Production of Lithium in the Galactic Disk

E. Casuso¹ and J. E. Beckman¹,²

Received 1999 April 3; accepted 2000 April 5

ABSTRACT. The abundance of Li in stars formed within the past 5 Gyr is log \( N(\text{Li}) = 3.2(\pm 0.2) \), while the corresponding value for the oldest stars in the Galaxy is \( N(\text{Li}) = 2.2(\pm 0.2) \). The global evidence suggests that the latter represents the full, or the major, part of the primordial abundance, so that the difference of an order of magnitude is due to Li produced in the Galaxy. It is well known that spallation of interstellar CNO by \( ^4\text{He} \) and protons in Galactic cosmic rays (GCRs) can produce Li, but models yield a shortfall of almost an order of magnitude compared with the current observed abundance range. Another GCR reaction, \( \alpha + \alpha \) fusion, has been invoked to explain some Li production in the early Galaxy, but application of this to the disk yielded too much early Li or too little current Li. These failures led to a search for alternative mechanisms, essentially stellar, at particular phases of evolution: the helium flash phase in asymptotic giant branch stars, in novae, and in supernovae (SNe).

Here we stress the importance of the observed upper envelope in the plot of Li versus Fe in stars as a constraint on any mechanism in any model aiming to account for disk Li. We show that a good match can be found assuming that low-energy GCRs produce the Li, with the \( \alpha + \alpha \) reaction as the key mechanism, although production in supernovae cannot at this stage be excluded. There is an apparent time delay in the Li production, relative to O and Fe, which if confirmed could be explained by the origin of a low-energy \( \alpha \)-particle component in processes associated with stars of intermediate and low mass. The \( \alpha \)-flux at a given epoch would then be proportional to the amount of gas expelled by low- and intermediate-mass stars in the Galaxy, though the acceleration of these \( \alpha \)-particles could still be linked to more energetic events as supernova explosions. The present scenario appears to account coherently for the closely related observations of the temporal evolution in the Galaxy (halo + disk) of abundances of \( ^{12}\text{C} \), \( ^{13}\text{C} \), \( ^{14}\text{N} \), \( ^{16}\text{O} \), \( ^{26}\text{Fe} \), the two main peaks (one in the halo and one in the disk) in the G-dwarf stellar frequency distribution, and the evolution of \( ^9\text{Be} \) and \( ^{10}\text{B} + ^{11}\text{B} \) via GCR spallation reactions without requiring the very high local cosmic-ray fluxes implied by the spallation close to SN. Adding a natural mechanism of differential depletion in red supergiant envelopes, we can explain the observed time evolution of the abundance of D and that of the isotopic ratios \( ^7\text{Li}/^6\text{Li} \) and \( ^{11}\text{B}/^{10}\text{B} \) starting from a standard big bang nucleosynthesis model with baryon density \( \rho_0 \approx 0.05 \). Our model also predicts the second Li “plateau” found for \([\text{Fe}/\text{H}]\) between \( -0.2 \) and \( +0.2 \), due to the “loop back” implied for Li (also for \(^9\text{Be} \) and B) because of the required infall of low-metallicity gas to the disk. Without ruling out other mechanisms for the main production of Li in the Galactic disk, the low-energy \( \alpha + \alpha \) fusion reaction in the interstellar medium offers a promising contribution.

1. INTRODUCTION AND OBSERVATIONAL BASE

A few seconds after the big bang, four light isotopes were produced: D, \(^3\text{He} \), \(^4\text{He} \), and \(^7\text{Li} \) (see, e.g., Walker et al. 1991; Copi, Schramm, & Turner 1995; Schramm & Turner 1998); all of these warrant careful study, and here we are focusing on \(^7\text{Li} \). The importance of understanding the evolution of the Galactic abundance of Li was highlighted in the key discovery by Spite & Spite (1982) that the observed abundance of Li in Galactic stars does not continue to fall uniformly with decreasing iron abundance below \([\text{Fe}/\text{H}] \approx -1 \), but levels off to a “plateau” at a level of \( N(\text{Li}) \approx 2 \), which Spite & Spite (1982) interpreted as corresponding to the abundance produced by standard big bang nucleosynthesis (SBBN). Spite & Spite measured the \(^7\text{Li} \) abundance as a function of metallicity (iron abundance) and surface temperature. They found that the \(^7\text{Li} \) abundance is flat for surface temperatures greater than about

¹ Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain; eca@iac.es.
² Consejo Superior de Investigaciones Científicas, CSIC, Spain.
5600 K; further, it is also flat for the stars with the lowest iron abundance. The first plateau suggests that the stars with the highest surface temperatures are not destroying their $^7\text{Li}$ by convection (the depth of the convective zone depends on surface temperature and is shallowest for stars with the highest surface temperatures). The second plateau indicates that any post–big bang production must be insignificant for the most metal-poor stars because the $^7\text{Li}$ abundance does not increase with iron abundance. The case against major depletion (and hence for a plateau abundance that reflects the primeval abundance) was strengthened by the observation of $^6\text{Li}$ in certain Population II stars (Smith, Lambert, & Nissen 1993; Hobbs & Thorburn 1994). Big bang production of $^6\text{Li}$ is negligible; the $^6\text{Li}$ seen was probably produced by cosmic-ray processes (along with beryllium and boron). Because $^6\text{Li}$ is much more fragile than $^7\text{Li}$ and yet still survived with the abundance relative to Be and B expected from cosmic-ray production, depletion of $^7\text{Li}$ cannot have been very significant (Steigman et al. 1993).

Using this interpretation, the primordial abundance is given by log $N_\rho(^7\text{Li}) = 2.2(\pm 0.2)$, a value confirmed in detailed work by a succession of authors (Rebolo, Beckman, & Molaro 1987; Hobbs & Thorburn 1991; Spite & Spite 1993; Thorburn 1994), which can be combined with the SBBN-produced abundance of $^4\text{He}$ (see, e.g., Pagel et al. 1992) to infer basic cosmological parameters: the universal baryon density $\Omega_b$, and the number of massless two-component neutrino types $N_\nu$. To be sure that the Population II abundance of $^7\text{Li}$ is a largely undepleted SBBN abundance entails two essential steps: showing that Population II stars (with $T_{\text{eff}} \geq 5500$ K) have not depleted or have barely depleted their $^7\text{Li}$ and showing that most of the $^7\text{Li}$ in Population I stars is of Galactic origin. The first step has already been accomplished via the theoretical work of the Yale group, who showed (Pinsonneault, Deliyannis, & Demarque 1992) that subsurface convective transport, and hence $^7\text{Li}$ depletion, is strongly suppressed at low metallicities. As a result of this, and of steadily accumulating observations, opinion (see Spite & Spite 1993) has swung strongly behind the view that log $N_\rho(^7\text{Li}) \approx 2.2$ is the SBBN value. Thorburn’s (1994) refined work on the “plateau” has brought out a scatter in the $^7\text{Li}$ versus [Fe/H] plot below [Fe/H] = $-1.5$, which is incompatible with zero production of $^7\text{Li}$ in the halo but in practice strongly supports a primordial value for $^7\text{Li}$ not far above log $N_\rho(^7\text{Li}) \approx 2$. The second step is quite complicated, because during the disk lifetime there may have been a number of significant production processes for Li, and also a number of destruction, or depletion, processes. The initial primordial abundance masks any Li evolution in the halo, so we concentrate our attention in the present paper on production in the disk and its interpretation.

The evolution of the lithium abundance in the Galactic disk can be followed via observations which define the upper envelope of the lithium abundance in stars over the range of iron metallicity, $-1.5 \leq [\text{Fe/H}] \leq 0.1$, which characterizes the disk population. The underlying assumption is that while lithium is in general depleted within stars, for a given value of metallicity the highest observed abundance value for a set of stars will correspond to minimum depletion and, hence, to an optimum approximation to the Galactic interstellar lithium abundance at the epoch when the stars were formed. Following the evolution of lithium should provide insight into the processes which form it similar to that which we can obtain by following the evolution of any other element. The rise in the ratio O/Fe with decreasing Fe, for example, provides the key to understanding the origin of a major fraction of Galactic oxygen in supernovae of Type II (SNIIe), whereas iron is formed in all stars with masses greater than or equal to 1 solar mass.

Although the general trend in Galactic Li evolution can be followed via the Li-Fe envelope, the effect of depletion imposes the need for the greatest care when interpreting the observed abundance in any single object. Depletion is well known to occur in cool stars (see, e.g., Pinsonneault et al. 1992; Deliyannis, Demarque, & Kawaler 1990)—those with $T_{\text{eff}}$ less than the solar value—and occurs also in the “lithium gap” (Boesgaard 1987) in the mid-F range of spectral classes. Stellar depletion renders lithium particularly interesting as a probe of stellar structure (Steigman et al. 1993) but makes it more difficult to interpret measured abundances in terms of production processes.

However, if we are not able to account adequately for the present-day and post–solar system abundance values, log $N_\rho(^7\text{Li}) \geq 3$, there must remain some room for doubt about the BBN value. For this reason, as well as for its intrinsic importance as a test of Galactic evolution models, the source(s) of Galactic lithium continue to be of considerable research interest. A number of production mechanisms have been proposed: cosmic-ray spallation of CNO (Reeves, Fowler, & Hoyle 1970; Meneguzzi, Audouze, & Reeves 1971; Walker, Mathews, & Viola 1985) and nucleosynthesis in novae (Arnould & Norgaard 1975; Starrfield et al. 1978), the atmospheres of red giants (Cameron & Fowler 1971), supernovae (Dearborn et al. 1989; Woosley et al. 1990), asymptotic giant branch (AGB) stars and carbon stars (D’Antona & Matteucci 1991), and black hole binaries (Martin et al. 1994). It is well accepted that processes in the interior of normal stars not only fail to yield lithium but tend to deplete it. In spite of the detection of individual lithium-rich objects which might be characteristic sources, models which incorporate such sources into a Galactic evolution scheme (Audouze et al. 1983; Abia & Canal 1988; D’Antona & Matteucci 1991) do not give good agreement with the observed lithium-iron envelope. Further, the spatial homogeneity of the Fe-Li curve indicates against sparse sets of point sources, even distributed sources, and in favor of a more diffuse origin for the lithium. Recent
detailed models of Li production assumed in carbon stars, massive AGB stars, SNIHe, and novae (Romano 1999) do not give fair fits to the very high slope of the Li abundance versus [Fe/H] near [Fe/H] $\sim -0.3$ (see Fig. 1 of Romano 1999).

The light nuclide $^6$Li is not produced significantly in SBBN and is expected to be produced over the lifetime of the Galaxy in Galactic cosmic-ray spallation as well as $\alpha + \alpha$ fusion reactions. Its high fragility to stellar processing makes it a less useful tool than $^7$Li to constrain big bang nucleosynthesis, but many authors have modeled the time evolution of $^6$Li because of the assumed connection with the $^9$Be and B abundances (Yoshii et al. 1997; Lemoine et al. 1997; Vangioni-Flam et al. 1999; Fields & Olive 1999; Ryan et al. 1999).

It has been suggested (see, e.g., Steigman 1993) that since (due to dust grain depletion and, uncertainly, ionization equilibrium) isotope ratios can be determined more reliably in the interstellar medium (ISM) than absolute abundances or ratios of different elements, the interstellar isotope ratio $^6$Li/$^7$Li might offer a better parameter to test source models than the absolute lithium abundance estimated directly in the ISM. However, measurements of the local interstellar $^7$Li/$^6$Li ratio (e.g., Lemoine et al. 1993; Meyer, Hawkins, & Wright 1993) show major variations, with differences of up to an order of magnitude from one interstellar cloud to another. Further, given the extreme difficulty of the ratio measurement in a stellar atmosphere and the consequent extreme paucity of such data as a function of metallicity, together with the difficult interpretation of these data in terms of differential stellar depletion as a function of stellar surface temperature, it would be especially risky to attempt to draw conclusions at this stage by using a chemical evolution model to predict the evolution of the isotope ratio against, say, iron abundance. Because of the apparent spatial inhomogeneity, it is not even safe to place too much emphasis on the well-measured solar system $^7$Li/$^6$Li ratio of 12.5 (Mason 1971). These considerations have led us to the present approach of concentrating on the overall Li abundance envelope as a key model constraint.

In this paper we adopt the technique we were the first to use in Rebolo, Molaro, & Beckman (1988) of assuming that the upper envelope of the lithium versus iron abundance plot is at least a close approximation to the undepleted curve. We do in fact examine the alternative hypothesis, that this envelope represents a depletion curve, and show that this interpretation is quantitatively improbable, so leaving the way clear for the use of the lithium versus iron...
envelope as a test of lithium production processes. The purpose of the paper is to show, using this envelope, which types of production processes are excluded and which are permitted. Without going into any numerical detail, it is evident from inspection (see Fig. 1) that the rise in the lithium abundance toward the values found in objects close to solar (iron) metallicity occurs relatively late in the Galactic disk evolution timescale; the lithium rise lags the rise in iron, precisely the opposite case to that of oxygen (see Fig. 3). A direct implication is that processes associated with SNIIe could, but with difficulty, yield the observed lithium production. This consideration covers not only hypothetical processes within the supernovae but interactions of the energetic particles which they produce in processes occurring in the ISM. This is just an example of how we can hope to constrain the Galactic lithium production process using the available observational data. Below we will use quantitative modeling (both analytical and numerical) with the aim of reproducing the Li-Fe envelope, thereby eliminating processes which predict significantly different envelopes. What remains will be candidate material for the process (or processes) which gave rise to some 90% of the lithium we can observe today.

In § 2 we show, using simplified analytical models, how the overall shape of the lithium-iron curve for the Galactic disk can be reproduced on the assumptions of delayed production of lithium and increasing infall of gas to the disk. In § 3 we describe briefly a numerical chemical evolution model used to handle the detailed evolution of lithium. In § 4 we examine quantitatively the problem of the Galactic cosmic-ray (GCR) flux as a candidate source for lithium. In § 5 we compare some of the suggested production mechanisms for lithium. Finally, we draw some conclusions about the primordial abundance of lithium.

2. ANALYTICAL AND SEMIANALYTICAL MODELS FOR THE TEMPORAL EVOLUTION OF Li: COMPARISON WITH DATA AND WITH PREVIOUS MODELING

Numerical modeling of Galactic chemical evolution, which we consider in § 3, offers the advantage of being able, in principle, to match realistically the physical variables which have driven it; in other words, given correct assumptions, it gives exact fits to the relevant observations. However, without descriptions of inordinate length and including a full listing of complete codes, such numerical models are not as transparent as desired. While analytical models are inevitably too simple to reproduce most data sets, their use is more didactic, enabling the underlying physics to be better demonstrated. For this reason we have chosen first to show analytical models which illustrate the physical requirements of any scheme that predicts the observed lithium-iron relation, before presenting our numerical models. The analytical models are designed according to standard methodology, which is based on the paradigmatic work of Tinsley (1980). As the observations give us directly the evolution of the abundance of one element versus that of another, and because the analytical treatment predicts the evolution of abundances versus time, we adopt hereafter our well-tested (see Figs. 2a and 2b) numerical results for the translation from the metallicity (taken as $[Fe/H]$ or $[O/H]$) plane to the time plane and vice versa. First, in the volume under consideration, we set the star formation rate, SFR, proportional to the gas fraction $\sigma_w$, following Schmidt (1959), so that

$$SFR(t) = \gamma \sigma_w(t),$$  \hfill (1)

and the time evolution of the star formation rate is given by

$$\frac{d[SFR(t)]}{dt} = -\gamma SFR(t) + \gamma E(t),$$  \hfill (2)

where $E(t)$ is the gas acquired by the zone per unit time due to expulsion by stars plus any net infall of gas to the volume, and SFR(t) is the rate of conversion of gaseous mass into stellar mass. Integrating equation (2) gives

$$SFR(t) = \gamma e^{-\gamma t + \int G[w(t)] dt},$$  \hfill (3)

where

$$G(t) = \frac{E(t)}{SFR(t)}.$$  \hfill (4)

To simplify the treatment, we will first approximate $E(t)$ to $SFR(t)$; this is the case, for example, where the star-forming process has efficiency close to 100% and rapidly consumes all the available gas in the volume so that in each time interval new star formation uses only gas expelled from existing stars. This is akin to the assumption of instantaneous recycling. In this case $G(t) \approx 1$ and $SFR(t) \approx \gamma$. A similar expression would be obtained if the infalling mass of gas added to the gas expulsion by stars, at time $t$, were comparable to the gas consumption by star formation at the same time $t$. The first assumption to test is that lithium is produced either in SNIIe or by processes in the ISM caused by energetic particles expelled from SNIIe. In this case the rate of lithium production will be proportional to the star formation rate, which gives

$$\frac{d[Li(t)]}{dt} \propto SFR(t) \propto \gamma,$$  \hfill (5)

which, integrating and translating from the time plane to the metallicity plane through a simple parabolic fit (of the
form \([\text{Fe/H}] \simeq -(1 - t/15)^2\) with \(t\) in Gyr) to the data of Figure 2a, gives

\[
\text{Li}(t) \simeq \text{Li}(0) + \gamma [1 - (\text{[Fe/H]} - 1)^{1/2}],
\]  

where \(\text{Li}(0)\) is the initial lithium abundance. From this we can deduce that models in which the bulk of Galactic Li is produced in processes involving SNIIe could satisfy the observational requirements, but with some degree of difficulty (see Fig. 3).

One can obtain an approximation to the effects of infall in this type of model in a less direct way, but which serves to illustrate the principle. Here we must refer ahead to a numerical model developed in §3, from which we take an approximate time dependence of the rate of SNIIe. It turns out to be approximately parabolic (see Fig. 5) centered at \(t = 80\) in unit model steps of 100 Myr, and we fit

\[
\frac{d[\text{Li}(t)]}{dt} \propto 1.5 \times 10^{-8}(t - 80)^2 + 5 \times 10^{-5},
\]  

which gives on integration

\[
\text{Li}(t) \propto 0.5 \times 10^{-8}(t - 80)^3 + 5 \times 10^{-5}t + \text{Li}(0).
\]  

The numerical coefficients show that for all times of interest \((t \geq 5\text{ Gyr})\) up to the present age of the disk, the cubic term can in fact be neglected, and the lithium abundance grows essentially as

\[
\text{Li}(t) \propto 5 \times 10^{-5}t + \text{Li}(0),
\]  

which shows the same behavior as that of equation (6) in the metallicity plane.

Thus processes whose rates are proportional to the number of SNIIe in the disk (either in stars or in the ISM) are not ruled out by the lithium-iron envelope test, in all scenarios, with or without infall of gas.

Processes which depend on the SNII rate included among current explanations for lithium production in the ISM (see, e.g., Ramaty, Kozlovsky, & Lingenfelter 1997)—spallation of CNO by highly energetic \(\alpha\)-particles—have been adduced to account for the major fraction of the lithium produced. An alternative nonstellar mechanism is the interaction of moderate-energy \(\alpha\)-particles with the existing abundant He nuclei in the ISM, producing lithium via the \(\alpha + \alpha\) fusion reaction. The sources of these low-energy \(\alpha\)-particles can be the winds of normal stars (see §4). In this case an additional interstellar acceleration mechanism is required to give the \(\alpha\)-particles sufficient energy, at least a few MeV, required for the \(\alpha + \alpha\) fusion reaction. One
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FIG. 3.—Normalized plots based on models embodying analytical schematic approximations to Li production rates and their evolution with Fe, to illustrate how some selected scenarios for the evolution of disk Li agree less with the form of the observations (the upper envelope of the points in Fig. 1a) than others. Points are the data as in Fig. 1. All curves are from analytic approximations by mathematical functions with two free parameters which are constrained to match the data envelope at \([\text{Fe/H}]^1\) (where the full disk initiates) and at \([\text{Fe/H}]^0\). Long-dashed line: from eq. (17). Solid line: from eqs. (6) and (19), which give a very similar result. Dashed line: from eq. (14). Dotted line: from eq. (12).

could assume that the effects of the presence of supernovae on the ISM can produce the required acceleration (but we have shown, using simple calculations, that the same results would follow using the acceleration in wind termination shocks of stars of all masses, as proposed by Rosner & Bodo 1996). The lithium production rate at a given epoch will then be proportional to the mass outflow from stellar winds multiplied by the supernova rate. We can approximate the latter as constant (cf. above), and the mass outflow rate from stars of a given mass will be proportional to the number of stars of that mass; for low-mass stars (those with masses less than 1 \(M_\odot\), and hence supplying gas only via winds because their lifetimes are greater than the life of the disk) this number is fully cumulative, and we have approximately [integrating in time SFR\(t\) = constant]

\[
N_{\text{stars}}(t) \propto t ,
\]

and so

\[
\frac{d[\text{Li}(t)]}{dt} \propto t ;
\]

hence integrating and translating from the time plane to the metallicity plane through the same fit to data than was taken for equation (6), one has

\[
\text{Li}(t) \approx \text{Li}(0) + \gamma'[1 - (\text{[Fe/H]}^{1/2})^2] (12)
\]

with \(\gamma'\) a constant; see Figure 3 to compare the predictions of equation (12) with data. Now, let us consider intermediate-mass stars (those with masses \(1 M_\odot \leq m \leq 3 M_\odot\), which supply gas mainly via processes in their late evolutionary stages) as the main producers of Li: because of their fairly long lifetimes, their expulsion of gas accumulates over times long after their birth, and for the lower part of this mass range keeps accumulating until the present epoch. We may approximate analytically the collective gas expulsion rate by an exponential, while SN(t) can be taken as approximately constant, as above. In this case one has

\[
\frac{d[\text{Li}(t)]}{dt} \propto e^{kt} ,
\]

and integrating and translating to the metallicity plane as above, we have

\[
\text{Li}(t) \approx \gamma''(1 + e^{k(1 - (\text{[Fe/H]}^{1/2})}) (14)
\]

with \(\gamma''\) and \(k\) constants.

In Figure 3 we can see the fit of this expression to the observations. One can go further and analyze in more detail the time dependence of the Li abundance on the properties of stellar mass ranges as follows: assuming an SFR approximately constant, and assuming that the production of Li is associated with the gas expulsion by stars of all masses, one has

\[
\frac{d[\text{Li}(t)]}{dt} \propto \int_{m_r}^{m_u} m^{-2.35} R(m) dm . (15)
\]

Taking an analytical approximation for \(R(m)\) in the form \(m^{0.2 - 0.58}\) (based on the numerical values of Renzini & Voli 1981) and integrating, one has

\[
\frac{d[\text{Li}(t)]}{dt} \propto -0.005 + \frac{m_r^{-1.15}}{1.15} - \frac{0.58}{1.35} m_r^{-1.35} . (16)
\]

Using the approximation relating the mass of a star and its lifetime as \(m_t \approx (11.7)^{1/2} t^{-1/2}\), translating to the metallicity plane as below, and integrating, one has, neglecting the first term which has a very low value compared with the other

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Fig. 4.—(a)–(d). Observations of Li vs. Fe compared with the predictions of models taken from the literature, with parameters described in the text, and also with models developed in the present paper. Graphs common to all panels: Model due to Prantzos et al. (1993) (dashed plus dotted line). Model due to Matteucci et al. (1995) (dotted line). Halo model due to Casuso & Beckman (1997) (solid line for $[\text{Fe/H}] \leq -1.3$ only). Differential curves: (a) $x + x$ model with GCR flux proportional to gas expulsion rate by stars of masses $\leq 3 \, M_\odot$ (solid line); model with GCR flux proportional to gas expulsion rate by stars of masses $\leq 2 \, M_\odot$ (dashed line). (b) $x + x$ model with GCR flux proportional to gas expulsion rate by stars with masses $\leq 3 \, M_\odot$, with exponentially increasing infall (solid line) or with no infall (dashed line). (c) $x + x$ model with GCR flux proportional to gas expulsion rate by stars with masses $\leq 3 \, M_\odot$ (solid line); model with GCR flux proportional to cumulative number of stars with masses $\leq 1 \, M_\odot$ (long-dash-dotted line). (d) $x + x$ model with GCR flux proportional to gas expulsion rate by stars with masses $\leq 3 \, M_\odot$ (solid line); model with no disk production but with linearly time-dependent stellar depletion from a "primordial" value of log $N(\text{Li}) \simeq 3.5$ (long- and short-dashed lines).
proportional to the gas expulsion rate by stars with masses of the model due to the finite time intervals employed. The steps in the curves are unsmoothed constructs of the model due to the finite time intervals employed.

two,

\[
\text{Li}(t) \approx \text{Li}(0) + k'' \left\{ -0.005[1 - (-[\text{Fe/H}])^{1/2}] 
- 0.049[1 - (-[\text{Fe/H}])^{1/2}]^{1.675} 
+ 0.13[1 - (-[\text{Fe/H}])^{1/2}]^{1.575} \right\}, \quad (17)
\]

where \( k'' \) is a constant; see Figure 3. If we place an upper limit on the mass range of stars contributing to the gas which yields Li, this analytical approximation leads to a sharp increase from zero Li production on short timescales to a high value when times reach the scale of lifetime of the upper mass limit stars. For example, for an upper mass limit of \( 1 \, M_\odot \), the Li production will be zero until the time is near 12 Gyr or \([\text{Fe/H}] \approx 0.0\) (see Fig. 3). Thus we can see, in general terms, that using a gas expulsion timescale and modulating the upper mass limit, we can find solutions leading to late-time production of Li, as apparently required by the observations.

For comparison one can set out a similar formulation using the assumption that Li production is proportional to the cumulative number of stars of all masses at a given time, which implies production within the stars or in their envelopes, rather than in the ISM via expelled gas:

\[
\frac{d[\text{Li}(t)]}{dt} \propto \int_{m_L}^{m_u} m^{-2.35} dm . \quad (18)
\]

Performing these integrations with the same approximation for the mass-time and time-metallicity dependences as before, and taking \( m_L = 0.1 \, M_\odot \), one has

\[
\text{Li}(t) \approx \text{Li}(0) + k'' \left\{ -0.084[1 - (-[\text{Fe/H}])^{1/2}]^{1.675} 
+ 16.58[1 - (-[\text{Fe/H}])^{1/2}] \right\}, \quad (19)
\]

where \( k'' \) is a constant. A comparison of these stylized models, with Li production proportional to the cumulative numbers of moderate-mass stars or, alternatively, to the cumulative flux of expelled gas, is given in Figure 3.

In all the approximations based on the proportionality of Li production rate to the gas expulsion rate by stars of low or intermediate masses (eqs. [12] and [14]) one can see a considerable resemblance to the observed lithium growth profile. The reason for the importance of intermediate-mass stars, rather than high-mass stars, as producers of \( x \)-particles leading to Li production is that the former turn out to be particularly efficient in expelling He. For stars with masses greater than \( 3 \, M_\odot \), the central temperature becomes high enough for the ignition of the triple-\( \alpha \) reaction (which transforms He to C) before the giant stage is reached. At the moderate densities of the central regions, this nuclear process gains importance in a gradual manner. On the other hand, for stars with masses between \( 0.5 \, M_\odot \) and \( \sim 3 \, M_\odot \) the central regions become degenerate and the triple-\( \alpha \) reaction ignites via the violent helium flash.

Although we would certainly not wish at this stage to exclude supernovae as key producers of Li in the Galactic disk, to be coherent with our general scenario of chemical evolution for the Galaxy, we have used the \( x + \alpha \) process in the ISM as illustrative of processes which follow the behavior of stars of intermediate and low masses, those whose lifetimes are long, and whose numbers in the disk have therefore grown cumulatively with time. Any process with equivalent time-dependent characteristics might, in general terms, satisfy this global observational constraint. Production of Li in novae (Arnould & Norgaard 1975; Starrfield et al. 1978), or in supernovae of Type I (SNIe), might also satisfy the criterion of delayed production because there the rate of production would be proportional to the number of stars with intermediate masses at each time (cumulative as their lifetimes are long). But as one can see in Figure 4, where we plot the results from different numerical models in the case of GCR flux proportional to the cumulative number of stars with masses less than or equal to \( 1 \, M_\odot \) (for upper mass limits greater than \( 1 \, M_\odot \), the increase in the number of stars with time is proportionally less and less), the prediction, although not bad, is clearly inferior in fit to that obtained using gas expulsion by stars of masses less than or equal to \( 3 \, M_\odot \) (and in fact also worse than that obtained using gas expulsion of stars with masses less than or equal to \( 2 \, M_\odot \)).

**Fig. 5.**—Example showing the essential difference in GCR flux as a function of time for two key models: proportional to SFR(t) (solid line) and proportional to the gas expulsion rate by stars with masses \( \lesssim 3 \, M_\odot \) (dotted line) against time, from our numerical model with increasing infall of gas to the solar neighborhood. The steps in the curves are unsmoothed constructs of the model due to the finite time intervals employed.
Another possibility which has been discussed is the production of Li in compact objects such as neutron stars and black holes, but the time evolution of the numbers of compact objects would be proportional to the rate of gas expulsion by all stars (which is mainly that of SNIa + SNIIt). This production is shown in Figure 1 from our numerical modeling. In fact, as one would expect, the curve is similar to that for the model in which Li production is proportional to the SFR, also shown in Figure 1.

Further possibilities for the production of Li, such as those in AGB stars or carbon stars (Matteucci, D'Antona, & Timmes 1995), are unable to satisfy the detailed observational constraints, as will be seen in Figure 5.

The aim of this section has been to show those categories of models, and hence of lithium sources, which can best account for the lithium-iron envelope observations. However, for a valid test of any process which is a candidate to have produced the observed disk lithium, we have no choice but to use quantitative, numerical, modeling methods.

3. NUMERICAL EVOLUTIONARY MODELS: THE BASIC FORMALISM

The model we have used for the evolution of the disk in the solar neighborhood employs the formalism already explained in Casuso & Beckman (1997), which embodies a numerical rather than an analytical approach, in order to take all the relevant physics adequately into account. The model allows us to follow the evolution, within a fixed volume of space, of the gaseous mass fraction \( \sigma_g \) and the abundances \( X_i \) of six nuclides: \(^{4}\text{He}, ^{12}\text{C}, ^{13}\text{C}, ^{14}\text{N}, ^{16}\text{O}, \) and \(^{56}\text{Fe}\), selected because observations of their evolutionary abundance behavior are available. The set of basic equations employed, in which the units are mass fraction per unit time interval, are

\[
d\sigma_g = -\Sigma\text{SFR}(t) + E(t) , \tag{20}
\]

\[
d(\sigma_g X_i) = \int_{m_i}^{m_{\ast}} \Sigma\text{SFR}(t - t_\ast) \phi(m) \left\{ Q_i(m) + X_i(t-t_\ast)(R(m) - Q_i(m)) \right\} \] \[ \times \left\{ R(m)X_i(t) \right\} dm + J(t) , \tag{21}
\]

with

\[
J(t) = P(t)[X_i(t) - X_i(t)] \tag{22}
\]

with

\[
E(t) = \int_{m_i}^{m_{\ast}} \Sigma\text{SFR}(t - t_\ast) \phi(m) R(m) dm + P(t) \tag{23}
\]

in which \( t_{\ast} \) is the lifetime of a star of mass \( m \), \( X_i(t) \) is the halo abundance, \( P(t) \) is the net inflow of material to the volume under study, \( \Sigma\text{SFR}(t) \) is the star formation rate, and \( \phi(m) \) is the initial mass function (IMF) of the stars. Within this volume there is a population of stars whose lifetimes \( t_{\ast} \), for a mass \( m \geq m_i \) (where \( m_i \) is the mass of a star which has a lifetime \( t_i \) are less than or equal to the value of the time variable \( t \) and which eject the products of their internal nucleosynthesis at a rate proportional to \( \Sigma\text{SFR}(t - t_\ast) \), the star formation rate at their birth. We term the fraction of its mass which a star ejects during its lifetime \( R(m) \), and \( Q_i(m) \) is the yield of nuclide \( i \) from a star of mass \( m \). The total mass which has been added to the ISM, either by stellar evolution or by net inflow into the volume under consideration, is called \( E(t) \). All relevant stages of stellar evolution have been taken into account, including post-main-sequence phases (e.g., AGB stars, planetary nebulae, and other gas ejection stages) and explosive processes.

We have used a simple proportionality law for the dependence of the star formation rate on the gas fraction, namely, \( \Sigma\text{SFR}(t) = \gamma \sigma_g(t) \) where, following the classical approach of Schmidt (1959), we have used \( k = 1 \) and \( \gamma = 0.11 \text{ Gyr}^{-1} \). The observed parameters of chemical evolution for the solar neighborhood are reasonably reproduced. As a suitable approximation to the IMF we have used the Salpeter (1955) law, that is, \( \phi(m) \propto m^{\alpha} \) with \( \alpha = 1.35 \), between 73 and 0.5 \( \text{M}_\odot \), and have approximated the flattening observed at low masses (see, e.g., Scalo 1986; Kroupa, Tout, & Gilmore 1993) with a plateau of value \( \phi(0.5) \) between 0.5 and 0.1 \( \text{M}_\odot \). This approximation is convenient for computations and represents a reasonable fit to the observations. Slightly better but more complicated fits to the observations would not affect any of the conclusions reached here. Finally, we approximated the stellar lifetime \( t_{\ast} \) as a function of mass \( m \), following Arimoto & Yoshii (1986), by \( t_{\ast} = 11,700/m^2 \) in units of Myr for \( t \) and solar masses for \( m \).

We have shown that our model can reproduce the well-established observed chemical abundance parameters of the Galactic disk in the solar neighborhood, the \(^7\text{Be}/\text{H} \) and \(^{10+11}\text{B}/\text{H} \) temporal evolution (see Casuso & Beckman 1997), as well as that of \( \text{D}/\text{H} \), \(^7\text{Li}/6\text{Li} \), and \(^{11}\text{B}/^{10}\text{B} \) (see Casuso & Beckman 1999).

It is well known that closed box models [with \( P(t) = 0 \)] of Galactic chemical evolution fail to reproduce several of the disk constraints, most notably the metallicity distribution in the disk, characterized by the low numbers of G dwarfs with low metallicities. They also fail to reproduce the disk evolution of Be and B versus Fe, and models which give adequate
fits to these observed data sets require increasing infall to the disk of metal-free or metal-poor gas (Casuso & Beckman 1997). We have therefore adopted the same representation of the infall as was used in that paper:

\[ P(t) = \frac{e^{\lambda t}}{M(t)}, \]  

(24)

where \( M(t) \) is the total mass of the zone at time \( t \) and \( \lambda^{-1} \) is a time constant which must be in the range of a few Gyr. It is notable that recent observations of abundances in the local interstellar medium (Fitzpatrick 1996) showing undepleted elements with abundances significantly below solar give support to the idea of steady dilution by infall of non-enriched gas to the disk. Including the global effect of depletion as in the model of Casuso & Beckman (1999) does not in practice yield significant improvements in the data fit compared to nondepleted models, within the limits of error.

4. APPLICATION OF NUMERICAL MODELING: INCORPORATION OF \( \alpha + \alpha \) BY GCRs IN THE ISM

A seminal early paper describing the physics of light-element production by spallation and fusion reactions, authored by Meneguzzi et al. (1971), has been the basis of much of the intervening work in the field. These authors showed that nuclides of light elements can be produced by spallation during collisions of GCR protons and \( \alpha \)-particles with nuclei of C, N, and O in the ISM and also by CNO in GCRs colliding with protons and \( \alpha \)-particles in the ISM. The contribution of the latter set of reactions to the production of Li, Be, and B nuclides by spallation has been estimated to be some 20% of the former (Meneguzzi & Reeves 1975); this should not have been very different in the past, assuming that the cosmic-ray composition reflects that of the ISM. This has meant that as far as spallation is concerned, we needed to calculate in detail only the former reactions, taking the latter into account by proportion. A further source of light-element nuclides, whose importance has been recognized more recently, is the production of \( ^6\)Li and \( ^7\)Li by fusion reactions between GCR \( \alpha \)-particles and those of the ISM. The relative importance of this mechanism may have declined somewhat, as the abundances of CNO in the ISM have grown relative to that of \( ^4\)He (although the abundance of the latter is still overwhelmingly greater), but in the early phases of the disk it was certainly an important mechanism (Montmerle 1977; Steigman & Walker 1992), and as we will see, it must still play a major role today.

In this work we have used the standard expression for the production of light-element nuclides by GCR protons and \( \alpha \)-particles in the ISM:

\[ \frac{dY_k}{dt} = \sum_j Y_j^{ISM}(t) \int F^\text{GCR}_i(E, t) \sigma^G_{ik}(E)dE, \]  

(25)

where \( Y_j(t) \) are the abundances, by number, of the various species; \( j \) refers to \( ^{12}\)C, \(^{13}\)C, \(^{14}\)N, \(^{16}\)O, or \(^{4}\)He; \( k \) refers to \(^{6}\)Li and \(^{9}\)Be, \(^{10}\)B, or \(^{11}\)B; and \( i \) refers to GCR protons or \( \alpha \)-particles. The term \( F^\text{GCR}_i(E, t) \) is the interstellar GCR flux spectrum, and \( \sigma^G_{ik}(E) \) is the cross section for each reaction \( i + j \rightarrow k \), which has a corresponding energy threshold \( E_F \). The quantities \( Y_j^{\text{ISM}}(t) \) are computed from the Galactic chemical evolution models described in §3. They are thus observationally constrained, and we have reasonably good estimates of their evolution with \( t \) during the disk lifetime. The spallation and fusion cross sections \( \sigma^G_{ik}(E) \) are also well known (see Read & Viola 1984; Mercer, Austin, & Glagola 1997) within narrow limits of error. These cross sections show rather similar global behavior, starting from thresholds \( E_F \) close to 10–20 MeV nucleon\(^{-1}\), peaking somewhere between 20 and 70 MeV nucleon\(^{-1}\), and declining rapidly to a plateau above \( \sim 100 \) MeV nucleon\(^{-1}\). There is, however, a key difference between the \( \alpha + \alpha \) process for \(^6\)Li and \(^7\)Li. (Of course, a fraction of \(^6\)Li is indeed formed by spallation in the higher energy range, but none of the \(^9\)Be or \(^{10,11}\)B can be formed via the \( \alpha + \alpha \) process.) This dichotomy has important consequences for the observationally very different time dependence, and hence the metallicity dependence, of \(^6\)Li on the one hand and \(^9\)Be or \(^{10,11}\)B on the other.

In order to try to reproduce the evolution of the light elements, it is clear that we need estimates of the current energy spectrum of the GCR component, of its flux, and of how these parameters have varied with time. For the present epoch the magnitude and spectral shape of the flux of GCR particles reaching the Earth are fairly well determined by direct experiment for particles with energies higher than a few hundred MeV nucleon\(^{-1}\), those which are directly observed at the Earth’s orbit. For these particles spectra of the forms \( F(E, t_0) \propto E^{-2.2} \) are found up to a few GeV nucleon\(^{-1}\) and \( F(E, t_0) \propto E^{-2.6} \) at higher energies (Ip & Axford 1985). However, at lower energies the GCR spectrum must be demodulated to take into account the blocking effects of the heliosphere. This has been a well-known cause of difficulties for light-nuclide production theory (Meneguzzi et al. 1971; Meneguzzi & Reeves 1975; Reeves 2000 PASP, 112:942–960
and the problem of determining the spectral dependence and the amplitude of the unmodulated interstellar component of the GCR spectrum below 100 MeV nucleon$^{-1}$ still lacks an entirely acceptable solution. In the present modeling exercise we follow Reeves & Meyer (1978) in taking a most probable value for solar demodulation of 5, for the whole GCR spectrum, and supplement this with a further mean factor of 15 for the particles with energies having energies $E \leq 100$ MeV nucleon$^{-1}$, which is consistent with the estimates made by McDonald et al. (1990) and McKibben (1991) from observations of the low-energy component of $\alpha$-particles out to a heliocentric distance of 43 AU with Pioneer 10 and Pioneer 11. More recent studies do not claim major improvements here, because no direct measurement beyond the heliopause has yet been made. To summarize, we take the spectral dependence of the flux to be proportional to $(E + E_0)^{-\lambda}$, where $E_0$ is the rest energy of the proton, and $\lambda$ takes values of 2.6 below 0.1 GeV nucleon$^{-1}$, 2.2 between 0.1 and 1 GeV nucleon$^{-1}$, and again 2.6 at energies higher than this; in these we follow previous studies on light-nuclide production by Walker et al. (1985) and by Steigman & Walker (1992). Finally, we normalized the flux to match the constraint imposed by the measured GCR proton flux for energies greater than 0.1 GeV nucleon$^{-1}$, 12.5 cm$^{-2}$ s$^{-1}$ GeV$^{-1}$ nucleon$^{-1}$ (Gloeckler & Jokipii 1967), together with a ratio of the $\alpha/p$ fluxes of 0.15, consistent with the observations of Gloeckler & Jokipii (1967) as reexamined by Webber & Leznik (1974). Of course, one must invoke (as must all models invoking GCR reactions to produce the light elements) effective magnetic confinement of GCRs in the Galaxy in order to obtain the required high absolute fluxes of GCR protons and $\alpha$-particles.

In the present work we are concerned with Li production, but in the models we have included depletion for the gas which has been processed into stars (we have assumed here that stars which expel their gas into the ISM have completely depleted their Li so that this expelled gas has zero Li abundance) and the “impoverishment” due to the infall of gas to the disk from the halo: we assume that this gas has the initial, that is, the primordial, Li abundance. However the inclusion, or not, of these effects influences the model results, that is, the effective production curve, significantly only in the range $-0.2 \leq [\text{Fe/H}] \leq +0.2$, where the effect of infall has been to cause a slight fall in the observable Li abundance.

One of the arguments of the present paper rests on a correct understanding of how the low-energy GCR particle flux has developed with time. Specialists in cosmic-ray physics have previously proposed that since the measured abundances of GCR nuclides show a dependence on the first ionization potentials of the parent atoms, the principal sources of these particles must be the atmospheres of relatively low-mass, relatively cool stars (see Cassé & Goret & Meyer 1978; Meyer 1985, 1993). The consequence of this for the time dependence of the GCR flux in the range of energies required to produce the light-element nuclides, and specifically for those below 100 MeV nucleon$^{-1}$ which participate in the $\alpha + \alpha$ fusion reaction, is an increase of the flux at later times due to the accumulation of stars with lifetimes comparable to that of the disk. In the seminal study of Meneguzzi et al. (1971) and also in the careful reexamination of light-element abundance production by Walker et al. (1985), the zero-order assumption was made using a GCR flux constant with time. A number of other workers in the field (Reeves & Meyer 1978, Mathews, Alcock, & Fuller 1990) used a time-varying scheme in which the GCR flux $F(E, t)$ is proportional to the supernova rate, SNR$(t)$, which in turn was set proportional to the star formation rate SFR$(t)$, in their models.

In their study Prantzos, Cassé, & Vangioni-Flam (1993) were well aware of the importance of the time dependence of the GCR flux and also assumed that it followed the supernova rate. However, in the present study we use the assumption that this flux follows the expulsion rate of gas from stars, and we have in fact varied the upper limit of the mass range from which expulsion is considered. The delay entailed allows the model predictions to avoid one of the main difficulties encountered by Prantzos et al.: that without this delay there would have to have been an early sharp increment in the disk of Li (in particular) against Fe, in the range of $[\text{Fe/H}]$ between $-2.0$ and $-1.0$, an increment which is not observed. This delay is due to the fact that although in the early disk there would have been a high SN rate, required to accelerate the GCR particles, the cumulative number of low- and intermediate-mass stars required to inject major quantities of He nuclei (Meyer 1985) was still low. Both injection and secondary acceleration are required to yield MeV range GCRs, and these conditions have been fulfilled simultaneously with increasing effect in the later disk, which explains the observed delay in the onset of disk Li production, even with respect to Fe (and a fortiori with respect to O).

In Figure 1 we contrast the evolution of the Li abundance in a typical model in which the GCR flux is proportional to the SFR with that in models chosen from those we have applied in the present paper, in which the flux is proportional to the gas expulsion rate from the stellar population at a given epoch. The qualitative difference is evident, and the relative reduction of the GCR flux in the early disk, compared with more recent epochs, is clear. There are two further points about the acceleration and propagation of GCRs which we should make here. As a result of many studies over the past 30 years, it is now a widely accepted possibility that the majority of the observed particles in the GCR flux have been accelerated in collisionless mode by shock waves which originate in supernova explosions and propagate through the dilute interstellar plasma (Lagage &
Cesarsky 1983; Blandford & Eichler 1987). In the model of GCR propagation by Prantzos et al. (1993), the high-energy part of the GCR flux spectrum is modulated according to the escape length of the particles as a function of their energy; this effect has changed with epoch in such a way that the current spectrum has a greater slope than the spectrum at early Galactic epochs. The low-energy fraction of the GCR flux has remained, however, virtually unaffected by this change, suggesting that the evolution of the Li production rate has been due rather to the time variation of $\alpha$-particle density than to the variation of the spectral index. Second, we must emphasize that provided there has been sufficient volume occupied by SN-affected ISM, the flux of low-energy $\alpha$-particles will depend principally on the population density of the injectors, low-mass stars, rather than the SN remnants which accelerate them. A final point here is that low-energy GCRs may in fact be accelerated by wind termination shocks due to stars of the full mass range. This process has been invoked by Rosner & Bodo (1996) to explain the diffuse nonthermal Galactic radio emission. Clearly acceleration via this process is not proportional to the SN rate but to the cumulative gas expelled by all stars present at a given epoch. Although taken alone it does not lead to sufficient delay to explain the abrupt rise in the Li-Fe envelope it is, a promising mechanism for $\alpha$-acceleration in the context of the Li abundance observations.

Here we should allude to the as yet not fully resolved question of the origin of cosmic rays. In early models of SN shock theory, the thermal gas in the ISM was regarded as the reservoir of seed particles which can become cosmic-ray nuclei. But this clashes with the source composition of GCRs (Meyer 1985). To solve this problem one needs to invoke an injection of suprathermal ions. There are two main types of scenarios here: one assumes that the observed local flux of GCRs has its origin in supernovae accelerating their own ejecta, and the other assumes an origin in the atmospheres of intermediate- and low-mass stars (for discussions, see Meyer, Drury, & Ellison 1997; Ellison, Drury, & Meyer 1997; Ramaty et al. 1997; Ramaty, Kozlovsky, & Lingenfelter 1998; Higdon, Lingenfelter, & Ramaty 1998). While the early Galactic beryllium data suggest production by cosmic rays originating from SNe accelerating their own ejecta, the observed composition of the cosmic-ray source material reflects a correlation with first ionization potentials, leading to the suggestion that cosmic-ray source material originates in the atmospheres of stars. As evidence for this, we know that the abundances of elements with low first ionization potentials are enhanced in the solar corona and in solar energetic particles, suggesting that similar shock acceleration in low-mass, cool stars could provide a particle injection source for acceleration by supernova shocks in the ISM. Both origins (SNe or low-mass stars) have as many problems as complete explanations of the origin of GCRs with energies greater than 1 GeV nucleon$^{-1}$ (see Ramaty et al. 1998). We cannot consider as coincidental the similarity between the composition of GCRs and that of the solar corona which is biased according to first ionization potential. We must also take very seriously the assertion of Ellison et al. (1997, p. 198) that "in the outer solar atmosphere the solar coronal gas, the solar wind, and the ~MeV solar energetic particles have undoubtedly a composition biased according to FIP," together with the fact that hydrogen and specifically helium are not well fitted by the alternative model of Meyer et al. (1997) and Ellison et al. (1997) based on volatility and mass to charge to explain the GCRs. In addition, we must note that the cosmic-ray electrons have very different spectra from those of the nuclear species at GeV energies and may, in fact, have entirely different origins (Berezinskii et al. 1990). In addition, atomic collisions of low-energy ions (corresponding to a distinct low-energy cosmic-ray component) produce characteristic nonthermal X-ray emission. On this point Tatischeff et al. (1999) have shown that a distinct Galaxy-wide low-energy cosmic-ray component could account for the hard component of the Galactic ridge X-ray emission in the 0.5–10 keV energy domain. Also, one must note the different behavior of helium and hydrogen data with respect to the other GCR nuclei when the energy of these particles is increased, as inferred from the observations in the solar corona, in the solar wind, in the solar energetic particles, and in GCRs (see Meyer 1985, 1993). One can see how He and H abundances decrease systematically as the energy increases, while the abundances of the other nuclei remain invariant. All these considerations point to an origin for the low-energy $\alpha$-particles which optimize Li production which could be quite different from that for the GCR nuclei at higher energies. In our coherent scenario of chemical evolution for the Galaxy, we point to the origin in low-mass stars of the low-energy (those below 0.1 GeV nucleon$^{-1}$) $\alpha$-particles of GCRs, consistent with the fact that the Li production cross section for the $\alpha$-$\alpha$ fusion reaction falls very steeply outside the energy range between 0.01 and 0.1 GeV nucleon$^{-1}$ (see, e.g., Ramaty et al. 1997).

In order to quantify our model, we will account for the energy needed for the $\alpha$+$\alpha$ fusion reaction to be coherent with the energy supplied by the intermediate-mass stars in a range when the Li production is efficient. Because our concern is essentially with $\alpha$-particles, and because the $\alpha$+$\alpha$ fusion reaction which yields Li has a distribution of measured cross sections which is very low outside the 10–100 MeV nucleon$^{-1}$ range, we calculate the energy budget by integrating the flux in that range. So, the energy per SNII will be the total GCR energy in this range during, for example, $10^8$ yr, taking 0.1 cm$^{-3}$ as an average current He abundance in GCRs and a section corresponding to the 500 pc radius taken here as the size of the selected circumsolar volume, all divided by the number of SNIIe needed by our
numerial model ($\sim 13,000$ during each $10^8$ yr):

$$\text{energy SNII}^{-1} = \left\{5 \times 15 \times \int_{0.1}^{0.1} E(E + E_0)^{-2.6} k dE \right\} / 13,000 \quad (26)$$

where $E_0 = 0.938$ GeV, $5$ is the solar demodulation factor, $15$ is a factor required to give a good fit to the data, and $k$ is the normalization constant which is obtained fitting the observed GCR flux of $\alpha$-particles at energies above $0.1$ GeV:

$$0.15 \times 12.5 \text{ cm}^{-2} \text{ s}^{-1} \text{ GeV}^{-1} \text{ nucleon}^{-1}$$

$$= \int_{0.1}^{1} k \times (E + E_0)^{-2.2} dE$$

$$+ \int_{1}^{\infty} k \times (E + E_0)^{-2.6} dE \quad (27)$$

From this one obtains the energy per SNII needed for our model to produce the Li observed in the disk by $\alpha$-particles, $2 \times 10^{50}$ ergs, which is in very reasonable agreement for energy available from SN model estimates. Taking the IMF used here, we also obtain the energy per star of intermediate mass ($1-3 M_\odot$) needed for the $\alpha$-particles produced in these stars, $10^{49}$ ergs, very reasonable for the helium flash or coronal mass injections.

The net accelerating power of the OB star environment in the local spiral arm has not, in this model, varied by more than a moderate fraction during the disk lifetime. The fact that the model produces some twice as much local GCR flux at the present epoch as at the beginning of the disk is due entirely to the accumulation of particles ($\text{H}, \text{He}, \text{C}, \text{N}, \text{O}$) emitted at low energies from low-mass stars, and not to any substantial change in the net efficiency of the SN mechanism which subsequently accelerates them, and which has been present constantly throughout the disk lifetime.

This scenario is consistent with other parameters such as the lifetimes of $\alpha$-particles in the ISM. First we must note that owing to the very high temperatures needed to deplete $^4\text{He}$, efficient destruction occurs in stellar interiors. However, the $\alpha$-particles can also disappear in principle as a result of fusion reactions with other $\alpha$-particles, $^{12}\text{C},^{14}\text{N}$, and $^{16}\text{O}$ in the ISM, leading to $^6\text{He},^6\text{Li},^7\text{Li},^7\text{Be},^9\text{Be},^{10}\text{Be},^{10}\text{B},^{11}\text{B},^{10}\text{C}$, and $^{11}\text{C}$. These latter reactions have cross sections below $100$ mbarn, and so, taking densities of the ISM below $10^5$ cm$^{-3}$, the lifetimes are greater than $10^{12} \text{ yr}$, that is, greater than the age of the universe.

On the other hand, the flux of $\alpha$-particles in the range of energies concerned here, that is, between $10$ and $100$ MeV nucleon$^{-1}$, could come from the $\alpha$-particles produced in later type stars at energies below $2.5 \text{ MeV}$ nucleon$^{-1}$. In the mass range $0.5 \ M_\odot \leq M \leq 3 \ M_\odot$, the central regions become degenerate and the triple-$\alpha$ reaction ignites via the violent helium flash. The central energy generation rate at the peak of this helium flash exceeds $10^{13}$ times that in the center of the Sun, causing the well-attested expansion to the giant phase before the bulk of the He has been consumed. For these stars the expulsion of He nuclei into the ISM occurs with much greater efficiency than for the less accelerated transformation to the giant phase accompanied by the burning of the He which occurs in stars with higher masses. Another realistic possibility to explain the required low-energy $\alpha$-flux is that the ions can be injected (at MeV energies) via coronal mass injections (mainly from the coronae of dMe and dKe dwarfs, by far the most numerous stars in the Galaxy) (Shapiro 1999).

One way of seeing the problem is via a two-stage scenario similar to that of Meyer (1985), which assumes the OB associations as the best sites of production of $\alpha$-particles of GCRs; there, a large number of later type stars are being formed together with a few short-lived massive stars; the former have a very high surface activity owing to their youth and should emit many of suprathermal particles, while the latter provide stellar wind and SN shock waves within their few $10^6$ yr lifetime; so injectors and high-energy accelerators are closely linked in space and time. Energies as low as $0.01-0.1 \text{ MeV}$ nucleon$^{-1}$ are sufficient for suprathermal particles to be accelerated much more efficiently than the thermal gas. Particles with energies below $2.5 \text{ MeV}$ nucleon$^{-1}$ undergo significant coulomb energy losses, which brake and thermalize the particles, impeding $\alpha + \alpha$ fusion production of Li. However, the time for thermalization is inversely proportional to the density of the medium in which suprathermal particles propagate. The $\alpha$-particles propagating in dense clouds thermalize within $10^4$ yr, but in the diffuse hot interstellar medium (HIM) where $n_\text{H} \sim 3 \times 10^{-3}$ cm$^{-3}$, the thermalization time is several times $10^6$ yr. We can then assume that the mechanisms already proposed by Meyer (1985) can operate. Ionized media confine energetic particles, so that suprathermal particles emitted in the HIM will not in general traverse any neutral, dense medium. In dense cloud complexes later type stars can form continuously while OB star formation will disperse the complex rapidly; Meyer (1985) brings out the possibility of reacceleration of suprathermal particles emitted by young late-type stars having migrated into the HIM just nearby the cloud complex.

But one might not in fact need a two-stage scenario if the intermediate-mass stars produce and also accelerate $\alpha$-particles to energies in the range $10-100 \text{ MeV}$ nucleon$^{-1}$, where the coulomb energy losses are not so efficient. Another possibility is that the $\alpha$-particles needed come from the so-called anomalous component of He nuclei which is observed precisely at the range of low energies here.
considered (below 100 MeV nucleon$^{-1}$). These He nuclei had appeared as an unusually flat helium spectrum, apparently unrelated to the GCR spectrum (Webber 1989). In fact, the solar modulation effects on this helium anomalous component, as observed on the Pioneer 10 spacecraft at $\sim 40$ AU from the Sun between 1985 and 1987 (when the solar modulation reached its minimum), show a change of a factor $\sim 100$ in the intensity of these particles between 10 and 20 MeV nucleon$^{-1}$ as they rapidly emerge from the background of low-energy GCRs (Webber 1989), in good agreement with this work where we need a total modulation of $5 \times 15 = 75$ over the “normal” GCRs.

We can now summarize the reasons why the present family of models gives an adequate prediction of the observed Li versus Fe evolution curve. In those older models where a constant GCR flux was used (e.g., Walker et al. 1985), which is in fact not too bad a first-order approximation to the time-delayed evolution for the low-energy flux which we obtain here, the importance of the $\alpha + \alpha$ fusion reaction was not realized. In more recent models, on the other hand, where $\alpha + \alpha$ reactions have been well included (Steigman & Walker 1992; Steigman et al. 1993; Prantzos et al. 1993), sophisticated time evolution schemes for GCRs have been used, which unfortunately do not explore the delayed contribution of lower mass stars to the low-energy GCR spectrum. In the former models normalized to give the correct Li abundance at say, [Fe/H] $\simeq -1.5$, there was simply not enough contemporary Li produced; in the latter models, while it would be feasible to attain the contemporary abundance value, log $N$(Li) $\sim 3$, this would entail abundances of Li at [Fe/H] $\sim -1$, which are too high by more than half an order of magnitude. In the next section we show that our models yield results in much better agreement with the observations.

5. PREDICTIONS OF THE FAMILY OF NUMERICAL MODELS: COMPARISON WITH OBSERVATIONS

In the present section we present the results of our modeling exercises. We have already shown in Figure 1 the observations that we have set out to model. We began with data which we ourselves reported (Rebolo et al. 1988) because of the ready availability of the complete data set, to which we have added a newer and extensive set of results from F. Spite (1996, private communication). In Figure 1 we show observations of Li versus Fe abundances over a wide range of surface temperatures and metallicities. The assumption we will make in interpreting these data is that the upper envelope shows, essentially, the evolution of Li with Fe, while the points which fall below the envelope refer to Li depleted in the individual objects observed.

In Figure 1 we see that the Li abundance remained essentially constant during the halo period (in which the Fe abundance was evolving from its lowest values to around $-1.5$) and then began to rise. The approximate plateau at low [Fe/H], the “Spite plateau,” corresponds roughly to primordial Li, while the later rise represents the presence of Galactic Li production modulated by any averaged depletion which may take place. A key observational result is the rather abrupt rise of the Li envelope at [Fe/H] $\sim -0.2$ to an essentially constant value between $-0.2$ and $+0.2$. This second plateau, although not as clear as the Spite plateau, appears to be consistent with our general model predictions, as one can see in Figure 1. This plateau is a natural consequence of the “loop back” in abundance of Li already shown in Casuso & Beckman (1997) to occur for the Be and B disk abundances (where it appears more distinctly because stellar depletion is much less important than for Li) and is due to the increase with time in the infall of gas to the disk, which dilutes the Li abundance and more so the Fe abundance, reducing the latter in recent epochs from a broad peak attained several Gyr ago.

The model shown in Figure 1, in which the GCR flux was held proportional to the gas expulsion rate from the whole stellar population, represents a first approach using delayed $\alpha + \alpha$ as the principal source of Li, and its relative success is encouraging, but in using gas expelled from the whole stellar mass range it does not try to take into account the fact that the low-energy component of GCRs, responsible for the $\alpha + \alpha$ process which we are postulating as the principal source of Li, may well originate mainly in lower mass stars. The most direct way to do this is to place upper stellar mass limits on the expulsion rate of gas for which the GCR flux, at each epoch, is deemed proportional. Curves ii and iii show the results of allowing the GCR flux which enters the $\alpha + \alpha$ reaction to be proportional to the gas expelled per unit time from stars of all masses and up to mass limit of 3 $M_\odot$, respectively. It is clear that the model with the upper limit of 3 $M_\odot$ gives a much better fit to the observed envelope shown here and goes far in demonstrating the need to include the implied time delay in the buildup of the GCR flux in the relevant energy range. The curve for the 2 $M_\odot$ upper limit shows a good fit to the form of the observations but yields rather low Li production.

Even given the observational uncertainties in the Li-Fe dependence, we can use these data and these models to constrain broadly the stellar mass range which serves as a significant source of low-energy GCR $\alpha$-particles. The fact that models with an upper mass restriction give better fits to the data is itself an argument in favor of intermediate- and lower mass stars as the principal sources of the GCR flux at low energies.

One further note should be added. Our evolutionary models were designed to account for the G-dwarf metallicity distribution and B and Be evolution in the disk. In fact, the latter data begin to be very weak statistically for [Fe/H] $> +0.1$, which is where the previous model predic-
Fig. 6.—Extrapolated model curve which can account for Li abundances observed with [Fe/H] > 0.1.

...tions terminate. In Figure 6 we show the result of a modified model where the upper limiting Fe abundance is +0.3. This is an $\alpha + \alpha$ model with the relevant GCR flux proportional to the gas expelled from stars with masses $\leq 3 M_\odot$, and it also accounts well for the observations. We must note, however, that the systematic uncertainties admitted by the observers for the stars with high Li abundances and high Fe abundance are in the sense of requiring lower [Fe/H] (0.1 instead of 0.3 or 0.4) (see, e.g., Boesgaard & Tripicco 1986).

6. DISCUSSION: ALTERNATIVE SOURCES OF DISK LITHIUM

We have used evolutionary models for the Galactic disk in the solar neighborhood to reexamine the theme of Li production. In the first part of this paper we presented analytical and semianalytical models, with their simplifying assumptions and limitations, and showed that models incorporating a delay in Li production compared with that of Fe give a fair description of the observed evolutionary history of Li, using the Fe abundance as a reference parameter. In the subsequent sections we showed that numerical models with infall of nonenriched gas during the disk lifetime give good fits to the observations, the best fits coming from models where the infall has shown a tendency to increase (see Fig. 5). One consequence of this has been the nonmonotonic evolution of the metallicity with time: [Fe/H] has grown to somewhat greater than solar values, and then fallen back slowly. This circumstance yields metal-plots with a characteristic fold back close to solar metallicities. The Li production depends in fine detail, but not in principle or in broad trend on this form of the infall model.

Applying this general evolutionary scheme to Li production, we have introduced one novel assumption which proves capable of resolving the hitherto difficult to reproduce Li-Fe curve. This assumption is that the part of the GCR flux responsible for the production of $^7$Li and $^6$Li by the $\alpha + \alpha$ fusion process, the low-energy flux (at least), is emitted principally by intermediate-mass stars, an assumption well supported in the literature on GCR production (see, e.g., Meyer 1985, 1993, and references therein). The novelty which this introduces into the models is that the production rate of $^7$Li and $^6$Li is then constrained to follow not the SFR but the rate of net expulsion of gas from stars within a mass range whose upper limit becomes an independent variable in the modeling scheme. This assumption leads to the delayed production of Li in the models, in good agreement with the observations.

The concept of late-time production of Li is not, of course, newly introduced within the present model, even though its use with a GCR source here is original. Other mechanisms for producing Li associated predominantly with lower mass objects might in principle be able to satisfy the observational constraints of the Li-Fe envelope of Figure 1, and a number of these have been suggested. Sites which have been put forward as serious candidates for a major fraction of Galactic Li production include novae, neutron stars, stellar mass black holes, red giants, AGB stars, and carbon stars—all of which might satisfy the constraint of delaying the Li production with respect to that of Fe—and also processes in supernovae, which satisfy this condition with greater or lesser degree of difficulty. It is not possible to dismiss these sources, but the fact that they each fare some difficulty, theoretical or observational, tends to reinforce our view that a GCR source rather than stellar production of Li has in fact predominated.

Results of earlier work by Arnould & Norgaard (1975) on novae, followed by the more detailed study of Starrfield et al. (1978), have been more recently called into question by Boffin, Paulus, & Arnould (1993) using new reaction cross sections. The latter authors conclude that it is much more difficult to produce a significant quantity of Li in novae than previously predicted. A search for lithium in late-type companions of several dwarf and classical novae has not yielded detections (Martin et al. 1995).

Measurements of Li in the youngest stars, in some of whose atmospheres production has been postulated to occur, tend to yield abundances close to the “canonical” value for moderately young stars, of log $N$(Li) $\approx$ 3.2 or 3.3, and do not seem to show sufficient Li to be strong candidates for major Galactic production. Martin, Magazzu, & Rebolo (1992) showed that in some cool companions of hot...
(i.e., young) stars, where simple atmospheric model analysis could appear to show Li abundances of up to 3.7, a more careful non-LTE study yields upper values of 3.4, with most objects falling below this. Similar results have been obtained by Duncan (1991), by Magazzu et al. (1992), and by Martin et al. (1992) for T Tauri stars. Here again careful analysis reduced apparently very high values of the Li abundance in some objects to values well within the range of the normal young stellar population.

There do appear to be giants especially overabundant in Li, notably, a subset of the C stars (Abia et al. 1991) and a fraction of normal K giants (De la Reza & Da Silva 1993). Observations here are still few, and conclusions are made somewhat more difficult by the convective tendency of giants to deplete Li (this of course strengthens any argument in favor of such stars being Li sources if strong Li absorption lines are seen in their spectra). In the most extensive sets of observations of field giants, however, very few indeed have particularly strong Li abundances (Brown et al. 1989). Thus if certain types of giants are important Li producers, since they are few, and therefore need to be strong sources, while sparsely distributed, one might expect more scatter in Population I Li than is observed. Nevertheless, production in giants remains a possible source, and the main argument we offer against its being the main source can only be that the GCR model presented is able to account for the relevant observations without a major extra Li contribution.

Similar consideration may be given to the postulated importance of Li production in late-type companions to neutron stars and black hole candidates. In a paper on these objects by Martin et al. (1994), Li abundances ranging up to 3.3 for Cen X-4 are detected which might be increased if there is substantial overionization of Li i due to UV and X-ray flux coming from the compact object. These authors claim that since Li undergoes depletion by convection in late-type stars, the presence of relatively high Li abundances in these objects marks them as Li producers and therefore candidates for major enrichment of the Galactic disk. Here again, while we see no immediate argument which can rule out this possibility, one may doubt that there are sufficient such sources. Martin et al. (1994) put forward the idea that there may well have been more X-ray binaries, especially high-mass binaries, in the past, but the curve of Li as a function of Fe implies that the production mechanism should not be associated with high-mass objects. Nevertheless, we are not in a position here to claim that processes in X-ray binaries cannot be responsible for a significant part of Galactic Li production, only that these appears to be no requirement for this as a major source.

In all the analytical approximations based on proportionality of Li production rate to the gas expulsion rate by stars of low or intermediate masses (eqs. [12] and [14]) one can see considerable resemblance to the observed lithium growth profile in the zone of interest, that is, with metallicities [Fe/H] between $-1.0$ and $0.0$ (see Figs. 1 and 3).

We have used the $\alpha+\alpha$ process in the ISM as illustrative of processes which follow the behavior of stars of intermediate and low masses, those whose lifetimes are long and whose numbers in the disk have therefore grown cumulatively with time. Any process with equivalent time-dependent characteristics could, in general terms, satisfy this global observational constraint. Production of Li in flares of red giants (Cameron & Fowler 1971) or in novae (Arnould & Norgaard 1975; Starrfield et al. 1978) could also satisfy, in principle, the criterion of delayed production because there the rate of production would be proportional to the number of stars with intermediate masses at each time (cumulative because of their long lifetimes) and not to the gas expulsion rate. But as one can see in Figure 4, where we plot the results from numerical model in the case of GCR flux proportional to the cumulative number of stars with masses less than or equal to $1 M_\odot$ (increasing this limit yields a decreasing rate of accumulation of Li producers), the prediction, although not too bad, is by no means as good as that obtained using gas expulsion by stars of masses less than or equal to $3 M_\odot$, and is also in fact worse than that obtained using gas expulsion of stars with masses less than or equal to $2 M_\odot$ (see Fig. 4).

As far as mechanisms which depend on the presence of SNIe are concerned, two arguments appear to weaken their claims. One is that the Li-Fe envelope in Figure 1 is not linear, which would be the dependence if the Li were either produced directly by the impact of SNIe on their immediate surroundings or by processes involving GCRs in a wider volume of space, produced by SNIe. The other is that the locally measured GCR abundances favor an origin, for the lower energy particles at least, in the thermal equilibria pertaining in the atmospheres of stars of moderate mass, rather than in the extreme conditions of a supernova. However here again we argue in terms of probabilities rather than claiming that this mechanism is excluded.

Another possibility is the production of Li in compact objects such as neutron stars and black holes, but the time evolution of compact objects would be proportional to the gas expulsion rate from all stars (which is mainly that of SNIe + SNIIf). This production is shown in Figure 1 from numerical modeling, and one can see how this implies overabundance of Li with respect to the observational constraints; in fact, its tendency is not too different from that of those GCR models where the flux is proportional to the SFR.

Other possibilities for production of Li, such as in AGB stars or carbon stars (Matteucci et al. 1993, Romano 1999), are shown not to reproduce the observations really as well as the delayed models, as one can see, for example, in Figure 4.
7. CONCLUSIONS

We have surveyed mechanisms of Li production in the disk and confronted them with the upper envelope of the Li-Fe observations, which we have taken to represent the Li-Fe evolution curves in the absence of stellar depletion for the individual objects observed. As a result we can conclude the following:

1. Mechanisms relying on SNIIe to produce Li cannot be excluded in at least an approximate explanation of the observations. This is true for production within the SNe themselves but also holds for GCR fluxes originating in SNIIe.

2. Mechanisms whose time dependence is that of the SFR give either too much Li in the early disk or too little in the later disk.

3. Mechanisms which rely on SNIIe to produce the Li (again either in the immediate surroundings of the SNe or via a more generally dissipated GCR flux originating in SNIe) predict that the disk Li should grow proportionally to Fe, which does not appear to fit the observations.

4. An attempt to reproduce the results on the assumption that the contemporary maximum abundance, \( \log N(\text{Li}) \approx 3.4 \), is the true primordial abundance and that the Li-Fe envelope is a pure depletion curve also fails by a wide margin.

5. Mechanisms which produce an increase in disk Li significantly delayed with respect to that of Fe can explain the observations very well.

In this article we have explored one such mechanism: the production of Li via \( \alpha + \alpha \) fusion reaction in the ISM due to low-energy cosmic rays whose source of origin is the atmospheres of low- and intermediate-mass stars. This mechanism has the virtue that these stars have lifetimes comparable with that of the disk, so that their collective gas expulsion rate has accumulated progressively throughout the disk lifetime, leading automatically to a delay with respect to Fe in the Li production curve. We have explained that even if the acceleration of the GCRs is due to SNe envelopes, the product of injection rates and acceleration rates retains the delay implied by the observations (further work on acceleration mechanisms such as that due to stellar wind termination shocks is, however, well worth exploring in this context). Support for the possibility of this mechanism is provided by the observed similarity between the composition of GCRs and that of the solar corona which is biased according to the first ionization potential, and we note in this context the statement of Ellison et al. (1997) that “in the outer solar atmosphere the solar coronal gas, the solar wind, and the \( \sim \) MeV solar energetic particles have undoubtedly a composition biased according to FIP,” together with the fact that hydrogen and precisely helium are not well fitted by the alternative model of Meyer et al. (1997) and Ellison et al. (1997) based on volatility and mass to charge to explain the GCRs. These considerations permit an origin in an environment close to thermal equilibrium, that is, typical of stars of moderate mass. We have incorporated the mechanism in an evolutionary model of the disk previously demonstrated to be capable of accounting well for the Be and B versus Fe observations (Casuso & Beckman 1997), and which gives a particularly good account of the G-dwarf metallicity distribution in the solar neighborhood. The resulting Li-Fe plots include very fair fits to the observed Li-Fe envelope.

We have included in this scenario a natural mechanism of differential depletion (Casuso & Beckman 1999) operating within red supergiant envelopes, which can account for the observed D/H versus time and isotopic ratios of \( ^7\text{Li}/^6\text{Li} \) and \( ^{11}\text{B}/^{10}\text{B} \) versus time.

However we would not at this stage wish to rule out the possibility of another mechanism or mechanisms for disk lithium production. The observational weight of the stellar Li abundances, as we have shown, does place some strong constraints on Li production models. One of the clearest conclusions we can draw is that the “high” value, \( \log N(\text{Li}) \approx 3.4 \), for the primordial Li abundance can be quantitatively rejected using the Li-Fe observational constraint. The assignation of a value close to the “Spite plateau” (Spite & Spite 1982) value, \( \log N(\text{Li}) \approx 2.2 \), as primordial is thereby strengthened. In this context the comprehensive study by Thorburn (1994) of Li in halo stars, in which a contribution to the plateau produced by the \( \alpha + \alpha \) reaction due to the halo GCR flux is shown to account well for the observed scatter and slight rise in the Li abundance below \( [\text{Fe/H}] = -1.5 \), makes a suggestive link with the disk model tested in the present paper. The importance of the \( \alpha + \alpha \) process has almost certainly been previously underestimated in the disk, and the powerful constraint on evolutionary processes and models implied by the Li versus Fe observations has not been adequately taken into account; it is these aspects of the lithium puzzle which the present paper has been designed to expose.

We are happy to thank F. Spite for supplying his lithium abundance data compilation, and for helpful suggestions and E. L. Martin for useful discussions. The anonymous referee made a number of valuable suggestions which led to significant improvements in the paper. This research was supported in part by grant PB97-0219 of the Spanish DGICYT.
**Note added in proof.**—New observations of Li and $^{7}\text{Li}/^{6}\text{Li}$ in the ISM (toward $\alpha$ Per and $\zeta$ Per) by D. C. Knauth, S. R. Federman, D. L. Lambert, & P. Crane (Nature, in press [2000]) give a variation in the $^{7}\text{Li}/^{6}\text{Li}$ ratio (from near 2, which is expected for Li production from spallation or $\alpha + \alpha$ fusion reactions, to near 11, which is very similar to the solar value), together with very similar reported values for Li/H abundance (near $11 \times 10^{-10}$) for the two clouds (in contrast with the solar value of $20 \times 10^{-10}$). Also, the two clouds are near the star-forming region IC 348. All of these data agree very well with our picture of the production of light elements in the ISM via GCRs (Be, B) (Casuso & Beckman 1997) and via $\alpha$-particles of low energy (Li). We explained this variation (in fact, a falloff) via a model in which the envelopes of red supergiant stars (so, a star-forming region) deplete differentially $^{6}\text{Li}$ and $^{7}\text{Li}$ and via the increasing infall of nondepleted gas with time (Casuso & Beckman 1999). And also, we explained in the present article the decay of the Li/H abundance from solar to the ISM ratios due precisely to the depletion in star-forming regions in addition to the infall on nonenriched gas (see Fig. 4). So, we can explain these data without the problem inherent in the explanation by Knauth et al., which suggests the differential production of Li in the $\alpha$ Per direction and in the $\zeta$ Per direction because of the higher flux of cosmic rays in the $\alpha$ Per direction, while observations point to almost the same total Li/H abundance.