GALACTIC EVOLUTION AND THE FORMATION OF THE LIGHT ELEMENTS*

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ABSTRACT
Evolution of the abundances of the light elements (H ≤ 11) is considered in the framework of current theories concerning their origin and alternative models for galactic evolution in the solar neighborhood. Results most consistent with observed abundances are obtained using galactic models in which most of the interstellar gas is processed through stars at early times, and in which there is an inflow of extragalactic gas at a rate comparable to the present stellar birthrate. These features are valuable in accounting, in particular, for the relative abundances of Be and Li, the possible dependence of Be abundance on stellar age, and the solar-system D abundance.

In the framework of evolutionary models, D and He may be produced either in the big bang or, less probably, during galactic evolution. The relative solar-system abundances of Li, Be, B, and H are readily accounted for by radiation of the interstellar gas by galactic cosmic rays, while most of the Li might be produced by supersolar particles (≈10 MeV per nucleon) either in supernova envelopes or in their vicinity. The effects of intrinsic uncertainties on these conclusions are studied, including the rate of destruction of the light elements in stellar envelopes, and the cosmic abundance of boron.

Subject headings: abundances — interstellar matter — nucleosynthesis — stellar evolution

I. INTRODUCTION

Chemical evolution of galaxies currently receives much attention because of its relevance to many fields of astrophysics, including nucleosynthesis in various stages of stellar evolution, star formation, ages of galaxies, and the very early history of the Universe. The unique nuclear properties of the light elements (H ≤ 11) make them particularly interesting, as shown by recent studies of the evolution of their abundances on a galactic scale by Truran and Cameron (1971; referred to as TC), Miller (1972), and Reeves et al. (1971; referred to as RAEF). The purpose of this paper is to reconsider these elements in the light of recent theories regarding their synthesis, new observational data, and various models for galactic evolution. This investigation has been motivated in particular by the recent data on deuterium and boron. These are reviewed briefly in § II, together with new hypotheses on the formation of the light elements to which they have led.

In order to explain the chemical composition of the solar system and its neighborhood, one needs an evolutionary model describing the history of the interstellar gas and of stellar births and deaths, in those parts of the Galaxy where the local material has been mixed. It will be seen below that particular relevance to the production and destruction of the light elements are the supernova rate, the mass and “metal” (≤ 12) content of the interstellar gas, and the extent of asestra (the processing of matter through stars). Two evolutionary models, chosen because of their contrasted properties, are considered in this paper, and are described in § III. With the help of these models, it is possible to show both the model-dependence of our results, and the usefulness of the light elements as a probe of the past history of the solar neighborhood.

Alternative sets of production and destruction rates for the light elements, suggested by the various theories reviewed in § II, are considered, and they are presented in § IV. The resulting evolutionary abundance curves (EAC) are presented and compared with observations in § V. Section VI is a summary of the results and conclusions.

As usual in this field, the large number of tentative input theories and free parameters prevents us from defining a unique model for galactic evolution and formation of the light elements. However, we are able to show which sets of hypotheses are mutually consistent at the present stage of the art.

II. REVIEW OF ABUNDANCE MODELS AND CURRENT THEORIES FOR THE ORIGIN OF THE LIGHT ELEMENTS

A detailed review of the knowledge of the abundances of the light elements up to mid-1972, as well as the current hypotheses to explain them, has been made
by RA5. The relevant observational data on $^3$He, Li, and Be can be found in this work. But since that date important new results have become available for D and H.

Deuteronium has been searched for this past year in various locations of the interstellar medium (1) in the direction of the galactic center, Cesarsky, Moffett, and Pasachoff (1978) propose $5 \times 10^{-8} < D/H < 5 \times 10^{-5}$ as an upper limit, $2 \times 10$ times the value of the time of formation of the solar system derived by Geiss and Reeves (1972) and by Trauger et al. (1973); in the direction of the Orion Nebula, Jeffries, Penzias, and Wilson (1973) found D/HCN $\approx 1/10$, while Cesarsky (1973) found D/H $< 10^{-8}$ in the same direction.

From these measurements in the direction of the Orion Nebula, it is clear that there is some chemical fractionation between the molecular ratios as D/HCN and the atomic ratio D/H. This has been discussed theoretically by Solomon and Voigt (1973), who claim that the molecular ratio in the Orion Nebula can correspond to D/H $\approx 10^{-7}$-10^{-8}. Similarly, Watson (1973) suggests that the interstellar HD molecule is more dissociated than H$_2$ by stellar ultraviolet radiation, and he argues that if current measurements are compatible with D/H $\approx 10^{-8}$ in the interstellar gas. (3) Results from the Copernicus satel- lite (Spitzer et al. 1973) give an abundance ratio HD/H$_2$ $\approx 10^{-8}$ in front of several stars, which they argue should be corrected to HD/H$_2$ $\approx 5 \times 10^{-9}$ to allow for different shielding of the two molecules. Most recently, Roberson and York (1973) have determined D/H = (1.4 $\pm$ 0.5) x 10^{-9} from observations of the Lyman lines in front of a 700A. This direct determination of D/H was confirmed by independent studies by Rogers and Reeves (1972), D/H = (2.5 $\pm$ 1) x 10^{-9}.

The present situation regarding boron is the following. (1) Cameron, Colgate, and Goswami (1973) made the first observation of boron in the solar system. They make the assumption that the carbonaceous condensates constitute the material which has the more primitive chemical composition. Boron has a relatively high abundance in these meteorites (see e.g., Urey 1972). For instance, Saffo-Rico and Wänke (1968) found B/H $\approx 3 \times 10^{-9}$ in type II carbonaceous chondrites. Cameron et al. (1973) take into account the fractionation pattern, for various volatile elements, between the different types of carbonaceous chondrites and the relative volatility of boron, in order to propose B/H $\approx 10^{-9}$. (2) On the other hand, the first accurate determinations of the interstellar medium (in front of a few Per). This upper limit is at least 5 times below the solar-system abundances proposed by Cameron et al. (1973), but it is compatible with the predictions for boron, B/H $< 6 \times 10^{-10}$ (Grevesse 1969; Engvold 1970), and with the value in ordinary chondrites, B/H = (2-5) x 10^{-10}. Moreover, for another volatile element, mercury, which presents a similar chemical fractionation pattern in the Sun and solar system to boron, a low abundance is adopted in agreement with the solar upper limit and the ordinary chondrites. For all these reasons, ALR supports again the low ratio B/H $\approx 5 \times 10^{-10}$ (within a factor 2), as previously noted by Cameron (1968). The new results (Cameron 1974) for interstellar boron yield B/H $< 10^{-10}$, which, if confirmed, is at least 2.5 times lower than the abundance in meteorites. This would suggest that B has been fractionated, lending support to the arguments of Cameron et al. (1973).

Possible theories for the origin of the light elements are summarized in Table 1. The choice depends on the adopted abundances of D and B. RA5, using the D abundance of Geiss and Reeves (1972), favored a big-bang origin for D and H, requiring a present mean universal density as low as $(2 \pm 1) \times 10^{-27} \text{ g cm}^{-3}$ (Wageto 1973). To account for the possible much larger abundance suggested by the interstellar molecules, Colgate (1973) and Hoyle and Fowler (1973) have suggested that this element may be formed in shock waves in supernovae and in supernovae stars, respectively. $^6$Li is produced as a by-product of D destruction in stellar envelopes, by Dp, $^3$He. It may also be produced significantly in the envelopes of red giant stars, since the abundance of $^6$Li can be as large as $10^{-10}$ in stars which generate $^7$Li by the Cameron-Fowler (1971) mechanism (see e.g., Sak- munna, Smith, and Despain 1974). Since the present interstellar abundances of D and $^6$Li are still compatible with a universal density a few times that deduced from the visible galaxies, we have no compelling reason to abandon the big-bang origin for them. In what follows, we consider both galactic and big-bang production.

In their discussion of the other light elements, RA5 attributed $^6$Li, $^7$Be, and $^7$B to galactic cosmic rays (GCR) impinging on the interstellar gas, following the analysis of Cameron and Heil (1972) and Cameron et al. (1971) referred to as MAR. RA5 took the cosmic B abundance to be $(3-10) \times 10^{-12}$, compatible with the small but not the larger estimate discussed above.

For $^6$Li, the situation is not clear. This element is, however, produced by the GCR process (MAR, Miller 1972), but it might be synthesized sufficiently in the big bang if the lepton number is not zero (Reeves 1972), and to some extent in red giants (Cameron and Fowler 1971; Stockmann et al. 1973; Scalo and Ulrich 1973). Finally, $^7$Li cannot be produced in large amounts (in such a way that the ratio $^7$Li/$^6$Li $> 10$, as observed) by particles with suprathermal energies, $\sim 10$ MeV per nucleon. These particles might constitute the low-energy part of the Galactic cosmic-ray spectrum, or they might be produced in the envelopes of supernovae, which are likely sources of Galactic cosmic rays. This possible source of $^7$Li has been noticed by Audouze and Traut (1973), Jacob et al. (1974), and Mazo- guzzi and Reeves (1974). The preliminary calculations of Audouze and Traut, used here, show that these particles (protons or α-particles) are accelerated.
according to their energy per nucleon, the large production of $^{12}\text{C}$ is not accompanied by significant production of boron; this case may satisfy the lower B abundance discussed above, as we shall see later. However, if the particles are accelerated according to their total energy, much more (up to B/Li ~ 5) is made with the $^{12}\text{C}$; this case satisfies the larger B abundance discussed above.

While preferring the lower abundance for the reasons given previously (see ALR), we consider both possibilities in the context of galactic evolution.

Another possibility which we investigate briefly is that there was a greater abundance, say B/H > $3 \times 10^{-8}$ (as suggested by the carbonaceous chondrites), at the time of formation of the solar system than in the present interstellar medium (B/H < $2 \times 10^{-8}$).

III. MODELS FOR GALACTIC EVOLUTION

Models for chemical evolution in the Galaxy generally follow the approach developed by Schmidt (1959, 1963). A brief review in the context of light element formation is given by Timler (1971). Here we study specifically the evolution of the pool of matter from which the solar system formed during the time (about 6 x 10^6 years) before condensation of the solar nebula, and subsequent evolution of the neighboring stars and interstellar gas. The present environment of the Sun does not exactly represent this material because of orbital motions (during which the gas density, rate of star formation, etc. vary because of spiral structure) and the acceleration of stars out of the galactic plane. Therefore, this study of chemical evolution applies to a region extended out of the plane and in an orbit around the galactic center. This region looks like a cylindrical shell-shaped volume which can be called our "nucleogenic pool".

Chemical evolution in this pool can be studied numerically in terms of a model that specifies the stellar birthrate (as a function of time and stellar mass), the rate at which each chemical element of interest is produced and/or destroyed in each star or in the interstellar medium, and the lifetime and remnant mass of each star. These parameters define the evolution of abundances of elements in the interstellar gas, and the composition of stars as a function of their birth epoch. They have often been used in comparison with data on stellar abundances, for elements with A > 12, to set constraints on evolutionary models (e.g., Schmidt 1963; Quirk and Timler 1973 referred to as QT; Talbot and Annett 1973; Biermann and Timler 1974). The light elements will be used here to derive further constraints, which are somewhat independent of those previously defined since rather than being produced in stars, the light elements are mainly destroyed there by exotic reactions, and made in the interstellar medium.

The method used for computing the abundances is the following. The model is evolved in time steps of 10^7 to 10^8 years, chosen to give small abundance changes in each interval, and in terms of a discrete set of stellar masses. Masses are in solar units in the following, unless otherwise stated. The mass of light element L in the interstellar gas at time t is denoted mL(t), and its fractional mass abundance in the gas is denoted $X_L(t)$, so that mL(t) = $X_L(t)$$m_L(t)$, where $m_L$ is the mass of interstellar gas. The change of mass of the element L in the time interval (t - 1, t) can be written

$$m_L(t) - m_L(t - 1) = \phi_X(t) + X_L\psi(t) - X_L(t - 1) \sum_X m_X\phi_X(t) + \sum_i m_L(m_i)\epsilon_L(m_i - m_L)$$

$$\phi_X(t) = \int_{-1}^{t} X_L(t - \tau)\phi_X(t)\phi_X(t)\phi_X(t)$$

The terms on the right-hand side of this expression will now be discussed. They refer, respectively, to production, infall of extragalactic gas, depletion by stellar births, and gain by mass loss from dying stars.

The term $X_L\phi_X(t)$ refers to the addition of element L with primary abundance $X_L$ due to infall of extragalactic gas occurring at a rate $\phi_X(t)$ per unit time. The quantity $X_L(t)$ is the number of stars of mass m in the time interval (t - 1, t). Since $X_L(t)$ changes little in this interval, $X_L(t - 1)$ represents accurately enough the abundance of element L entering the stars born in the interval. The lifetime (up to the ejection of its envelope matter into the interstellar gas) of a star of mass m is denoted $\tau(m)$, so $\phi_X(t) = \int_{-1}^{t} X_L(t - \tau)\phi_X(t)\phi_X(t)\phi_X(t)$ represents the number of stars dying during the interval (t - 1, t), and $\epsilon_L(m_i) - m_L$ is the original abundance of element L inside these stars. The fraction of the mass of a star of mass m in which element L is not destroyed is denoted $\epsilon_L(m)$.
equation (1) gives the mass of element F which has not been destroyed during the stellar lifetime and which returns to the gas during time interval \((t - 1, t)\) through stellar mass loss.

The production term \(g(t)\) can be written

\[
q(t) = a(0)Q(t),
\]

where \(a(0)\) is the present time, \(Q(t)\) is the present production rate of the element in solar masses per unit time, and \(Q(t)\) is the rate of the element depends on the production process. Three expression of interest:

1) If the element is produced in supernova envelopes, production varies with the supernova rate, \(r_{SN}\):

\[
Q_{SN}(t) = r_{SN}a(0)Q(t).
\]

The rate \(r_{SN}\) is the death rate of stars in the mass range producing supernovae, so it depends both on the galactic model and on the uncertain stellar mass range. Here we assume that supernovae are produced by massive stars, with lifetimes \(\approx 10^5\) years; there is indeed some empirical evidence for this hypothesis (Moore 1973). If in fact they are produced by stars with lifetimes \(\approx 10^6\) years, the results will be affected only in very early times, less than \(10^5\) years, where there is no way of comparing them with observational data, so this uncertainty is not important. (The evolutionary models refer only to the disk population in the solar neighborhood and not to the Population II component.)

2) If the element is produced by spallation of interstellar heavy elements by cosmic-ray protons and \(\alpha\)-particles, the rate varies according to

\[
Q_{CR}(t) = r_{CR}(t)\rho(t)X(E_{CMB})Z(Z_{H}(t)Z(k))\rho(k),
\]

where \(Z_{H}\) is the heavy-element (\(Z \geq 12\) abundance) of the gas. Here we assume that the rate of production of cosmic rays varies as the supernova rate and that their composition does not depend on time. It is also assumed that the relative abundance of the heavy (\(Z \geq 12\)) elements with respect to each other do not change enough to alter significantly the proportionality of the total production to \(Z_{H}\).

3) If the element is produced by spallation of interstellar hydrogen and helium by cosmic-ray particles with \(\leq 12\), the rate varies according to

\[
Q_{CR}(t) = r_{CR}(t)\rho(t)X(E_{CMB})Z(Z_{H}(t)Z(k))\rho(k).
\]

Here the same assumptions are made about cosmic-ray production and composition; the further assumption is that the interstellar H and He abundance \((X + Y)\) change negligibly. All these assumptions are supported by rather good theoretical and/or empirical evidence (see, for instance, the studies of chemical evolution by Truran and Cameron 1971 and Talbot and Arnett 1973a, b).

Cases (2) and (3) apply to production by GCR whatever the energy of the GCR particles (suprathermal or high-energy particles). For instance, an alternative to case (1) is to assume that the reactions of the suprathermal particles occur in the interstellar medium near the supernovae rather than in their envelopes.

Generally, production of a given element will involve simultaneously more than one of these processes. When there is no inflating abundance, one can simply add the contributions to \(Q(t)\) from each process. (This is because if \(X_{CMB} = 0\), every term in eq. (1) except \(g(t)\) is linearly dependent on \(X_{CMB}\), with coefficients that depend on the galactic model but not on the light elements.) Here we have considered processes (2) and (3) for the interstellar component, using simply

\[
Q_{CR}(t) = 0.7Q(t) + 0.3Q_{SN}(t),
\]

in agreement with an estimate from MAR that about 70 percent of GCR production is due to process (2) and 30 percent to (3). By trying other such linear combinations, we have shown that if we were to introduce properly the effects of evolution of interstellar abundances on the cross-section, the computed \(X(t)\) would be affected only in the first few billion years. Thus, no error is introduced that affects comparison with available observations, but our results should not be relied upon too much at times less than \(3 \times 10^9\) years.

In studies of evolution of the solar neighborhood, such as those cited at the beginning of this section, it should be recognized that there are so many uncertain hypotheses and free parameters that the construction of models is essentially a game in which the player can rather freely choose those rules which lead to success. However, the outcome of such games is the extraction of certain sets of hypotheses and parameters consistent with the data studied.

To illustrate the effects of uncertainties in galactic evolution theories on the light elements, we consider two models which are internally consistent, but have useful contrived properties: these are the "consistent" model of TC (referred to as model TC), and the "full" model of QT (referred to as model QT). Model behavior is determined to a large extent by the time-dependence of the stellar birthrate, which is given by either extreme and opposite functions. In these models: consider the family of models in which the birthrate varies as some power of the gas mass, say \(n^x\). The gas mass, at present, support a rate, and other quantities in models with \(x = 1\) behave very similarly to those in model TC, on the other hand, models with \(x \approx 1.5\) behave very like model QT. Thus, two models exist here can be used to discuss the dependence of the light elements on galactic evolution in rather general terms. For example, the model considered by Birnboim and Tinsley (1974) has \(n = 1.5\), and behaves similarly to model QT, so the present results on the light elements for model QT apply qualitatively to that model also. Generalization of the present results to other consistent models for chemical evolution will be discussed in a forthcoming paper (Tinsley 1974).

The characteristic features of models QT and TC are the following.
Model QT has initially very efficient star formation so that the gas content is reduced to its present value in \(10^8\) years. After that, the gas fraction is maintained at a constant value by requiring stars to form at the rate needed to compensate for stellar mass loss and mass inflow. Infall of extragalactic gas is included, as suggested by Fowler (1972) and Larson (1972). It has primordial composition, and enters at a rate of 2 per cent of the total mass per \(10^7\) years, which is consistent with Oort's (1970) analysis of the high-velocity clouds. Since other interpretations of the high-velocity clouds are possible (cf. Veilleux 1973; Hulsbooch and Oort 1973; Davis 1972), the rate of infall is rather uncertain. Further chemical evidence on infall has been cited by Fransson (1972).

In model TC, an exponential decrease of the birthrate is assumed with a time constant chosen to give the present gas content. There is no infall. An important feature of this model is a galactic burst of very massive stars, enriching the gas to almost its present metal content before the birth of galactic stars. Subsequently, little further contamination occurs, because TC assumes that stars more massive than \(8 M_\odot\) leave black-hole remnants large enough to swallow their enriched cores.

Figure 1 shows the evolution in both models of quantities of importance for light-element synthesis. The gas content has been discussed above. The supernova rate, defined as for equation (3), is nearly proportional to the stellar birthrate so it illustrates this rate also. The metal (\(A \geq 12\)) content of the gas, \(Z_g\), level off then fall in model QT because the infalling metal-free gas dilutes the continuous stellar output, which is computed according to the code in Tinsley (1972; cf. Tielbo and Arnett 1975a). In TC, the metal content does not increase, because of the formation of black holes. TC in their paper show a slow increase of \(Z_g\) during the galactic lifetime, which is not apparent in figure 1 because its \(Tinsley's\) (1972) code starts with massiv less than \(9 M_\odot\) producing no metal whereas in TC they produce a little. This discrepancy between the original TC model and our version affects the light elements completely negligibly.

Both of these models are homogeneous, meaning that the content of the "solar neighborhood" (the solar neighborhood) has been implicitly averaged in space around a galactic orbit and smoothed over corresponding time intervals. This simplification is somewhat unrealistic, although Reeves (1972b) finds that the occurrence of inhomogeneities due to the discrete- ness of supernova events in very small. Scobel (1972) and Tanbun and Arnett (1973b) have shown that the distribution of metal abundance among the stars may be greatly affected by inhomogeneities, but we do not believe that the evolution of the light-element abundances would be seriously altered.

IV. INPUT PRODUCTION AND DESTRUCTION RATES
a) Deuterium and Helium 3

We first consider whether these elements are mainly produced in the big bang, according to the calculations of Wagoner (1973). The choice of big-bang parameters (the entropy per baryon, \(s/F\)), where \(s\) is the mean present density of the universe and \(F\) is the background radiation temperature) is made by requiring that the computed solar-system D abundance will agree with the value of Griss and Reeves (1972). Since each star probably destroys its D entirely (TC, RAOS), the fraction of primordial D entering the solar system is the fraction of gas at time \(\approx 6 \times 10^8\) years (Fowler 1972) which has not been averted. In model QT, most of the matter is averted in the first \(10^6\) years, but the averted fraction declines because of the infall of unenriched gas. In model TC, the averted fraction rises steadily. In both models, the fraction is \(\approx 0.8\) at \(6 \times 10^8\) years, \(\approx 0.4\) of the primordial D remains. The required big-bang abundance, 1.4 times the Griss and Reeves value, arises. If \(\rho = 1.4 \times 10^{-18} \text{ g cm}^{-3}\), a possible value (§ II).

![Figure 1. Evolution of the gas fraction (m/m_0), interstellar metal abundance (Z_g), and supernova rate (s) in the two models for galactic evolution, QT and TC.](image-url)
He and Li also have appreciable big bang abundances in this case. In model QT, the values are $X_{\text{He}} = 1.0 \times 10^{-5}$, $X_{\text{Li}} = 2.4 \times 10^{-5}$, $X_{\text{Be}} = 2.5 \times 10^{-5}$; in model TC they are slightly different (cf. table 3).

We consider as an alternative the possibility that D is produced in supernova envelopes, adopting the estimates of Colgate (1973). We assume that $10^{14}$ atoms of D are produced in each supernova and that other sources are negligible; this would be true of the big-bang contribution if the universal density were only several times greater than the above value. In this case, He is a by-product of the burning of D (from supersnovi) in stellar envelopes. At present, we recall that Reeves (1973) argues that energy limitations must restrict the production of D in supernova envelopes to ~1 percent of Colgate's value, so this process may in fact contribute negligibly to the galactic abundance.

The production of D by supernovae stars has not been considered explicitly, since there is no way to specify any difference from the case of supernova production.

He is also a normal product of stellar hydrogen burning (e.g., Bethe 1967). In the following calculations we neglect this possible source of He for two reasons: (1) Previous studies (TC; RAAS, Talbot and Arnett 1973) have shown that the observed abundance can be explained in terms of He from the big bang and from D-burning in stellar envelopes; if D abundance (from whatever source) is constrained to agree with that observed, these sources alone tend to overproduce He. (2) The amount of He ejected after stellar production is extremely uncertain. Possible effects on our conclusions of neglecting this source of He will be discussed in $\S$ VIII and VI.

b) The Quinet $\text{Li, Li', Be, } B$, $\text{B'}$ $\text{B''}$

The several alternatives are summarized in used arguments in table 2, which gives the production rates at the present time, $p$, in atoms per second per gram of interstellar matter with cosmic compositions. These rates $p$ are related to the quantities $q(x,y)$ defined in $\S$ III by

$$q(x,y) = 3.17 \times 10^{15} \text{ cm}^3 \text{ atom}^{-1} \text{ sec}^{-1} \text{ g}^{-1} \text{ yr}^{-1},$$

where $x$ is the atomic weight of the element, $y$ is the mass of the hydrogen atom in grams, and the present gas content $m_{\text{gas}}(x,y)$ is in solar units. The different $s$ correspond to different assumptions for the process producing each element, as follows.

1) MAR-1. These rates are taken from MAR in the case where the "quinet" is assorted to be produced by galactic cosmic rays (GCR) impinging on the interstellar medium, and the GCR spectrum varies as $W^{-2.5}$, where $W$ is the total energy of the cosmic-ray particles. These rates are very close to those derived by Miler (1972) in his study of the GCR products.

2) MAR-2. These rates are derived from model C of MAR (cf. their table 3), in which they assume the existence of an intense low-energy flux of cosmic rays (below a few eV of MeV), specifed in such a way as to account for the large abundance of $\text{Li (Li')}$ $10^{-5}$. This flux would lead to some heating of the interstellar medium, so future observations of interstellar ion ratios by the Copernicus satellite may provide a test of whether such cosmic rays exist (Rogers et al. 1973). It will be found that although MAR-2 has an advantage over MAR-1 in accounting for the ratio $10^{-5}$, both of these cases lead to $10^{-5}$ whereas the observed isotope ratio is $\approx 10^{-10}$.

3) AT-1. Three rates and the following include the calculations of Audouze and Truran (1973) of light-element production by superthermal protons and $\alpha$-particles in low-energy cosmic rays or possibly in or near supernova envelopes; these alternative production sites will be considered in each case, since they lead to different time-dependences of the production rate (cf. the above discussion of eqs. 3-6). For AT-1, we select the case where there is a large flux of low-energy protons and 10-MeV proton-nucleon $\alpha$-particles. In this case, Li is the only member of the quinet produced significantly by superthermal particles. To account for the others (assuming B/H has the low value preferred by ALM), the contribution from GCR given by MAR-1 is added. We are free to normalize superthermal components of Li and Be (but not B) to the supernova, in way consistent with the energy requirement, discussed by Audouze and Truran (1973). In this case the normalization relative to the GCR component is chosen so that $\text{Li'/Li} = 10$.

4) AT-2. This case is supposed to account for the somewhat unlikely possibility that B/H $\approx 10^{-5}$. To produce this amount of boron along with the necessary Li, we select the case where there is a large flux of superthermal protons and $\alpha$-particles with 15-30 MeV (in total energy). The contribution given by MAR-1 is added, to account only for Li and Be.

5) AT-3. Finally, we consider the possibility that the actual B abundance is $B/H \sim 2 \times 10^{-12}$, the upper limit determined from the Copernicus interstellar data by ALM. The production rates in this case are a combination of MAR-1 and superthermal contributions which is 0.12 times that of AT-2.

c) Destruction of the Light Elements in Stellar Envelopes

The light elements are expected to be destroyed in stellar envelopes by thermonuclear reactions, at rates which increase in the order $\text{He, Be, Li, D}$. The
extent of destruction in a star of given mass at the end of its life is very uncertain because of the uncertain degree of envelope mixing, but we use the values given by TC as a reasonable estimate. Deutrium, 4Li, and 7Li are assumed to be totally destroyed before ejection from any star. For 4He, TC's prescription is: for masses $M > 25 M_\odot$, he is completely destroyed; for masses $10 M_\odot < M < 25 M_\odot$, he survives only in the outer 10 percent by mass of the star; for masses $3 M_\odot < M < 10 M_\odot$, he survives only in the outer 25 percent by mass of the star; for masses $M < 3 M_\odot$, he survives in the entire outer envelope structure above the hydrogen burning shell. This prescription will be referred to here as the "standard" surviving fractions; to test other possibilities, we simply scale the surviving fractions for each star relative to this "standard" set of parameters. For Be and B, we consider surviving fractions between 0 and 1 times the standard fractions. These prescriptions determine the parameters $f(m)$ to be used in equation (1).

V. RESULTS

Relative abundances by mass, $X_j(m)$, are given in tables 3 and 4, along with the solar-system abundances adopted (Geiss and Reeves 1972; Cameron 1973; ALR) and estimated uncertainties. The results for each element will now be discussed in turn, and used to derive constraints on viable consistent theories.

a) Deuterium

Evolutionary abundance curves (EACs) are shown in the case where D is produced only in the big bang, in models QT and TC, in figures 2a and 2b, respectively. In model QT, D is initially transformed rapidly into $^3$He during the first 10 years when there is intense star formation, but later it is restored by the infalling gas. In model TC, there is simply a gradual destruction by astration. The big-bang parameters have been chosen to get agreement with solar-system abundances (1.0%). The inflow of D in model QT results in a slight increase in interstellar D/H between the time the solar system formed and now; this result may in the future provide a test of the initial hypothesis.

At present, the observations are still too uncertain to allow this test to be made.

In the case where D is produced only by supernova, EACs are shown in figures 2c and 2d; the production rate chosen is $10^{16}$ D atoms per supernova, while if other rates were chosen the resulting abundances would simply be proportional to the production rates. The D abundance derived at the time of formation of the solar system ($\approx 10^9$ years) agrees well with the empirical value in model TC. It is about 4 times too low in model QT, but it would not be inconsistent with Colgate's (1973) estimates to suggest that production occurs at four times the chosen rate. However, it as suggested by Reeves (1972) the production rate has to be revised down by a factor greater than 100; this process could not account for the observed abundance.

The conclusion for D is that evolutionary models cannot distinguish between big-bang and supernova production; nor can a model with a great deal of aastration be ruled out if there is infalling gas with sufficient big-bang D.

b) Helium 3

Figures 2e and 2f show the EACs in the case where $^3$He is produced in the big bang and in the D-burning zones of stellar envelopes ($\approx 10^8$), and with standard fractions surviving in these envelopes ($\approx 10^8$). In model QT, $^3$He is at first enriched by D burning, but is then depleted by aastration and the infall of gas with less $^4$He. In model TC, in which aastration is less

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>BIG-BANG ABUNDANCE</th>
<th>OTHER PRODUCTION</th>
<th>SURVIVAL</th>
<th>GALACTIC MODEL</th>
<th>TIME (10^9 yr)</th>
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<tbody>
<tr>
<td>D</td>
<td>1.0 (-4)</td>
<td>D burning</td>
<td>0</td>
<td>QT 1.7(-2)</td>
<td>3.6(-2) 5.2(-2)</td>
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<tr>
<td>H³</td>
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<td>4.6(-3) 3.6(-3)</td>
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<td>0.5</td>
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<td>4.6(-3) 3.6(-3)</td>
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<td>D</td>
<td></td>
<td></td>
<td></td>
<td>QT 2.4(-2)</td>
<td>4.0(-2) 3.5(-2)</td>
</tr>
<tr>
<td>H³</td>
<td>6.0(-7)</td>
<td></td>
<td></td>
<td>QT 2.4(-3)</td>
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<tr>
<td>He³</td>
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<td></td>
<td></td>
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<td>4.0(-4) 3.5(-4)</td>
</tr>
<tr>
<td>D</td>
<td>8.5 (-5)</td>
<td></td>
<td></td>
<td>TC 7.5(-5)</td>
<td>3.5(-5) 2.3(-5)</td>
</tr>
<tr>
<td>H³</td>
<td>1.2(-5)</td>
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<td>TC 2.5(-5)</td>
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<tr>
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<td>TC 2.8(-5)</td>
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<tr>
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<td>H³</td>
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<td></td>
<td>TC 1.4(-5)</td>
<td>2.8(-5) 3.7(-5)</td>
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</tbody>
</table>

* Adopted solar-system abundances: $X_0 = 3.5 \pm 0.5(10^{-5})$, $X_0 = 2.0 \pm 0.5(10^{-5})$.
1 Fraction of stellar envelopes in which the element is not destroyed during aastration, normalized to unity for the fractions given by TC for $^4$He.
<table>
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<tr>
<th>Element and Solar-System Abundance</th>
<th>Production</th>
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<th>Model TC, Time (y)</th>
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<td>SURVIVAL</td>
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<td>AT-3 (SN and IS)</td>
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</tr>
<tr>
<td>⁵⁴Mn: 5.0±5.0, -2.79(-9)</td>
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<td>AT-3 (IS)</td>
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</table>

* After each solar-system abundance is given the power of 10 multiplying all values in the table for that element.

* SN refers to the case where the superthermal particles react in the Kuiperova envelopes, and IS refers to the case where the superthermal component is produced in the interstellar medium near the Sun's corona.

I Fraction of each stellar envelope in which the element is not destroyed by accretion, normalized to unity for the fractions given by TC for *8He.
important, the abundance increases steadily by D burning.

It is seen that in both models most straight-
forward assumptions for synthesis and destruction
lead to 3-5 times the solar-system abundance. To test
the effects of uncertainties in the destruction rate,
we have tried cases where He survives in less than the
standard fractions of stellar envelopes. Table 3 gives
the results for 0.5 times the standard fractions: the
abundance now 6 x 10^7 years is still about twice too
large in model QT; but it agrees within the uncertain-
ties in model TC. Best agreement in both models is
obtained with survival up to 2 times the standard frac-
tions, but the results for B and C below suggest that
He is unlikely to be destroyed to that extent. Con-
sidering the uncertainties in the abundances of D and
He, it is possible to adjust the big-bang production so
that D is near its lower limit and He near its upper
limit, even with standard survival, so this discrepancy
may not be important. (Analytical approximations
[Tinsley 1974] suggest that the discrepancy would be
resolved if we adopted the interstellar D/H of Roger-
son and York [1973], which was published after the
present calculations were completed.) Because of the
uncertainties in D/H and He/H, evolutionary studies
cannot be used to determine the destruction rate
of He in stellar envelopes.

Independently of these uncertainties, we can con-
clude that if D is produced in the big-bang, and He in
corresponding proportions there and later by D burn-
ing in stars, any contribution to the galactic He from
production in red giants must be minor.

If D is produced in supernovae as discussed in
[3a] above, substantial He abundance may result
from burning of that D. Figures 2c and 2d show the
EACs derived in the case where that is the only
source of He, and for a standard survival. In model
TC, the resulting abundance agrees well with the
solar-system value, as does that of D in the same case,
showing that Colgate's estimates are compatible with
both the D and He abundances in an evolutionary
model without very much astraion.

However, in model QT, too much He is produced,
as a direct result of the large degree of astraion which
led to too little D. If the production rate of D is
assumed to be ~4 times greater, the discrepancy with
He is ever worse. A significant reduction of the He
abundance would require that very much less He
survives astraion than the amount estimated by TC.
The supernova origin for D, and subsequently He,
thus has more difficulties in the context of an evolu-
tionary model in which a large fraction of the matter
is astraion early in time.

c) Lithium 6

This element is produced almost entirely by the GCR
impinging on the interstellar gas; there is an
appreciable superthermal contribution only in case
AT-2. Figure 3 shows the EACs in a typical case,
AT-1. In model QT, the abundance rises rapidly at
first because of the high supernova rate and gas mass,
but then falls because of the total destruction of Li by
astraion; the hill is more drastic than for D, be-
cause there is no H in the medium. In model TC,
both the initial rise and the loss through astraion are
less. The resulting overabundance in QT and under-
abundance in TC are probably not outside the range of
uncertainty in the solar-system value.

FIG. 2.—EACs of D and He. In all cases, no D survives
astraion, and the standard fractions of He survive. (a) Both
elements are produced in the big bang, and He also by D-
burning in stellar envelopes. Model QT. (b) As (a), model TC—
He only in stellar envelopes during burning of the D. Model
QT. (c) As for (b), model TC. Big-bang abundances were
chosen to reproduce D/H. He production would be less ex-
sive if the correct D abundance is smaller or if more He is
destroyed by astraion.

FIG. 3.—EACs of Li for each evolutionary model QT and
TC. Production is by GCR, according to AT-1, and no He
survives astraion. The solar-system abundance is shown at an
indicative time of 6 x 10^7 years.
Abundances produced in the other cases are given in table 4. Here, and for the other elements, separate values are shown for the alternative sites of superthermal production: "SN" if it occurs in the supernova envelopes, and "IS" if it occurs in the interstellar medium. Similar results are obtained in cases MAR-1, AT-1, AT-2, and AT-3, MAR-2 produces rather more \(^{44}\)Ti, which is clearly too much in a model with as little astration as.

b. Lithium 7

The origin of this element is less certain than that of \(^{44}\)Ti (§ II), but we explore here the possibility that \(^{6}\)Li is produced by processes similar to those for the other members of the quintet. Table 4 gives results for each production case and model. If a big-bang abundance is included at the level consistent with D and \(^{40}\)He in a universe with zero baryon number (Wagoner 1973), i.e., \(X_{\nu} \approx 3.5 \times 10^{-10}\), its contribution is negligible after a few 10^10 years.

Typical EACs are shown in figure 4 for case AT-1 with production in and near supernova envelopes. The latter case gives a more rapid initial rise because of the enhanced interstellar gas content. Production by GCR, as in case MAR-1 and MAR-2, and by superthermal particles near supernovae in cases AT-2 and AT-3, gives EACs the same shape as the IS curves in figure 4. Production in supernova envelopes is cases AT-2 and AT-3 gives EACs like the SN curves. Numerical results are given in table 4.

The results show that in model QT, cases MAR-2 and AT-2 give about the right solar-system abundance, AT-1 gives somewhat too little \(^{6}\)Li (probably within the uncertainties), while AT-3 and especially MAR-1 give too little \(^{6}\)Li. In model TC, the small astration results in too much \(^{6}\)Li except in cases MAR-1 and AT-1 and AT-3 (each for production in supernova only). The isotopic ratio \(^{3}\)Li/\(^{6}\)Li rules out MAR-4 and MAR-2 in any model, as mentioned in § I. B. It has the value nearest to that observed in case AT-1. Thus the best choice for the origin of \(^{6}\)Li seems to be given by AT-1, where \(^{6}\)Li is produced by GCR and \(^{4}\)Li by superthermal particles, rather than interstellar medium or supernova envelopes) for the latter is possible in model QT, but only production within the supernova envelopes is compatible with model TC.

Specific calculations for \(^{6}\)Li production in red giants have not been made, since this production seems very weak (§ II) and it would probably be accompanied by excessive production of \(^{6}\)He according to the results in § I. B. If \(^{6}\)Li is produced significantly in the big bang (§ II), its EACs would resemble those of D shown in figure 2, and a big-bang abundance of \(^{6}\)Li would account for all the \(^{6}\)Li. According to Reeves (1972), this is possible in a universe of low baryon density and slightly negative electron lepton number.

c. Beryllium 9

Most \(^{9}\)Be is produced by GCR in all the cases considered, except in AT-2, where half is produced by suprathermal particles. Although the production mechanisms are thus like those of \(^{6}\)Li, the EACs of \(^{9}\)Be are different since it may not be entirely destroyed by astration.

Figure 5 gives typical EACs for alternative assumptions as to the surviving fractions, and table 4 gives the results in all cases, with the extreme possibilities of no survival and survival according to the standard \(^{9}\)Be prescription. It is seen that these alternatives make much more difference in model QT than in model TC, because of the small amount of astration in TC. In QT, the observed abundance can be accounted for with MAR-2 if no \(^{9}\)Be survives astration, and in the other cases if \(>0.3\) of the standard fractions of \(^{9}\)Be do not destroy \(^{9}\)Be. These are in accord with the different reaction rates of \(^{9}\)Be and \(^{9}\)He. Since in most TC, the abundance of \(^{9}\)Be is too great even if no \(^{9}\)Be survives in the stars.

![FIG. 4.—EACs of \(^{44}\)Ti for each evolutionary model (QT and TC). Production is according to AT-1, i.e., mostly all due to suprathermal particles, either in supernova envelopes (SN) or in interstellar medium (IS). The solar-system abundance is indicated as in fig. 3.](image1)

![FIG. 5.—EACs of \(^{9}\)Be, (a) in model QT, (b) in model TC. Production is according to AT-1, i.e., mostly all due to GCR. The three curves in (a) correspond to a survival of \(^{9}\)Be in fractions of stellar envelopes given by the standard astration, 0.3 times the standard fractions, and no survival, respectively; the solar-system abundance is indicated as in fig. 3. For TC only the curves corresponding to the standard astration (upper curve) and to no survival (lower curve) have been presented.](image2)
From these results, we find that the abundance of $^8$Be, and particularly its ratio to $^9$Li which is produced similarly, gives evidence for the astration of a significant fraction of galactic matter during evolution. It should be remembered that deuterium by itself is not a useful element to test the extent of astration, since if its primordial abundance is significant it may be restored by infalling gas.

An interesting feature of the EACs of $^7$Be is model GT, that astration and infall cause the abundance to decrease by a factor up to 5 over the last $10^9$ years. This type of model may thus partially explain the puzzling increase of surface Be abundance with age in field stars (Wallstein and Conti 1969; MAR).

f) Boron

The discussion of boron is complicated by the ambiguities in its abundance (§ II). In table 4 we adopt the low abundance favored by ALR, but we discuss below how the conclusions would be affected if a greater abundance is still valid. The rate of stellar destruction is also uncertain, so different cases between 0 and 1 times the standard surviving fractions are considered.

In case MAR-1, MAR-2, and AT-1,all or nearly all the boron is produced by GCR, while in cases AT-2 and AT-3 there is also a superthermal contribution. The EACs plotted in figures 6–8 and tabulated in table 4 reflect the different time-dependence for these cases, including the two possible superthermal production sites (supernova or interstellar medium, cf. § Vd).

Figure 6 shows the EACs for case AT-1, for each model and for alternative destruction rates; results for $^{10}$B are given by the scale on the right, for $^7$B on the left. Model QT reproduces the adopted abundances in this case, if the surviving fractions are ~0.5 times the standard fractions, which is a reasonable requirement considering the relative destruction rates of B, Be, and

![Graph showing EACs for different models and times](image)

**Fig. 6.—EACs of $^{10}$B (right ordinate scale) and $^7$B (left scale) with production rates AT-1, i.e., nearly all by GCR. For each model the upper curve is for survival in the standard fraction of stellar envelopes, and the lower curve is for no survival after astration. The empirical abundance estimates are shown for each isotope, with arrows indicating the corresponding scale, and the points are labeled. The solid error bar gives the abundance supported by ALR; the dashed error bar is the result of a crossed and the present interstellar abundance derived by ALR, and the top of the dashed error bar is the value proposed by Cameron et al. (1975).**

$^7$Be. On the other hand, model TC gives too much B in this case, even if it is totally destroyed by astration. The same conclusions hold for MAR-1, since it is identical to the GCR component of AT-1.

The results from other production rates will now be discussed for each model in turn, since the different

![Graph showing EACs for different models and times](image)

**Fig. 7.—EACs of $^{10}$B, with production rates (a) AT-2, (b) AT-3 and a standard survival after astration. Figures EACs are shown for the cases where the superthermal component is produced in supernova envelopes (SN) or within (YS), as labeled in (a) and indicated by corresponding lines in (b). Various abundance estimates are indicated as in fig. 6.**

![Graph showing EACs for different models and times](image)

**Fig. 8.—EACs of $^{10}$B, with production rates AT-2 (right ordinate scale) and AT-1 (right scale), i.e., essentially all superthermal in both cases, for a standard survival after astration. The calculations with the model and production sites are distinguished by different lines as in fig. 7, and the various abundance estimates are indicated as in fig. 6.**
effects of aatration and infall lead to different conclusions regarding the possible boron abundances.

1. In model QT, MAR-2 and AT-3 can give the adopted abundance of destruction is nearly complete (cf. table 4). On the more plausible assumption that nearly the standard fractions survive, these cases give present abundances closer to B/H = 2 x 10^{-4} (X_B = 2.8 x 10^{-4}; X_H = 1.3 x 10^{-4}), i.e., to the upper limit from the solar system data (ARL), which motivated case AT-3. MAR-2 has been invalidated by the lithium isotope ratio (p 326); the ECAs for AT-3 are shown in figures 7b and 8 (high-hand scale), for standard surviving fractions. In this case, B/H might have been ~25 percent greater at the time of formation of the solar system than at present. Such evolution is not enough to account for a meteoritic ratio of 10^{-4} proposed by Cameron et al. (1973).

Case AT-2 was chosen to give B/H = 10^{-4} in the solar system (X_B = 1.4 x 10^{-4}; X_H = 6 x 10^{-4}), as proposed by Cameron et al. (1973), although ARL have found this hypothesis difficult to support. The ECAs for standard surviving fractions are shown in figures 7a and 8 (high-hand scale), and other numerical results are given in table 4. Since nearly all the B is superabundant in this case, the production rates could be normalized to give the desired abundance for any choice of surviving fractions; the choice in AT-2 gives B/H = 10^{-4} with survival slightly less than that standard. The decrease shown by the EAC for this case over the last few 10^{10} years is not sufficient to make a meteoritic B/H = 10^{-4} compatible with a present interstellar limit of 2 x 10^{-4}.

2. In model TC, all cases give more B than the low abundance favored by ARL. The result is independent of the destruction rate and cannot be altered by re-normalization. The best values for the MAR-1 GCR production which is tied to the observed cosmic-ray spectrum. Thus, a low B abundance requires a model with considerably less stration and/or infall of gas with no B, a conclusion similar to that for He. However, both MAR-2 and AT-3 are consistent with the Cosmic Ray upper limit, B/H = 2 x 10^{-4}, while MAR-2 and AT-3 are consistent with B/H = 10^{-4}. It follows that in a model like TC, it is possible to choose subphotospheric production rates in order to account for B/H = 10^{-4} while GCR production alone is consistent with B/H = 2 x 10^{-4}. There is no significant decrease with time over the past few 10^{10} years in such a model.

SUMMARY AND CONCLUSIONS

A variety of production theories and models for galactic evolution have been found more or less consistent with the observed abundances of the light elements. While no definite conclusions can be drawn, it is at least possible to show that some hypotheses are more plausible than others, and we summarize these tentative conclusions here.

1. A high-binding origin for deuterium seems to be the most consistent with present observations since production at a sufficient rate in supernova envelopes may meet energetic difficulties. These difficulties are not encountered in the production of Li, up to 2Li/H = 10^{-8}, in supernova envelopes, since contamination of He and CNO (induced by superthermal protons and a-particles need not be as complete as for B-production. Evolutionary models are consistent with big-bang production of the overabundance O/H = 2.5 x 10^{-4}, provided that a large fraction of the matter is assumed early in the galactic history there is an inflow of primordial gas containing D. Infall may cause O/H to increase somewhat over the last few 10^{10} years, but observations cannot yet be used to test this.

2. If D is produced in the big bang, He must be destroyed in stellar envelopes at least to the extent suggested by TC, and these need not be a significant contribution from production in red giants. This is because big-bang production of He and its formation as a product of D-burning are sufficient to account for the solar-system He. However, the uncertainties in the abundances are such that stellar production of He might not be negligible.

3. If D is produced only in supernovae and He comes only from the destruction of He during accretion, the present abundance of He is reproduced only if stration is not important, otherwise, D-burning gives rise to too much He, and correspondingly too little D. Once again, a stellar contribution to He cannot be ruled out, although it is not necessary.

4. With tritium is produced by GCR (a) relative to the solar-system abundance unless there is considerable stration and/or infall during galactic evolution, and (b) relative to Li unless He is destroyed in stellar envelopes considerably faster than He. These conclusions depend on our assumption that the rate of production of GCR is proportional to the supernova rate. The same result would follow as long as the MAR-1 and AT-1 models, with the birth rate of massive stars (M > 3 Msun), infall and stration also cause a decline in interstellar Z/H over all but the first 10^{10} years, which may help to provide its explanation for the trend to greater stellar He abundances at later epochs.

5. Lithium-6 is entirely produced by GCR, but this process gives relatively too little Li, independently of the galactic model and a possible large flux of low-energy cosmic rays. Low-energy (~0 MeV) particles in or near supernova envelopes can explain the Li abundance rather well, in which case a choice of particle energies can be made to account also for the adopted boron abundance. Alternatively, production of Li in a big bang with neutrino- leptonic number is consistent with the galactic models.

6. Since it seems now likely that the cosmic boric abundance is as low as B/H = 5 x 10^{-11}, GCR are adequate to produce boron, and a subphotospheric component is needed to account for Li only.

A galactic model with large initial accretion and continual flow of primordial gas (e.g., model QT with AT-4 rates) can reproduce satisfactorily the observed abundances (within the uncertainties) of Li,B,B. On the other hand, too much Be and C are produced in a model without these features.

7. If the cosmic D/H is < 10^{-3} < 10^{-4}, as suggested.
<table>
<thead>
<tr>
<th>Element and Solar-System Abundance</th>
<th>Production Rate</th>
<th>Survival</th>
<th>1</th>
<th>3</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Li</strong> 50.0±5.0, -2.7±9</td>
<td>1</td>
<td>2</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>Be</strong> 1.0±0.6, -0.6±10</td>
<td>1</td>
<td>2</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>B</strong> 0.7±0.7, -0.3±0.9</td>
<td>1</td>
<td>2</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>C</strong> 0.3±0.3, -0.16±0.8</td>
<td>1</td>
<td>2</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

*After each solar-system abundance is given the power of 10 multiplying all values in the table for that element. The superscript refers to the case where the superthermal component is produced in the interstellar medium near the supernova.*

1 Fraction of each stellar envelope in which the element is not destroyed by accretion, normalized to unity for the fractions given by TC for *Be*. 

**TABLE 4**

<table>
<thead>
<tr>
<th>Component</th>
<th>Time (yr)</th>
<th>Time (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAR-1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>MAR-2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>AT-1 (SN)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>AT-2 (SN)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>AT-3 (SN)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>AT-4 (SN)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>AT-5 (SN)</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

**Notes:**
- **MAR:** Mars
- **AT:** Asteroid
- **SN:** Supernova
- **TC:** Tungsten-Clad

**Production Rates (x10^{-6} erg/cm^3/s):**
- **Li:** 6.3, 110, 0.7, 0.25, 0.1, 0.07, 0.03
- **Be:** 1.3, 2.0, 0.7, 0.2, 0.1, 0.07, 0.03
- **B:** 0.3, 0.5, 0.3, 0.2, 0.1, 0.07, 0.03
- **C:** 0.3, 0.5, 0.3, 0.2, 0.1, 0.07, 0.03

**Survival Rates:**
- **1:** 1.4, 2.0, 1.4, 1.0, 0.3, 0.1, 0.07, 0.03
- **3:** 2.0, 2.0, 1.4, 1.0, 0.3, 0.1, 0.07, 0.03
- **6:** 1.0, 1.0, 0.7, 0.5, 0.3, 0.1, 0.07, 0.03


Tränker, E. 1973b, ibid., p. 59.


———. 1974, in J., in press.


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