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Galactic fly-bys: New source of lithium production

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Observations of low-metallicity halo stars have revealed a puzzling result: the abundance of ^{7}Li in these stars is at least three times lower than their predicted primordial abundance. It is unclear whether the cause of this disagreement is a lack of understanding of lithium destruction mechanisms in stars or the non-standard physics behind the big bang nucleosynthesis (BBN). Uncertainties related to the destruction of lithium in stars can be circumvented if lithium abundance is measured in the ''pristine'' gas of the low metallicity systems. The first measurement in one such system, the small magellanic cloud (SMC), was found to be at the level of the pure expected primordial value, but is on the other hand, just barely consistent with the expected galactic abundance for the system at the SMC metallicity, where important lithium quantity was also produced in interactions of galactic cosmic rays and presents an addition to the already present primordial abundance. Because of the importance of the SMC lithium measurement for the resolution of the lithium problem, we here draw attention to the possibility of another post-BBN production channel of lithium, which could present an important addition to the observed SMC lithium abundance. Besides standard galactic cosmic rays, additional post-BBN production of lithium might come from cosmic rays accelerated in galaxy-galaxy interactions. This might be important for a system such is the SMC, which has experienced galaxy harassment in its history. Within a simplified but illustrative framework we demonstrate that large-scale tidal shocks from a few galactic fly-bys can possibly produce lithium in amounts comparable to those expected from the interactions of galactic cosmic-rays produced in supernovae over the entire history of a system. In case of the SMC, we find that only two such fly-bys could possibly account for as much lithium as the standard, galactic cosmic ray production channel. However, adding any a new mechanism for post-BBN production of lithium, like the one proposed here, would contribute to the observed SMC lithium abundance, causing this measurement to be more in tension with the primordial abundance predicted by the standard BBN.

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I. INTRODUCTION

One of the key tests of the hot big bang model are predictions of the primordial abundances of light elements, made in the big bang nucleosynthesis (BBN). The discovery of the lithium abundance plateau (a uniform, metallicity independent, lithium abundance) measured in low-metallicity halo stars [1] indicated that primordial abundance had been observed. However, in the past decade, it became evident that primordial lithium abundance, $(^7\mathrm{Li/H})_\mathrm{p} = 5.24 \times 10^{-10}$ [2], predicted in the standard big bang nucleosynthesis framework and calibrated by the cosmic microwave background observations [3], is a factor of 2–4 higher than the observed plateau value, $(^7\mathrm{Li/H})_\mathrm{plateau} = 1.23 \times 10^{-10}$ [4]. This is commonly referred to as the lithium problem.

Recently, more extensive observational surveys, higher resolution spectra, and improved stellar modeling have revealed more complexity in the appearance of the ''Spite plateau.'' They indicate a greater dispersion in lithium abundance below metallicity $[\mathrm{Fe/H}] \lesssim -3$, where lithium depletion levels show significant variations from star to star [5–7]. The notion of a plateau has consequently been replaced by an upper envelope of lithium abundance at the level of $(^7\mathrm{Li/H})_\mathrm{plateau}$ for stars with $[\mathrm{Fe/H}] \lesssim -1.5$. Very few outliers have been reported to lie in the ''forbidden zone'' above this envelope [8–10].

In addition to BBN, ^{7}Li is also produced in cosmic-ray interactions [11] and by the neutrino process [12]. In fact, most of the light isotope ^{6}Li observed in the present epoch ($(^6\mathrm{Li/H}) \sim 10^{-10}$) was made by interactions of cosmic rays with the interstellar medium (ISM)[11]. Smaller amounts of ^{6}Li ($(^6\mathrm{Li/H})_\mathrm{p} \sim 10^{-14}$) were also created in the BBN

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[13,14] and possibly, as recently pointed out, in accretion processes [15]. Furthermore, as supernova remnants are thought to be the dominant galactic source of cosmic rays (GCRs), ^{6}Li abundance is expected to increase with metallicity. This prediction has been challenged by reports of a tentative ^{6}Li plateau in low-metallicity halo stars [16]. Since then, several of the originally reported "plateau values" of ^{6}Li abundance have been revised after improved three-dimensional non-LTE modeling [17–21]. However, at least two anomalously high ^{6}Li measurements remain, and, if confirmed, their explanation would require an additional, nonstandard source of ^{6}Li, and consequently ^{7}Li.

One possible solution to this puzzle may be in the form of the nonstandard BBN [22–25]. Alternatively, one could appeal to early cosmic-ray populations different from standard GCRs [for, e.g., [26,27]]. A difficulty encountered by all models is that they fail to produce significant amounts of ^{6}Li without violating metallicity or energy constraints, and overproducing other light elements [28]. In order to establish levels of ^{6}Li and ^{7}Li which are uncomplicated by the details of processing in stellar atmospheres, it has been proposed that their abundances be measured in the pristine and unprocessed gas of low metallicity systems [29–31]. The first such observation of gas phase lithium beyond our galaxy has been carried out recently in the small magellanic cloud (SMC), and is an important step towards finding the cause of the observed discrepancy between expected primordial abundance and that measured in low-metallicity halo stars. It revealed a value of lithium abundance, $(^7\mathrm{Li/H})_{\mathrm{SMC}} = 4.8 \times 10^{-10}$, which is consistent with the primordial value [32]. On the other hand, in the systems at $1/5$ of solar metallicity, such is the case with the SMC, some, non-negligible post-BBN production of lithium is also expected, due to interactions of GCRs with the gas in the interstellar medium. This would add to the already present primordial abundance, and be included in the observed value. Hence, at $1/5$ solar metallicity, total lithium abundance in the gas phase of this system should be higher than the primordial. In the case of the SMC, the observed abundance is just marginally consistent with expected abundance for the system at given metallicity. Therefore, while a new lithium source (different from the GCRs) may be needed to explain the ^{6}Li excess in some systems, SMC measurement leaves little room for any nonstandard post-BBN source which would yield significant amount of ^{7}Li. Consequently, if any additional significant source of lithium is present, the current SMC measurement would then become inconsistent with the expected abundance (BBN + post-BBN production), just is the case with lithium measured in atmospheres of low-metallicity halo stars.

In this work, we point out that tidal cosmic rays (TCRs) could be a significant source of lithium in systems that have undergone strong tidal interactions with their neighbors. If present, this could be a source of lithium that has not been previously taken into account but might result in important consequences. Close halo fly-bys play an important role in the evolution of the earliest dark matter halos and their galaxies, and can still influence galaxy evolution in the present epoch [for, e.g.,[33]]. Galactic mergers and close fly-bys are known to give rise to large-scale shocks in the gas of interacting galaxies [34–39]. These shocks are favorable locations for acceleration of cosmic rays, which in turn can produce lithium. However, shocks triggered by galaxy interactions are not directly accompanied by fresh metal yields and could in principle circumvent the problem of overproduction of metals faced in other models. They can nevertheless be indirectly accompanied by fresh metal yields, as galaxy interactions are known to enhance star formation [40–43]. If so, tidal cosmic-ray populations may be accompanied by some increase in metallicity, but the correlation would be weaker than in supernovae, which eject fresh metals and accelerate particles at the same time.

At high redshift, where destructive interactions of comparable mass galaxies were more common, the TCRs may have competed with the GCRs accelerated by the first generation of massive stars in the production of light elements. At low redshift, TCR nucleosynthesis could be important for low metallicity systems, which continue to experience tidal disruptions by their neighbors, such as the SMC [see, e.g., [44–46]]. In these systems, at a given metallicity, one would thus expect to find a significantly higher ^{6}Li abundance and consequently, a lower ^{7}Li-to-^{6}Li ratio relative to that predicted by standard galactic chemical evolution models. If the Milky Way (MW) has not suffered a major tidal encounter with its neighbors at high redshift, TCRs may not have contributed much to the lithium measured in halo stars. We propose that this effect may be important for the SMC, which is actively interacting with the MW and the Large Magellanic Cloud (LMC), and that lithium abundance measurements in these galaxies should reflect their different evolutionary paths.

Using a simple analysis, we show that the energy imparted by galactic tidal encounters is sufficient to produce significant lithium abundance. We also find that only a few galactic fly-bys can yield large enough TCR fluxes which could result in lithium amounts comparable to those produced by the GCRs over the entire history of a galaxy. Finally, in case of the SMC, we show that its gas phase lithium abundance could have been significantly enriched in tidal encounters with its immediate neighbors, the Milky Way and the Large Magellanic Cloud. Thus, the two main objectives of this work are: (1) to point out to a new cosmic-ray population which may arise in interacting systems and have important consequences for nucleosynthesis and expected gamma-ray and radio emissions, (2) to draw attention to the fact that though extremely important, the SMC lithium gas-phase measurement currently does not provide a definitive answer about the lithium problem, and that any additional, significant post-BBN production of lithium can tip the scale, thus having important consequences for the further analysis of this problem.

II. ENERGETICS

In order for galactic interactions to be a viable source of energy for production of Li in metal poor environments, they have to satisfy two important criteria: (1) the energy released in large scale tidal shocks should account for the energy necessary to produce the level of Li measured in these systems, and (2) tidal shocks must be capable of accelerating a population of cosmic rays responsible for Li production. In this section we place an upper limit on the energy available for nucleosynthesis, by estimating the kinetic energy of the encounter for fiducial parameters representative of a minor encounter of a primary galaxy with its less massive satellite. The available energy can be estimated as

$$E_{\rm kin} = \frac{qGM_1^2}{d} \approx 4\times 10^{57}\ {\rm erg}\left(\frac{q}{10^{-3}}\right)\left(\frac{M_1}{10^{12}M_\odot}\right)^2\left(\frac{d}{50\ {\rm kpc}}\right)^{-1}, \tag{1}$$

where G is the gravitational constant, $q = M_2/M_1 < 1$ is the mass ratio of the satellite to primary galaxy, and d is their separation. Note that the expression for kinetic energy is evaluated for a satellite galaxy plunging toward the primary on a nearly radial, marginally gravitationally bound orbit. As indicated by simulations of galactic mergers, this type of encounter is typically more damaging for the satellite galaxy which is tidally stripped of its mass as it falls into the larger galaxy [47,48]. Because of its shallower potential well, the gas in the satellite galaxy which is not lost to tidal stripping can be strongly shocked, even though the satellite may inflict little damage to its host. The shock is expected to be more severe for plunging satellites, and, as in this case, strong perturbation to their potentials occurs rapidly, on a dynamical time scale. On the other hand, slowly inspiralling satellites experience changes in their potential over many orbits, during which the gas and stars gradually adjust to a new quasiequilibrium.

We estimate the strength of the shocks that arise during the minor tidal interaction described above by calculating the Mach number of the interaction for assumed properties of the ISM in the satellite galaxy as

$$\mathcal{M} = \frac{V_{\rm sat}}{c_{\rm s}} \approx 460\mu^{1/2}\left(\frac{M_1}{10^{12}M_\odot}\right)^{1/2}\left(\frac{d}{50\ {\rm kpc}}\right)^{-1/2}\left(\frac{T}{100\ {\rm K}}\right)^{-1/2}, \tag{2}$$

where $V_{\rm sat}$ is the infall velocity of the satellite, $c_{\rm s}$ is the average speed of sound of the ISM gas in the satellite galaxy, μ is its mean atomic weight, and T is the mass weighted average temperature. Note that $T = 100$ K corresponds to cold neutral medium, composed mostly of hydrogen with typical densities of 20–50 $\rm cm^{-3}$. In reality however, the ISM gas is likely to be a mixture of several phases at different temperatures [49] and this value would vary as a function of satellite properties and redshift. However, even an order of magnitude increase in the mass weighted average temperature of the ISM of a particular satellite would still allow strong shocks to develop as a consequence of its infall. We will use this robust property of tidal shocks to constrain the spectrum of the produced cosmic rays that can give rise to Li formation.

We further estimate what fraction of the kinetic energy in a galactic encounter is converted into the acceleration of energetic particles. We assume that the composition of cosmic rays reflects the composition of the ISM, and consequently, that the $\alpha + \alpha$ fusion channel dominates lithium production at low metallicities [50]. This assumption is justified for the low metallicity gas in the Small Magellanic Cloud, which we employ as a case study in this work. Following Prantzos [28], we assume that it takes $\epsilon_6 = 16$ erg of energy to produce one nucleus of ^{6}Li via $\alpha + \alpha$ fusion channel (note that different compositions of the cosmic-ray population imply different energy requirements per nucleus). The adopted production energy per nucleus was derived within the standard "leaky box" framework, where cosmic rays accelerated in supernova remnants (SNRs) are allowed to escape from the Galaxy and suffer other losses as they propagate through it. This results in an equilibrium cosmic-ray spectrum which is steeper at the higher energy end, and shallower at the low-energy end, relative to the initial injection spectrum produced at the location of the strong supernova shocks. Given the high Mach number value estimated in Eq. (2), which falls within the wider range of values characteristic for supernovae shocks, we assume that tidal shocks with $\mathcal{M} > 100$ will have cosmic-ray injection spectrum similar to the injection spectra from supernovae. Subsequently, the tidal cosmic-ray population is expected to suffer similar loses during TCR propagation through the galaxy, resulting in an equilibrium spectrum similar to that of galactic cosmic rays. This is the key assumption (see discussion in Sec. V) which will later allow us to evaluate the efficiency of TCR nucleosynthesis relative to GCR nucleosynthesis, without making explicit choices for the (unknown) TCR spectrum.

It is worth noting though that the uncertainty involved in the nature and evolution of the TCR spectrum is somewhat offset by the fact that the adopted energy per ^{6}Li nucleus is less sensitive to a specific particle acceleration mechanism and can be applied to a wide range of acceleration scenarios [28]. Expressed per gram of ISM matter, this energy requirement is

$$\omega_6 = \epsilon_6 y_6 \frac{1}{m_{\rm p}} = 1.5\times 10^{15}\ {\rm erg\,gr^{-1}}\left(\frac{\epsilon_6}{16\ {\rm erg}}\right)\left(\frac{y_6}{y_{6,\odot}}\right), \tag{3}$$

where $m_{\rm p}$ is the proton mass, while the solar abundance of ^{6}Li is $y_{6,\odot} \equiv (^6{\rm Li/H})_\odot = 1.53\times 10^{-10}$ [51]. The total energy required to pollute the amount of gas $M_{\rm gas}$ with lithium abundance y_6 is

$$E_6 = \omega_6 M_{\rm gas} = 3 \times 10^{57}\ {\rm erg}\left(\frac{\epsilon_6}{16\ {\rm erg}}\right)\left(\frac{y_6}{y_{6,\odot}}\right)\left(\frac{M_{\rm gas}}{10^9 M_\odot}\right). \tag{4}$$

The derived value of energy implicitly depends on the assumed cosmic-ray spectrum, escape length, and metallicity (through the choice of energy-per-nucleus); we discuss the importance of these parameters in Sec. V.

III. REQUIREMENTS FOR SIGNIFICANT LITHIUM PRODUCTION

Tidal shocks that arise from close galactic fly-bys can accelerate charged particles and in such way as to give rise to a new cosmic-ray population within an interacting galaxy. While standard GCRs are expected to be produced in SNRs over the entire history of a galaxy, tidal cosmic rays are injected in the interstellar medium episodically, and only during sufficiently strong tidal events ($\mathcal{M} > 100$), as indicated by the Mach number of the encounter. After the point of closest approach in a fly-by, the TCR flux is likely to rapidly decrease due to energy losses, and subsequent nucleosynthesis would stop. As tidal shocks in galactic fly-bys can affect much larger ISM volumes than supernovae shocks, they can, in principle, compensate for their low "duty cycle" by their high volume feeling fraction. Whether the GCR or TCR driven nucleosynthesis dominates in a given galaxy depends on the parameters of the encounter and properties of the interacting galaxies. Modeling such encounters requires high resolution hydrodynamic simulations to capture the structure of the tidal shocks, and is beyond the scope of this paper. Instead, we focus on the question of whether cosmic rays accelerated in tidal shocks are a plausible and important source of lithium in galaxies which have experienced close encounters in their history.

We assume that tidal shocks propagate through the magnetized ISM of the satellite galaxy, causing perturbations in its magnetic field, and accelerating charged particles. This is similar to the diffusive shock acceleration of standard GCRs [52–54], which is a first order Fermi particle acceleration process and a mechanism routinely adopted in a variety of astrophysical environments. In addition to first order, second order Fermi particle acceleration can arise in the downstream region of tidal shocks, although its contribution to the dominant diffusive shock acceleration process is likely to be small and negligible [55].

Given the similarity of the acceleration mechanisms and the strength of the shocks as given by their Mach numbers, we proceed by assuming a comparable efficiency of TCRs and GCRs in the production of lithium. We estimate the volume of the ISM in an interacting galaxy that needs to be shocked in order to give rise to a TCR flux sufficient to produce an abundance of lithium equal to that produced by GCRs over the entire history of the system. Thus, we start by equating the total number of Li nuclei produced by the TCRs and GCRs, $N_{\rm Li,TCR} = N_{\rm Li,GCR}$. In both cases, the number of Li nuclei can be expressed in terms of their production rate per unit volume $\dot{n}_{\rm Li}$ as $N_{\rm Li} = \int \dot{n}_{\rm Li} V_{\rm sys} dt$, where $V_{\rm sys}$ is the volume in which the CRs interact with the ISM in each scenario. The production rate of lithium however depends on the number density of the ISM ($n_{\rm ISM}$), the cross section for lithium production in $\alpha + \alpha \rightarrow {\rm Li}$ fusion channel (σ), and on the cosmic-ray flux ($\Phi_{\rm cr}$) as

$$\dot{n}_{\rm Li} = n_{\rm ISM} \sigma \Phi_{\rm cr}, \tag{5}$$

where $\Phi_{\rm cr}\ [{\rm cm}^{-2}\ {\rm s}^{-1}] = \int \phi(E) dE = \int v_{{\rm cr},E}(dn_{{\rm cr},E}/dE) dE \propto \int E^{-\alpha} dE$ with cosmic-ray spectral index α. The energy integrated cosmic-ray flux can also be written in terms of the mean CR velocity and CR number density as $\Phi = \langle v_{\rm cr}\rangle n_{\rm cr}$. The lithium production rate then becomes $\dot{n}_{\rm Li} = n_{\rm ISM}\sigma\langle v_{\rm cr}\rangle N_{\rm cr}/V_{\rm sys}$. Assuming that the cosmic-ray flux does not vary much over the production timescale $\tau_{\rm cr}$, i.e., that the cosmic-ray flux is in equilibrium, the total number of lithium nuclei produced can now be written as

$$N_{\rm Li} = n_{\rm ISM}\sigma\langle v_{\rm cr}\rangle N_{\rm cr}\tau_{\rm cr}, \tag{6}$$

where $N_{\rm cr}$ is the total number of cosmic rays accelerated by a given process over the entire timescale. Assuming the same spectral index of both cosmic-ray populations, mean cosmic-ray velocities $\langle v_{\rm cr}\rangle = \int v_{{\rm cr},E}(dn_{{\rm cr},E}/dE)dE/\int(dn_{{\rm cr},E}/dE)dE$ will be equal. It then follows that

$$N_{\rm TCR} = N_{\rm GCR,tot}\frac{\tau_{\rm GCR}}{\tau_{\rm TCR}}. \tag{7}$$

The two cosmic-ray populations are not actively producing lithium over the same time-scales. GCRs are producing lithium continuously over the life time of a galaxy, and we take this timescale ($\tau_{\rm GCR}$) to be comparable to the age of the Universe, $\tau_{\rm GCR} = 10^{10}$ yr. TCRs, on the other hand, are accelerated only during close galactic fly-bys, while tidal shocks propagating through the satellite galaxy remain strong. Their duty-cycle time scale is comparable to the dynamical time scale for the interaction of the two galaxies for which we adopt a value $\tau_{\rm TCR} = 10^9$ yr (see Sec. V for discussion). It follows that

$$N_{\rm TCR} = 10 N_{\rm GCR} N_{\rm SN}\left(\frac{10^9\ {\rm yr}}{\tau_{\rm TCR}}\right), \tag{8}$$

where $N_{\rm GCR}$ is the number of cosmic rays accelerated in one SNR and $N_{\rm SN}$ is the number of supernovae that have occurred up to some epoch, defined by a given metallicity threshold. We express the number of cosmic rays (either TCRs or GCRs) accelerated per fly-by, or in a single SNR, in terms of the dimensionless injection parameter, $\eta = N_{\rm acc}/N_{\rm s}$ as defined in [56], which represents the number of accelerated particles relative to the number of particles swept up by the shock. In case of GCRs $\eta_{\rm GCR} = N_{\rm GCR}/N_{\rm SN,s}$ where $N_{\rm SN,s}$ is the number of particles swept up by a single supernova shock. In case of TCRs, $\eta_{\rm TCR} = N_{\rm TCR}/N_{\rm T,s}$, where $N_{\rm T,s}$ is the number of particles swept up by a tidal shock. Taking these into account we rewrite Eq. (8) as

$$N_{\rm T,s} = 10 N_{\rm SN} N_{\rm SN,s} \left(\frac{\eta_{\rm GCR}}{\eta_{\rm TCR}}\right)\left(\frac{10^9\ {\rm yr}}{\tau_{\rm TCR}}\right). \tag{9}$$

While our result does not explicitly depend on the adopted value of the injection parameter η, which encodes the acceleration efficiency, it does depend on the relative efficiency of particle injection in tidal shocks relative to supernovae shocks. By adopting $\eta_{\rm TCR} \sim \eta_{\rm GCR}$ in this estimate, we are making an implicit assumption that tidal shocks are as strong as supernovae shocks. In reality, tidal shocks are significantly weaker than the strong shocks in young SNRs where the velocity of the blast wave can be as high as $2 \times 10^4\ {\rm km\,s^{-1}}$. The velocity of a tidal wave is, however, similar in strength (as quantified by the Mach number) to shocks driven by the moderately evolved SNRs sweeping the ISM with velocities $\lesssim 10^3\ {\rm km\,s^{-1}}$. Since weaker shocks are characterized by slightly higher η values [57], our assumption about the comparable strength of the two types of shocks is conservative.

The number of particles swept by one supernova can then be estimated as

$$N_{\rm SN,s} = n_{\rm ISM} V_{\rm SNR} = 1.2 \times 10^{59} \left(\frac{n_{\rm ISM}}{1\ {\rm cm^{-3}}}\right)\left(\frac{R_{\rm SNR}}{10\ {\rm pc}}\right)^3 \tag{10}$$

normalized to fiducial values of the ISM number density $n_{\rm ISM} = 1\ {\rm cm^{-3}}$ and the corresponding maximal SNR radius within which particles are efficiently accelerated. We note, however, that depending on the energy of the explosion and on the ISM density, the maximal SNR radius for which the associate shock wave is still capable of accelerating particles to cosmic ray energies, can be taken to be up to 25 pc [56].

We now estimate the number of supernova events that occurred by a certain epoch as determined by the threshold metallicity that these SNe contributed to the interacting galaxy. Adopting the solar abundance of iron $y_{\rm Fe_\odot} \equiv (n_{\rm Fe}/n_{\rm H})_\odot = 3 \times 10^{-5}$ [51] and mass fraction $X_{\rm Fe_\odot} \equiv (\rho_{\rm Fe}/\rho_{\rm gas})_\odot = 1.25 \times 10^{-3}$, the total iron mass of such a system is

$$M_{\rm Fe} = X_{\rm Fe_\odot} M_{\rm gas} = 1.25 \times 10^6 M_\odot \left(\frac{y_{\rm Fe}}{y_{\rm Fe,\odot}}\right)\left(\frac{M_{\rm gas}}{10^9 M_\odot}\right). \tag{11}$$

We calculate the number of SN events that give rise to the solar metallicity by adopting a mean iron yield per supernova $M_{\rm Fe,SN} = 0.2 M_\odot$ [58]:

$$\begin{aligned} N_{\rm SN} &= M_{\rm Fe}/M_{\rm Fe,SN} \\ &= 6.25 \times 10^6 \left(\frac{0.2 M_\odot}{M_{\rm Fe,SN}}\right)\left(\frac{y_{\rm Fe}}{y_{\rm Fe,\odot}}\right)\left(\frac{M_{\rm gas}}{10^9 M_\odot}\right). \end{aligned} \tag{12}$$

Using Eqs. (9), (10), and (12) we write the number of particles swept up by the tidal shock as

$$\begin{aligned} N_{\rm T,s} \approx{}& 7.5 \times 10^{66} \left(\frac{0.2 M_\odot}{M_{\rm Fe,SN}}\right)\left(\frac{y_{\rm Fe}}{y_{\rm Fe,\odot}}\right)\left(\frac{M_{\rm gas}}{10^9 M_\odot}\right)\left(\frac{\eta_{\rm GCR}}{\eta_{\rm TCR}}\right) \\ &\times \left(\frac{n_{\rm ISM}}{1\ {\rm cm^{-3}}}\right)\left(\frac{R_{\rm SNR}}{10\ {\rm pc}}\right)^3\left(\frac{10^9\ {\rm yr}}{\tau_{\rm TCR}}\right). \end{aligned} \tag{13}$$

Finally, we estimate the amount of gas swept over by tidal shocks that would yield the same level of lithium abundance as galactic supernovae:

$$M_{\rm T,s} = \mu N_{\rm T,s} \tag{14}$$

$$\begin{aligned} &\approx 8 \times 10^9 M_\odot \left(\frac{0.2 M_\odot}{M_{\rm Fe,SN}}\right)\left(\frac{y_{\rm Fe}}{y_{\rm Fe,\odot}}\right)\left(\frac{M_{\rm gas}}{10^9 M_\odot}\right)\left(\frac{10^9\ {\rm yr}}{\tau_{\rm TCR}}\right) \\ &\times \left(\frac{n_{\rm ISM}}{1\ {\rm cm^{-3}}}\right)\left(\frac{R_{\rm SNR}}{10\ {\rm pc}}\right)^3\left(\frac{\eta_{\rm GCR}}{\eta_{\rm TCR}}\right), \end{aligned} \tag{15}$$

$$\begin{aligned} \frac{M_{\rm T,s}}{M_{\rm gas}} ={}& 8 \left(\frac{0.2 M_\odot}{M_{\rm Fe,SN}}\right)\left(\frac{y_{\rm Fe}}{y_{\rm Fe,\odot}}\right)\left(\frac{10^9\ {\rm yr}}{\tau_{\rm TCR}}\right)\left(\frac{n_{\rm ISM}}{1\ {\rm cm^{-3}}}\right)\left(\frac{R_{\rm SNR}}{10\ {\rm pc}}\right)^3 \\ &\times \left(\frac{\eta_{\rm GCR}}{\eta_{\rm TCR}}\right), \end{aligned} \tag{16}$$

where we assumed the mean atomic mass $\mu = 1.3 m_{\rm H}$, appropriate for the neutral ISM.

Equation (16) indicates that in order for TCRs to produce as much lithium as GCRs, up to a certain epoch in time characterized by the solar metallicity, the entire galactic ISM must be tidally shocked 8 times. For galactic encounters that can drive strong tidal shocks in the interstellar medium of a "tidally harassed" satellite galaxy, this would imply the occurrence of at least 8 close fly-bys. However, even a single fly-by could result in a non-negligible increase in lithium abundance in these galaxies. In the next section we describe the implications of this model for the Small Magellanic Cloud.

IV. IMPLICATIONS FOR THE SMALL MAGELLANIC CLOUD

Adopting a SMC gas mass of $M_{\rm gas}(r < 3\ {\rm kpc}) = 3 \times 10^8 M_\odot$ [59], the total energy required to pollute all of the SMC gas with the solar level of ^{6}Li abundance would be $E_6 \sim 10^{57}$ erg. To estimate the kinetic energy of its galactic encounters, we consider the interactions of the SMC with the Milky Way and the Large Magellanic Cloud, given that both of these have had significant gravitational impact on the SMC during its history [for, e.g.,[44]. The total mass (including the dark matter halo, gas, and stars) of the MW is $M_{\rm MW} \approx 10^{12} M_\odot$ [60] and the total mass of the SMC is $M_{\rm SMC}(r < 3~{\rm kpc}) \approx 4 \times 10^9 M_\odot$ [61]. The present day separation of MW-SMC is $d = 61$ kpc [62] and, using Eq. (1) we estimate the kinetic energy of their encounter as $E_{\rm kin} \approx 10^{58}$ erg. Thus, if the tidal interaction of the SMC and the MW was to enrich the entire ISM of the SMC to a solar metallicity value of ^{6}Li, less than 10% of the kinetic energy of the encounter at the current epoch would be used towards particle acceleration. On the other hand, if we consider the LMC as the primary tidal partner of the SMC, then with its total mass $M_{\rm LMC}(r < 9~{\rm kpc}) \approx 13 \times 10^9 M_\odot$, and 23 kpc present day separation from the SMC [63,64], we estimate the total kinetic energy from this interaction to be $E_{\rm kin} \approx 4 \times 10^{56}$ erg [65]. Consequently, the kinetic energy between the LMC and SMC, as they are *today*, is insufficient to account for a significant ^{6}Li abundance production. The gravitational interaction between the LMC and SMC has likely been much stronger in the past, during their close approaches, and hence, could have contributed to the total abundance of lithium in the SMC. We discuss the implications of the evolution of the SMC-LMC interaction over time in Sec. V.

Since the observed metallicity of the SMC is approximately 1/5 solar [66], our model implies that tidal shocks would have to sweep over the entire SMC ISM only about *twice* to accelerate enough particles which would produce the same amount of lithium as the GCRs. However, since any production of ^{6}Li by GCRs must scale with metallicity, it follows that $^6{\rm Li}_{\rm GCR}/^6{\rm Li}_\odot \approx 0.2$. For a typical GCR spectrum with spectral index $s = 2.75$, the production ratio between lithium isotopes from the same CR population is $^7{\rm Li}/^6{\rm Li} \approx 1.3$ [67]. Thus, if TCRs have produced the same amount of ^{6}Li in the SMC as GCRs, this means that SMC ^{6}Li abundance should in fact be $^6{\rm Li}_{\rm SMC}/^6{\rm Li}_\odot \approx 0.4$, while the isotopic ratio should be

$$\begin{aligned}\left(\frac{^7{\rm Li}}{^6{\rm Li}}\right)_{\rm SMC} &= \frac{^7{\rm Li}_{\rm BBN} + {}^7{\rm Li}_{\rm GCR} + {}^7{\rm Li}_{\rm TCR} + {}^7{\rm Li}_*}{^6{\rm Li}_{\rm GCR} + {}^6{\rm Li}_{\rm TCR}} \\ &= \frac{^7{\rm Li}_{\rm BBN} + 2 \times {}^7{\rm Li}_{\rm GCR} + {}^7{\rm Li}_*}{2^6{\rm Li}_{\rm GCR}} \\ &= \frac{^7{\rm Li}_{\rm BBN} + 2 \times 1.3 \times {}^6{\rm Li}_{\rm GCR} + {}^7{\rm Li}_*}{2^6{\rm Li}_{\rm GCR}} \\ &\approx 10 + \epsilon_*, \end{aligned} \tag{17}$$

where $\epsilon_* \equiv {}^7{\rm Li}_*/(2^6{\rm Li}_{\rm GCR})$ is a small correction to the lithium isotopic ratio that comes from the stellar production of ^{7}Li. For primordial and solar abundances, we adopt $(^7{\rm Li}/H)_{\rm BBN} = 5.2 \times 10^{-10}$ [2] and $(^6{\rm Li}/H)_\odot = 1.53 \times 10^{-10}$ [51], respectively. Note that the resulting ratio in Eq. (17) is almost a factor of 2 smaller than the isotopic ratio ~18 for the SMC, when GCRs are considered to be the only post-BBN source of lithium. The value obtained in Eq. (17) is consistent within error with the best fit of the isotopic ratio recently obtained from observations of the SMC by Hawk *et al.*, who found an $(^6{\rm Li}/^7{\rm Li})_{\rm SMC} = 0.13 \pm 0.05$ [32]. Note that our estimate of the lithium isotopic ratio is not very sensitive to the precise nature of the shocks and remains $(^7{\rm Li}/^6{\rm Li})_{\rm SMC} \approx 10$ even in the case of cosmic rays with a spectral index $\alpha = 2$ where lithium isotopes are produced in a ratio $^7{\rm Li}/^6{\rm Li} \approx 2$.

V. DISCUSSION

In this section we discuss in more detail the importance of the assumptions and parameters adopted in this model. The key assumption of the model pertains to the unknown spectrum of the tidal cosmic-ray population that arises in galactic interactions. A physical property directly affected by this uncertainty is ϵ_6, the energy required to create one nucleus of ^{6}Li, which in addition to the injection spectrum, also depends on the cosmic-ray composition and confinement. For example, a lower energy threshold would be obtained for systems where cosmic-ray confinement is stronger (lower escape losses which results in a harder, less steep, propagated spectrum) and where metallicity is sufficiently high for the production of ^{6}Li through the CNO channel to become important. It has been shown however, that for a wide range of plausible parameter choices, ϵ_6 has a value in the range of 5–100 erg [28]. In case of the maximum energy threshold, the kinetic energy of a close fly-by would be an order of magnitude below that required to produce the solar lithium abundance. The implication is that the fly-by model alone would fall short of explaining the anomalously high abundance of ^{6}Li in some galaxies, but could still account for some non-negligible fraction of it.

Similarly, our estimate of the number of galaxy-galaxy encounters capable of producing significant quantities of lithium also relies on the assumption that the spectrum of the TCRs is indistinguishable from the standard GCR spectrum in some galactic system. Note, however, that a particular choice of cosmic-ray source composition and form of cosmic-ray injection spectra (momentum vs energy spectrum, see [28] for discussion) apply to both cosmic-ray populations, and thus do not introduce additional degrees of freedom to our model. The expression for spectrum and cosmic-ray composition, however, do affect the energy-per-nucleus threshold in the way discussed in the previous paragraph.

If the spectral indices of the two cosmic-ray populations are different (e.g., if the TCRs are accelerated in weaker shocks resulting in a softer, steeper spectra), this would result in a higher energy per nucleon requirement for a steeper cosmic-ray spectrum, driven by the larger ionization losses [28]. In that case, Eq. (16) would effectively depend on the ratio of fluxes $\Phi_{\rm GCR}/\Phi_{\rm TCR} \propto E_{\rm th}^{\alpha'}$ where $E_{\rm th}$ is the threshold energy and $\alpha' = \alpha_{\rm TCR} - \alpha_{\rm GCR}$. In our fiducial case we take this difference between spectra to be zero, and thus the ratio of the fluxes comes down to the ratio between normalizations. Related to this is our assumption of the instantaneous and constant TCR flux, where we have omitted the unavoidable evolution of the TCR flux as this cosmic-ray population is accelerated, and assumed that equilibrium flux is established. Given that TCRs are accelerated during the isolated events of close galactic fly-bys, it is probably not true that TCR flux will reach equilibrium, thus evolution will have to be taken into account. However, adopting this assumption is, for all practical purposes of this work, equivalent to adopting a constant, mean TCR flux.

The fundamental difference between tidal and SN shocks is their physical scale—tidal shocks in satellite galaxies operate on much larger spatial scales than SNe. They can extend over a significant fraction of the galaxy size, as traced by its stars and gas, and reach scales over several kpc. We thus envision tidal shocks as large scale SNR-like structures. For a single supernova, the cosmic-ray injection spectrum and maximal acceleration energy depend on conditions like the blast energy, local ISM density, and properties of the magnetic field. On galactic scales however, a global GCR equilibrium spectrum is reached through the contribution of many supernova events throughout the galaxy. Thus, we only consider mean SNR properties, averaged over a number of SN events in comparison of TCR and GCR efficiency. In other words, we assume that the two mechanisms operate under similar ‘‘global’’ conditions. Hence, as long as the velocity of the blast wave of the two processes is comparable over some stage of their evolution, their ability to accelerate charged particles should also be comparable.

An additional level of complexity may be present due to the origin and evolution of the TCR population. While GCRs can reach an equilibrium between constant losses and continuous injection over the lifetime of a system, the TCR spectrum could reach an equilibrium only during epochs when large-scale tidal shocks are actively propagating through the ISM and accelerating particles. Once the particle injection ceases, TCRs would continue to interact with the ISM, but their spectrum would be evolving rapidly due to energy loses. In our work, we consider the equilibrium time scale for TCRs comparable to the dynamical time of the interacting system of galaxies. The time scale we adopt approximately accounts for strong encounters, i.e., those capable of driving strong shocks and accelerating the TCRs, for which the Mach number $\mathcal{M} > 100$. Our adopted value was estimated for the specific encounters analyzed in this work and is essentially in agreement with numerical simulations [63]; however, this value can be in the range $\tau_{\rm TCR} \sim$ few $\times\, 10^8$–10^9 yr. With respect to the limits of applicability, our simple model, fails to explain any substantial level of ^{6}Li abundance in galaxies when $\tau_{\rm TCR} \lesssim \tau_{\rm GCR}/100$. In reality, the equilibrium time scale for the TCR flux depends on the properties as well as the evolution of the ISM in a tidally ‘‘harassed’’ galaxy. Clearly, careful numerical modeling of both tidal shocks and particle acceleration is required for precise determination of the resulting TCR spectrum; however, the purpose of this work is to demonstrate the plausibility of this scenario, and we defer the details to follow-up work.

It is also worth noting that the SMC has experienced at least two close encounters with the LMC, and is currently experiencing an ongoing encounter with the MW [44,63]. The relative strength of these interactions has varied as a function of time and orbital parameters of the three galaxies. Cosmological models predict that both the SMC and LMC could have been up to ten times more massive at the time of their infall in the MW [63,68]. The Milky Way, on the other hand, had a lower mass in the past than today, since its mass increased over cosmic time. Simulations of cosmological structure formation favor a scenario where the Magellanic Clouds are currently on their first approach to the MW, thus implying that the distance between the MCs and MW was larger in the past [63]. All this points to a lesser role of the MW in tidal interactions with the two satellites a few to ten billion years ago. The same set of simulations finds that dwarf-dwarf galaxy interactions of the SMC and LMC are the dominant driver of their evolution over the past 5–6 Gyr, during which they evolved as a gravitationally bound pair. During this time, the evolution of their baryonic component has been dominated by tidal stripping and shocks. The SMC and LMC have most likely had several close encounters with one another in the past, during 2–3 pericentric passages when their separation could have been as small as a few kpc. Given the larger masses and smaller separation of the MCs in the past, it follows that the kinetic energy of their interaction could have reached two orders of magnitude higher values than that estimated for the SMC and MW system at the present time. If so, strong interactions of the SMC with LMC are likely to have played a more important role for the acceleration of TCRs, and the production of lithium in both dwarf galaxies than their present day interactions with the Milky Way. Given that over their cosmic history the total mass of the LMC remained at least a few times larger than that of the SMC, the LMC would have been less prone to tidal harassment by its smaller companion and the Milky Way galaxy. Thus, the past existence of the TCR population acting within Magellanic Clouds can be tested by comparing lithium isotopic ratios in the Magellanic Clouds. Specifically, a TCR population would have been more prominent in the smaller interacting system, which implies a lower $^7{\rm Li}/^6{\rm Li}$ ratio in the SMC relative to the LMC. Different star-formation histories of these two systems, on the other hand, resulted in an SMC metallicity which is 0.2 of the solar, while the LMC metallicity is at the level of 0.4 [69]. In the absence of TCRs from both systems, from Eq. (17) it follows that the isotopic ratio would be lower in the LMC ($^7{\rm Li}/^6{\rm Li} \approx 10$) compared to the SMC ($^7{\rm Li}/^6{\rm Li} \approx 18$). Therefore, if the lithium isotopic ratio was measured in the LMC and was found to be comparable or higher than the SMC ratio $(^7{\rm Li}/^6{\rm Li})_{\rm SMC} \lesssim (^7{\rm Li}/^6{\rm Li})_{\rm LMC}$, this would be a strong indication that a tidal cosmic-ray population was present (at some epoch) within the SMC and has significantly impacted its chemical evolution.

Although acceleration of the TCRs is independent of SNe, the presence of tidal shocks in the ISM may trigger star-formation, and result in an additional metallicity increase. However, our model does not distinguish between secular star formation and that triggered by galaxy-galaxy interactions, but instead takes into account the integral number of supernova events over the history of the system. In this sense, our model is not sensitive to the exact star-formation history of the SMC. Therefore, even with enhanced star-formation at some epoch, it can be shown that tidal cosmic rays could have potentially produced lithium in quantities comparable to what is expected from GCRs alone, resulting in an anomalous lithium isotopic ratio.

VI. CONCLUSIONS

Cosmic-ray nucleosynthesis is the dominant production channel of ^{6}Li and one of the dominant sources of ^{7}Li, especially in higher metallicity systems, where supernova remnants are taken as the main acceleration sites of cosmic rays in star-forming galaxies. In this work, we propose that tidal shocks which arise from close galactic fly-bys can be an important source of cosmic rays, and thus of lithium as well. Strong tidal shocks which could affect a significant fraction of the gas content of a galaxy can occur in satellite systems like the Small Magellanic Cloud, during its close fly-bys with the Large Magellanic Cloud or the Milky Way. As a consequence, a population of tidal cosmic rays that arises in satellite systems can present an additional source of both lithium isotopes.

The enrichment of SMC gas with extra lithium may bare important consequences for the existing "lithium problem." Because of the discrepancy between the predicted primordial lithium abundance and that measured in the low-metallicity halo stars, it was suggested that lithium should be measured in the gas phase of low metallicity systems. The first measurement of this kind was recently carried out by Howk *et al.* [32], in SMC gas with a metallicity of $1/5$ solar, and is an important step toward the resolution of this problem. The measured ^{7}Li abundance, is consistent with the expected primordial abundance, but is also just marginally consistent with abundance expected for a system at $1/5$ solar metallicity where significant post-BBN lithium was produced in GCR interactions. This marginal consistency means that there is little room for post-BBN production of this isotope through stellar process or cosmic-ray interactions. Therefore, with an additional cosmic-ray population present, such as tidal cosmic rays, the tension would be even greater, resulting in a discrepancy that is similar to that observed in the low-metallicity halo star lithium. Consequently such a scenario would indicate that the resolution of the lithium problem is more likely to be found in nonstandard BBN.

In case of the SMC, where Li has now been measured in the gas phase, our model shows that only two close fly-bys affecting the entire ISM of the SMC are sufficient for the tidal cosmic rays to produce as much ^{6}Li as the galactic cosmic rays have produced over the entire history of the SMC. Thus, given the already existing problem with the lithium abundances, and the recent measurements of lithium in the gas phase of the SMC, which are consistent with the predicted primordial abundance and above the observed lithium plateau values in halo stars, it is crucial to test the fly-by hypothesis presented in this work, and to confirm that the SMC is really a suitable environment for testing the lithium problem. On the other hand, if SMC gas was enriched by additional lithium due to TCRs, this has to be taken into account and corrected for in order to check the consistency of the SMC gas-phase lithium abundance with the expected primordial value.

As discussed in Sec. V, one possible test of the presence of a new cosmic-ray population would be to compare the lithium isotopic ratios between LMC and the SMC. Another possible approach is based on the radio emissions of the interacting galaxies. Tidal shocks accelerate electrons to ultra-relativistic energies and provide conditions for strong synchrotron radio-emission over relatively short time-scales ($\sim 10^7$ yr). Therefore, an increase in radio luminosity is expected in interacting systems, and especially in a smaller member of the system. Indeed, a nearby interacting system of galaxies, M51, shows an enhancement in radio-luminosity mostly contributed by its smaller member, M51b, at low radio-frequencies, that is two orders of magnitude higher relative to the unperturbed galaxies. Such tidal interactions, however, also lead to increased star-formation and GCR flux, and consequently, enhanced radio-luminosity. For this reason, suitable candidates for testing the presence of TCRs with radio observations would be galaxies in the early stage of interaction, or those that have not reached the peak of fly-by driven star formation.

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