence of dust it always follows that $\mathrm{Li_{HVC}} \geq Li_\mathrm{obs}$). The value in Eq. (16) includes the Galactic contribution, which is essentially "guaranteed." Now, SFCRs should provide an additional Li source, particularly if the HVCs really are intragroup gas which has been exposed to the Local Group SFCR flux. In Section 2. we have used a model-independent way to constrain the SFCR-Li abundance range, which, by using Eq. (16), comes to be about $0.4-5.6$ of the Galactic HVC lithium component. Thus, if Li in HVCs was found to be sufficiently above the primordial level, the excess over the Galactic contribution could be attributed to SFCRs, which would then give us more insight into this cosmic-ray population. This way we could limit the level of contamination of ISM-Li with SFCR-made Li which could possibly find its way into our Galaxy through the in falling HVCs.

However, we stress that measuring lithium below the level in Eq. (16) is also not excluded, in which case the already existing lithium problem would become more severe. Granted, one would then be able to argue that this just indicates that there is more dust than it was assumed at first, but one would then have to explain why lithium would have been more affected by dust than some other elements which indicate low presence of dust (Tripp et al. 2003).

Another valuable insight we would gain by looking for lithium in HVCs would be related to the already observed deuterium in Complex C (Sembach et al. 2004) – this would be the first primitive system with both D and Li and thus we could compare their ratio to the BBN and ISM values. Finally, if Li isotopic information became available, one could obtain a more robust separation of cosmic-ray and BBN components.

Finally, in Prodanović and Fields (2004b), we conclude that measuring even just elemental lithium in low-metallicity HVCs is of great importance, for it may hold a key to the resolution of the lithium problem, and because it will give us a great insight into any additional sources of pre-Galactic lithium.

4. DISCUSSION

Although the existence of SFCR species is highly expected, a lot of important questions about them and the consequences of their existence still remain open. What is their history? What is their injection spectrum? How much can they contribute to the EGRB? How much lithium can they make? Can they leak into galaxies? If so, can we distinguish them from GCRs accelerated in SNRs? Do they contribute, and to what level, to the gamma-ray emission from the Galactic plane? These are some of the questions that need to be answered. There is no single, unique method that would allow us to answer all of them at the same time. Thus, we use different approaches, different tools to get a greater insight into the SFCR species.

The first main point discussed in this paper is that there is a tight connection between ^6Li and EGRB as measures of cosmic-ray history. Thus, if SFCRs dominate the pionic EGRB, then, by using this connection, we can estimate the associated ^6Li production. Unfortunately, current EGRB data are such that we were able to place only a weak constraint, that is, we cannot exclude the possibility that a significant portion of pre-Galactic lithium is due to SFCRs. Moreover, using this method, we have also created a potentially significant problem as was shown in Section 2.3.1. The general belief is that GCRs are the dominant channel for ^6Li production. However, in our model-independent analysis we have discovered that solar ^6Li abundance, if produced by GCRs, requires too high of an EGRB (above the observed). Although our analysis is model-independent and points out a very important connection between γ-ray background and ^6Li production, it is also just a rough estimate in the sense that:

1) We have neglected other production channels of ^6Li, namely $p(\mathrm{CNO}, {}^6Li)$ and $\alpha(\mathrm{CNO}, {}^6Li)$;

2) We have neglected the ^6Li-astration when comparing our γ-ray-predicted ^6Li abundances with the solar one. The solar ^6Li abundance is smaller than the total lithium that was produced due to the fact that a fraction of the total produced ^6Li was astrated, that is, was destroyed in stars. Thus, by taking the solar ^6Li abundance, we have in fact underestimated the pionic EGRB that would accompany the total amount of ^6Li that was produced by cosmic rays till present day;

3) We have adopted a commonly-used propagated GCR spectrum, which becomes inaccurate at lower energies. Thus, we need to do a more careful treatment of propagation effects since Li production happens at low energies.

Our preliminary results, where we include other channels of ^6Li production and more correctly propagated cosmic-ray spectra, indicate that we will be able to close this loophole.

The second point made in this review, as stated in Section 3., is that measuring Li abundance in low-metallicity, HVCs could be a crucial step toward finding the solution to the primordial lithium problem. Moreover, it would constrain the pre-Galactic lithium that was produced by SFCRs. With such measurement (or limit!) in hand, we could theoretically separate isotopic components and use ^6Li as SFCR diagnostic tool. In the long term, it would be important to measure isotopic lithium abundances by using a high-dispersion spectrum, however since such measurement would require a large exposure time, it is important to justify it with a successful measurement of just elemental Li.

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Appendix

A.1. Notation and Normalization Conventions

The interactions of cosmic-ray species i with target nucleus j produces species k at a rate per target particle of

$$\Gamma_k = \int_{E_{\rm th,k}} dE\, \sigma_{ij\to k}(E)\phi_i \equiv \sigma_{ij\to k}\Phi_i, \qquad (17)$$

Here E is the cosmic-ray energy per nucleon, $\sigma_{ij\to k}$ is the energy-dependent production cross section, with threshold $E_{\rm th,k}$, and ϕ_i is the cosmic-ray flux. The rate per unit volume for $i+j\to k$ is thus $q_k = \Gamma_k n_j$.

Note that the flux in Eq. (17) is position- and time-dependent. To isolate this dependence, it is useful to define a total, energy-integrated, flux

$$\Phi_i = \int_{E_{\rm th,min}} dE\, \phi_i, \qquad (18)$$

where we choose the lower integration limit to always be the *minimum* threshold $E_{\rm th,min}$ for all reactions considered; in our case this is the $\alpha+\alpha \to {}^7Li$ threshold of 8.7 MeV/nucleon. From Eqs. (17) and (18) it follows that

$$\sigma_{ij\to k} = \Gamma_k/\Phi_i, \qquad (19)$$

represents a flux-averaged cross section. Also note that if the spectral *shape* of ϕ_i is constant (as we always assume), then so is $\sigma_{ij\to k}$, and the flux Φ_i contains all of the time and space variation of Γ_k.

Finally, two conventions are useful for quantifying abundances. Species i, with number density n_i, has a "mole fraction" (or baryon fraction) $Y_i = n_i/n_{\rm b}$. It is also convenient to introduce the "hydrogen ratio" $y_i = n_i/n_{\rm H} = Y_i/Y_{\rm H}$.

A.2. Li-Gamma Connection: Full Derivation

For Li production at location $\vec{x}$, the production rate per unit (physical) volume is

$$\begin{aligned} q_{\rm Li}(\vec{x}) &= \sigma_{\alpha\alpha}\Phi_\alpha^{\rm cr}(\vec{x}) n_{\alpha,\rm gas}(\vec{x}) \\ &= y_{\alpha,\rm cr} Y_\alpha^{\rm ism} \sigma_{\alpha\alpha}\Phi_p^{\rm cr}(\vec{x}) n_{\rm b,gas}(\vec{x}) \\ &\equiv \mu(\vec{x})\Gamma_{\rm Li}(\vec{x}) n_{\rm b}(\vec{x}), \end{aligned} \qquad (20)$$

where $\Phi_\alpha^{\rm cr}$ is the net cosmic-ray He flux, which we can write in terms of cosmic-ray proton flux $y_{\alpha,\rm cr} = \Phi_\alpha^{\rm cr}/\Phi_p^{\rm cr}$. Here, $y_{\alpha,\rm cr} = (\alpha/p)_{\rm cr} \approx (\alpha/p)_{\rm ism}$ is the cosmic-ray He/H ratio, and it is assumed to be constant in space and time.[6] Cross section of ${}^6Li$ production, appropriately averaged over the cosmic-ray energy spectrum, is written as $\sigma_{\alpha\alpha}$. The target density of (interstellar or intergalactic) helium is $n_{\alpha,\rm gas}$, which we write in terms of its ratio $Y_\alpha^{\rm ism} = n_{\rm He}/n_{\rm b}$ to the baryon density, that is, in terms of the ISM He mole fraction. We take $Y_\alpha^{\rm ism} \approx 0.06$ to be constant in space and time, but we do not assume this for the baryon density $n_{\rm b}(\vec{x})$. The baryonic gas fraction

[6] That is, we ignore the small non-primordial ${}^4He$ production by stars, and we neglect any effects of H and He segregation. Both of these should be quite reasonable approximations.

$$\mu = n_{\rm b,gas}/n_{\rm b}, \tag{21}$$

accounts for the fact that not all baryons need to be in a diffuse form. Finally, we will find it convenient to write $q_{\rm Li}(\vec{x})$ in terms of the local baryon density and the local Li production rate $\Gamma_{\rm Li}(\vec{x})$ per baryon.

With these quantities, we have

$$\frac{d}{dt} Y_{\rm Li}(\vec{x}) = \mu(\vec{x})\Gamma_{\rm Li}(\vec{x}), \tag{22}$$

which we can solve to get

$$Y_{\rm Li}(\vec{x},t) = \int_0^t dt' \ \mu(\vec{x},t') \ \Gamma_{\rm Li}(\vec{x},t'), \tag{23}$$

$$= y_{\alpha,\rm cr} Y_\alpha^{\rm ism} \sigma_{\alpha\alpha} \int_0^t dt' \ \mu(\vec{x},t') \ \Phi_p^{\rm cr}(\vec{x},t'), \tag{24}$$

$$= y_{\alpha,\rm cr} Y_\alpha^{\rm ism} \sigma_{\alpha\alpha} F_p(\vec{x},t), \tag{25}$$

where $F_p(\vec{x},t) = \int_0^t dt' \ \mu(\vec{x},t') \ \Phi_p^{\rm cr}(\vec{x},t')$ is the local proton fluence (time-integrated flux), weighted by the gas fraction. Thus, we see that Li (and particularly ^6Li) serves as a "cosmic-ray dosimeter" which measures the net local cosmic-ray exposure.

We now turn to γ-rays from hadronic sources, most of which come from neutral pion production and decay: $pp \rightarrow \pi^0 \rightarrow \gamma\gamma$. The extragalactic background due to these process is expected to be isotropic (at least to a good approximation). In this case, the total γ-ray intensity $I_\gamma = dN_\gamma/dA\,dt\,d\Omega$, integrated over all energies, is given by the integral

$$I_\gamma(t) = \frac{c}{4\pi} \int_0^t dt' \ q_\gamma^{\rm com}(t') \tag{26}$$

of the sources over the line of sight to the horizon. We are interested in particular in the case of hadronic sources, so that $q_{\rm com} = a^3 q$ is the total (energy-integrated) comoving rate of hadronic γ-ray production per unit volume; here a is the usual cosmic scale factor, which we normalize to a present value of $a_0 = a(t_0) = 1$.

The comoving rate of pionic γ-ray production per unit volume at point $\vec{s}$ is

$$\begin{aligned} q_{\gamma,\pi^0}^{\rm com}(\vec{s},t) &= \sigma_\gamma \Phi_p(\vec{s},t) n_{\rm H,gas}^{\rm com}(\vec{s},t) \\ &= \mu(\vec{s},t)\sigma_\gamma \Phi_p(\vec{s},t) n_{\rm H}^{\rm com}(\vec{s},t), \end{aligned} \tag{27}$$

where $n_{\rm H}^{\rm com}$ is the (comoving) hydrogen density, and $\Phi_p = 4\pi \int I_p(\epsilon)d\epsilon$ is the total (integrated over the energy ϵ) omnidirectional cosmic-ray proton flux. The flux-averaged pionic γ-ray production cross section is

$$\sigma_\gamma \equiv 2\xi_\alpha \zeta_\pi \sigma_{\pi^0} = 2\xi_\alpha \frac{\int d\epsilon\, I_p(\epsilon)\, \zeta_\pi \sigma_{\pi^0}(\epsilon)}{\int d\epsilon\, I_p(\epsilon)}, \tag{28}$$

where the factor of 2 accounts for the number of photons per pion decay, σ_{π^0} is the cross section for pion production, ζ_π is the pion multiplicity, while the factor $\xi_\alpha = 1.45$ accounts for $p\alpha$ and $\alpha\alpha$ reactions (Dermer 1986).

Then we have

$$\begin{aligned} I_{\gamma,\pi^0}(t) &= \frac{n_{\rm b,0}c}{4\pi} Y_{\rm H} \sigma_\gamma \int_0^t dt \ \mu(\vec{s}) \ \frac{n_{\rm b}^{\rm com}(\vec{s})}{n_{\rm b,0}} \ \Phi_p(\vec{s},t) \\ &= \frac{n_{\rm b,0}c}{4\pi} \sigma_\gamma Y_H^{\rm ism} F_p(t), \end{aligned} \tag{29}$$

where

$$F_p(t) = \int_0^t dt \ \mu(\vec{s}) \ \frac{n_{\rm b}^{\rm com}(\vec{s})}{n_{\rm b,0}} \ \Phi_p(\vec{s}), \tag{30}$$

is the mean value of the cosmic-ray fluence along the line of sight, where the average is weighted by the gas fraction and the ratio $n_{\rm b}^{\rm com}(\vec{s})/n_{\rm b,0}$ of the local baryon density along the photon path. Note that the γ-ray sources are sensitive to the overlap of the cosmic-ray flux with the diffuse hydrogen gas density, and thus need not be homogeneous. Even so, we still assume the ERGB intensity to be isotropic, which corresponds to the assumption that the line-of-sight integral over the sources averages out any fluctuations.

Finally, we see that the lithium abundance and the pionic γ-ray intensity (spectrum integrated from 0 energy) arise from very similar integrals, which we can express via the ratio

$$\frac{I_{\gamma,\pi^0}(t)}{Y_i(\vec{x},t)} = \frac{n_{\rm b}c}{4\pi y_{\alpha,\rm cr} y_{\alpha,\rm ism}} \ \frac{\sigma_\gamma}{\sigma_{\alpha\alpha}^i} \ \frac{F_p(t)}{F_p(\vec{x},t)}, \tag{31}$$

ФОРМИРАЊЕ СТРУКТУРА КАО ИЗВОР КОСМИЧКИХ ЗРАКА: ИДЕНТИФИКАЦИЈА ПОСМАТРАЧКИХ ОГРАНИЧЕЊА

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Оригинални научни рад

Сматра се да шокови настали приликом спајања структура и прилива барионске материје у току процеса формирања структура могу бити извор космичких зрака. Ови космички зраци настали у процесу формирања структура (КЗФС) би заправо имали првобитан састав, наиме, били би углавном сачињени од протона и алфа-честица. Међутим, врло мало се зна о овој популацији космичких зрака. Један начин да се тестира њихова заступљеност би био да се погледају производи хадронских реакција између КЗФС-а и међузвезданог материјала. Савршено средство за тестирање ових реакција би био ^6Li. Редак изотоп ^6Li настаје искључиво путем космичких зрака, превасходно у $\alpha\alpha \rightarrow {}^6Li$ фузионој реакцији са међузвезданим хелијумом. Стога, овај нуклид представља јединствено средство за дијагностику историје космичких зрака. Управо због ове јединствене особине је ^6Li најподложнији утицају присуства неких других популација космичких зрака. Међутим, ово би такође могло имати значајне последице за нуклеосинтезу "Великог праска": космички зраци настали током космолошке формације структура би довели до пре-галактичке производње литијума што би "контаминирало" примордијалан састав ^7Li у хало звездама које су сиромашне металима. С обзиром на већ постојећи проблем успостављања сагласности између ^7Li мереног у хало звездама и примордијалног ^7Li предвиђеног путем "Wilkinson Microwave Anisotropy Probe" мерења, ограничење степена ове "контаминације" је од пресудног значаја. Међутим, историја КЗФС-а није довољно позната. Стога ми предлажемо неколико начина, независно од модела, за тестирање КЗФС популације и њихове историје, као и постојећег проблема везаног за литијум: 1) успостављамо везу између производње гама зрака и литијума, те смо тако у могућности да, користећи мерења ван-галактичког позадинског гама зрачења, поставимо ограничење на количину литијума коју КЗФС могу произвести; 2) предлажемо нову локацију за тестирање примордијалног литијума и литијума произведеног путем КЗФС-а; наиме, облаке великих брзина и ниске металичности, који имају пре-галактички састав. Иако коришћење искључиво једне методе не мора поставити велика ограничења, коришћење више метода истовремено ће нас довести до нових сазнања о КЗФС популацији и можда одговорити на нека битна питања везана за актуелни проблем литијума.