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GALACTIC EVOLUTION AND THE FORMATION OF THE LIGHT ELEMENTS*

JEAN AUDOUZE
California Institute of Technology, Pasadena, California, USA; Radioastronomie, Observatoire de Meudon, 92190 Meudon, France;† Laboratoire René Bernas, BP 1, 91406 Orsay, France;† and Service d'Electronique Physique, 91190 Saclay, France†

AND

BEATRICE M. TINSLEY
The University of Texas at Dallas and at Austin;† and University of Maryland, College Park, Maryland
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ABSTRACT

Evolution of the abundances of the light elements ($A \leq 11$) 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 ^{9}Be and ^{6}Li, the possible dependence of Be abundance on stellar age, and the solar-system D abundance.

In the framework of evolutionary models, D and ^{3}He may be produced either in the big bang or, less probably, during galactic evolution. The relative solar-system abundances of ^{6}Li, ^{9}Be, ^{10}B, and ^{11}B are readily accounted for by spallation of the interstellar gas by galactic cosmic rays, while most of the ^{7}Li might be produced by suprathermal particles (~ 10 MeV per nucleon) either in supernova envelopes or in their vicinity.

The effects of various 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 ($A \leq 11$) 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), Mitler (1972), and Reeves *et al.* (1973; referred to as RAFS). 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 the 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 with which the local material has been mixed. It will be seen below that of particular relevance to the production and destruction of the light elements are the supernova rate, the mass and "metal" ($A \geq 12$) content of the interstellar gas, and the extent of astration (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 state of the art.

II. REVIEW OF ABUNDANCES 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

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† Present address.

by RAFS. 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 B.

Deuterium 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 (1973) propose $3 \times 10^{-5} < D/H < 5 \times 10^{-4}$. The upper limit is ~20 times the value at the time of formation of the solar system derived by Geiss and Reeves (1972) and by Trauger *et al.* (1973); (2) in the direction of the Orion Nebula, Jefferts, Penzias, and Wilson (1973) found DCN/HCN $\approx$ 1/170, while Cesarsky (1973) found $D/H < 10^{-3}$ in the same direction.

From the two measurements in the direction of the Orion Nebula, it is clear that there is some chemical fractionation between such molecular ratios as DCN/HCN and the atomic ratio D/H. This has been discussed theoretically by Solomon and Woolf (1973), who claim that the molecular ratio in the Orion Nebula can correspond to $D/H \sim 10^{-6}$–10^{-5}. Similarly, Watson (1973) suggests that the interstellar HD molecule is more dissociated than H_2 by stellar ultraviolet radiation, and he argues that all current measurements are compatible with $D/H \approx 10^{-4}$ in the interstellar gas. (3) Results from the *Copernicus* satellite (Spitzer *et al.* 1973) give an abundance ratio $HD/H_2 \sim 10^{-6}$ in front of several stars, which they argue should be corrected to $HD/H_2 \approx 5 \times 10^{-3}$ to allow for different shielding of the two molecules. Most recently Rogerson and York (1973) have determined $D/H = (1.4 \pm 0.2) \times 10^{-5}$ from observations of the Lyman lines in front of β Cen. This direct determination of D in the interstellar medium is quite comparable to the protosolar value adopted by RAFS from Geiss and Reeves (1972), $D/H = (2.5 \pm 1) \times 10^{-5}$.

The present situation regarding boron is the following. (1) Cameron, Colgate, and Grossman (1973) have made a redetermination of its abundance in the solar system. They make the assumption that the carbonaceous chondrites 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, Quijano-Rico and Wänke (1968) found $B/H \sim 3 \times 10^{-9}$ 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, to propose $B/H \sim 10^{-8}$. (2) On the other hand, the first accounts of ultraviolet interstellar lines from the *Copernicus* ultraviolet observatory (Morton *et al.* 1973), interpreted in the case of boron by Audouze, Lequeux, and Reeves (1973; referred to as ALR), lead to an upper limit $B/H < 2 \times 10^{-9}$ in the interstellar medium (in front of ξ Per). This upper limit is at least 5 times below the solar-system abundance proposed by Cameron *et al.* (1973), but it is compatible with the present upper limit for solar boron, $B/H < 6 \times 10^{-10}$ (Grevesse 1969; Engvold 1970), and with the value in ordinary chondrites, $B/H \sim (2$–$5) \times 10^{-10}$. 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 support again the low ratio $B/H \approx 5 \times 10^{-10}$ (within a factor 2), as previously listed by Cameron (1968). The new results of Hall (1974) on solar boron would give $B/H < 10^{-10}$, which, if confirmed, is at least 2.5 times lower than the abundance in enstatites. 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. RAFS, using the D abundance of Geiss and Reeves (1972), favored a big-bang origin for D and ^{3}He, requiring a present mean universal density as low as $(2 \pm 1) \times 10^{-31}$ g cm^{-3} (Wagoner 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 or in supermassive stars, respectively. ^{3}He is produced as a by-product of D destruction in stellar envelopes, by D(p, γ)^{3}He. It may also be produced significantly in the envelopes of red giant stars, since the abundance by mass, X_3, can be as large as 10^{-4} in stars which generate ^{7}Li by the Cameron-Fowler (1971) mechanism (see e.g., Sackmann, Smith, and Despain 1974). Since the present interstellar abundances of D and ^{3}He are still compatible with a universal density a few times that deduced from the visible galaxies, we see 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, RAFS attributed ^{6}Li, ^{9}Be, ^{10}B, and ^{11}B to galactic cosmic rays (GCR) impinging on the interstellar gas, following the analysis of Meneguzzi, Audouze, and Reeves (1971; referred to as MAR). RAFS took the cosmic B abundance to be $(3$–$10) \times 10^{-10}$, compatible with the smaller but not the larger estimate discussed above.

For ^{7}Li, the situation is not clear. This element is underproduced by the GCR process (MAR, Mitler 1972), but it might be synthesized sufficiently in the big bang if the leptonic number is not zero (Reeves 1972*a*), and to some extent in red giants (Cameron and Fowler 1971; Sackmann *et al.* 1973; Scalo and Ulrich 1973). Finally, ^{7}Li can be produced in large amounts (in such a way that the ratio $^7Li/^6Li \gtrsim 10$, as observed) by particles with suprathermal energies, ~10 MeV per nucleon. These particles might constitute the low-energy part of the Galactic cosmic-ray spectrum, or might be produced in the envelopes of supernovae, which are a likely source of Galactic cosmic rays. This possible source of ^{7}Li has been noticed by Audouze and Truran (1973), Jacobs *et al.* (1974), and Meneguzzi and Reeves (1974). The preliminary calculations of Audouze and Truran, used here, show that if these particles (protons or α-particles) are accelerated

TABLE 1

Possible Processes for Production of Light Elements

Element	Big Bang	Supermassive Star Explosions	Supernovae	Stars, Red Giants, ...	Galactic Cosmic Rays (High Energy)
D	Possible	Possible	Possible	No	No
^{3}He	Possible	?	Unlikely	Possible	No
^{4}He	Possible	Possible	No	Possible	No
^{6}Li	No	?	Unlikely	No	Possible
^{7}Li	Plausible	?	Possible	Possible	Unlikely
^{9}Be......	No	?	Unlikely	No	Possible
^{10}B......	No	?	Possible	No	Possible
^{11}B......	No	?	Possible	No	Possible

according to their energy per nucleon, the large production of ^{7}Li 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 boron (up to B/Li $\sim$ 5) is made with the ^{7}Li; 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 B abundance, say B/H $\gtrsim 3 \times 10^{-9}$ (as suggested by the carbonaceous chondrites), at the time of formation of the solar system than in the present interstellar medium (B/H $< 2 \times 10^{-9}$).

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 Tinsley (1973). Here we study specifically the evolution of the pool of matter from which the solar system formed during the time (about 6×10^9 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 "nucleogenetic 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 $A \geq 12$, to set constraints on evolutionary models (e.g., Schmidt 1963; Quirk and Tinsley 1973 [referred to as QT]; Talbot and Arnett 1973*b*; Biermann and Tinsley 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 exothermic 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 10^9 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 $m_L(t)$, and its fractional mass abundance in the gas is denoted $X_L(t)$, so that $m_L(t) = X_L(t)m_g(t)$, where m_g is the mass of interstellar gas. The change of mass of the element L in the time interval $(t-1, t)$ can be written

$$\begin{aligned} m_L(t) - m_L(t-1) &= q(t) + X_{pL}m_F(t) - X_L(t-1)\sum_m mb(m, t) \\ &\quad + \sum_m mf_L(m)X_L(t-\tau_m)b(m, t-\tau_m)\,. \quad (1) \end{aligned}$$

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 $X_{pL}m_F(t)$ refers to the addition of element L with primordial abundance X_{pL}, due to infall of extragalactic gas occurring at a rate $m_F(t)$ per unit time. The quantity $b(m, t)$ is the number of stars of mass m born in the time interval $(t-1, t)$. Since X_L 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 τ_m, so $b(m, t-\tau_m)$ represents the number of stars dying during the interval $(t-1, t)$, and $X_L(t-\tau_m)$ 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 $f_L(m)$. Thus the last term in equation (1) gives the mass of element L 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 $q(t)$ can be written

$$q(t) = q(t_0)Q(t)\,, \tag{2}$$

where t_0 is the present time, $q(t_0)$ is the present production rate of the element in solar masses per unit time, and $Q(t)$ is an evolutionary factor, of which the expression depends on the production process. Three expressions are of interest:

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

$$Q_{\rm sn}(t) = r_{\rm sn}(t)/r_{\rm sn}(t_0)\,. \tag{3}$$

The rate $r_{\rm sn}$ is the death rate of stars in the mass range producing supernovae, so it depends both on the galactic model and on the rather uncertain stellar mass range. Here we assume that supernovae are produced by massive stars, with lifetimes $\lesssim 10^7$ years; there is indeed some empirical evidence for this hypothesis (Moore 1973). If in fact they are produced by stars with lifetimes $\sim 10^8$ years, the results will be affected only in very early times, less than 10^9 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 α-particles, the rate varies according to

$$Q_Z(t) = r_{\rm sn}(t)m_g(t)Z_g(t)/r_{\rm sn}(t_0)m_g(t_0)Z_g(t_0)\,, \tag{4}$$

where Z_g is the heavy-element $(A \geq 12)$ abundance of the gas. Here it is assumed 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* abundances of the heavy $(A \geq 12)$ elements with respect to each other do not change enough to alter significantly the proportionality of the total production cross-section to Z_g.

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

$$Q_{XY}(t) = r_{\rm sn}(t)m_g(t)/r_{\rm sn}(t_0)m_g(t_0)\,. \tag{5}$$

Here the same assumptions are made about cosmic-ray production and composition; the further assumption is that the interstellar H and He abundances (X and 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 1973*a*, *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 infalling abundance, one can simply add the contributions to m_L or X_L from each process. [This is because if $X_{pL} = 0$, every term in eq. (1) except $q(t)$ is linearly dependent on X_L, with coefficients that depend on the galactic model but not on the light elements.] Here we have combined processes (2) and (3) for the interstellar component, using simply

$$Q_{\rm IS}(t) = 0.7Q_Z(t) + 0.3Q_{XY}(t)\,, \tag{6}$$

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-sections, the computed $X_L(t)$ 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 3×10^9 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 players 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 on theories for the light elements, we consider two models which are internally consistent, but have useful contrasted properties: these are the "consistent" model of TC (referred to as model TC), and the "infall" 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 rather 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 m_g^n. The gas mass, astration, supernova rate, and other quantities in models with $n \sim 1$ behave very similarly to those in model TC; on the other hand, models with $n \geq 1.5$ behave very like model QT. Thus, the two models used 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 Biermann 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 $\sim 10^9$ 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 percent of the total mass per 10^9 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. Verschuur 1973; Hulsbosch and Oort 1973; Davies 1972), the rate of infall is rather uncertain. Further chemical evidence for infall has been cited by Truran (1973).

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 pregalactic 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 assume 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 each model 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, levels off then falls 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. Talbot and Arnett 1973*a*). 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 in Tinsley's (1972) code stars with masses less than 9 $M_\odot$ produce no metals 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 "nucleogenetic pool" (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 (1972*b*) finds that the occurrence of inhomogeneities due to the discreteness of supernova events is very small. Searle (1972) and Talbot and Arnett (1973*b*) 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 that these elements are mainly produced in the big bang, according to the calculations of Wagoner (1973). The choice of big-bang parameter (the entropy per baryon, or ρ/T^3, where ρ is the mean present density of the universe and T is the background radiation temperature) is made by requiring that the computed solar-system D abundance will agree with the value of Geiss and Reeves (1972). Since each star probably destroys its D entirely (TC, RAFS), the fraction of primordial D entering the solar system is the fraction of gas at time $\sim 6 \times 10^9$ years (Fowler 1972) which has not been astrated. In model QT, most of the matter is astrated in the first 10^9 years, but thereafter the astrated fraction declines because of the infall of unastrated gas. In model TC, the astrated fraction rises steadily. In both models, the fraction is ~ 0.6 at 6×10^9 years, so ~ 0.4 of the primordial D remains. The required big-bang abundance, 1/0.4 times the Geiss and Reeves value, arises if $\rho \sim 1.4 \times 10^{-31}$ g cm^{-3}, a possible value (§ II).

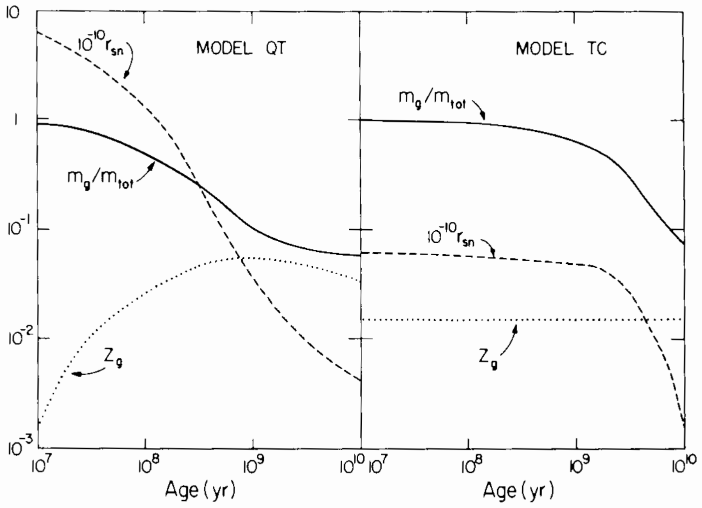

FIG. 1.—Evolution of the gas fraction (m_g/m_{tot}), interstellar metal abundance (Z_g), and supernova rate (r_{sn}) in the two models for galactic evolution, QT and TC.

^{3}He and ^{7}Li also have appreciable big-bang abundances in this case. In model QT, the values are $X_{p2} = 1.0 \times 10^{-4}$, $X_{p3} = 2.4 \times 10^{-3}$, $X_{p7} = 3.5 \times 10^{-10}$; 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^{54} 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, ^{3}He is a by-product of the burning of D (from supernovae) in stellar envelopes. At this point, 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 deuterium abundance.

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

^{3}He is also a normal product of stellar hydrogen burning (e.g., Iben 1967). In the following calculations we neglect this possible source of ^{3}He for two reasons: (1) Previous studies (TC; RAFS; Talbot and Arnett 1(973*a*) have shown that the observed abundance can be explained in terms of ^{3}He from the big bang and from D-burning in stellar envelopes; if the D abundance (from whatever source) is constrained to agree with that observed, these sources alone tend to overproduce ^{3}He. (2) The amount of ^{3}He ejected after stellar production is extremely uncertain. Possible effects on our conclusions of neglecting this source of ^{3}He will be discussed in §§ V*b* and VI.

b) The Quintet ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B

The several alternatives used are summarized in table 2, which gives the production rates at the present time, *p*, in atoms per second per gram of interstellar matter with cosmic composition. These rates *p* are related to the quantities $q(t_0)$ defined in § III by

$$q(t_0) = 3.17 \times 10^{16}\, A\mathrm{H} m_g(t_0) p \quad M_\odot/10^9\,\mathrm{yr}\,, \qquad (7)$$

where *A* is the atomic weight of the element, H is the mass of the hydrogen atom in grams, and the present gas content $m_g(t_0)$ is in solar units. The different sets of *p* correspond to different assumptions for the process producing each element, as follows.

TABLE 2

PRODUCTION RATES OF Li, Be, B

Case	^{6}Li	^{7}Li	^{9}Be	^{10}B	^{11}B
MAR-1...	1.1(−4)	1.7(−4)	2.8(−5)	1.2(−4)	2.8(−4)
MAR-2...	1.9(−3)	3.4(−3)	8.4(−5)	2.8(−4)	1.0(−3)
AT-1.....	1.1(−4)	1.4(−3)	2.8(−5)	1.2(−4)	3.0(−4)
AT-2.....	1.6(−4)	3.7(−3)	5.6(−5)	3.5(−3)	1.4(−2)
AT-3.....	1.2(−4)	7.2(−4)	3.2(−5)	6.4(−4)	2.4(−3)

NOTE.—Units are number of atoms per second per gram of interstellar matter of standard cosmic composition (the numbers in parentheses are powers of 10).

1) *MAR-1.* These rates are taken from MAR in the case where the "quintet" is assumed to be produced by galactic cosmic rays (GCR) impinging on the interstellar medium, and the GCR spectrum varies as $W^{-2.6}$, where *W* is the total energy of the cosmic-ray particles. These rates are very close to those derived by Mitler (1972) in his study of the GCR process.

2) *MAR-2.* These rates are derived from model C of MAR (cf. their table 7), in which they assume the existence of an intense low-energy flux of cosmic rays (below a few tens of MeV), specified in such a way as to account for the large abundance of ^{7}Li (^{7}Li/H ~ 10^{-9}). 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 (Rogerson *et al.* 1973). It will be found that although MAR-2 has an advantage over MAR-1 in accounting for the ratio ^{7}Li/H, both of these cases lead to ^{7}Li/^{6}Li ~ 2, whereas the observed isotope ratio is $\gtrsim 10$.

3) *AT-1.* These rates and the following include the calculations of Audouze and Truran (1973) of light-element production by suprathermal protons and α-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 10-MeV protons and 10-MeV-per-nucleon α-particles. In this case, ^{7}Li is the only member of the quintet produced significantly by suprathermal particles. To account for the others (assuming B/H has the low value preferred by ALR), the contribution from GCR given by MAR-1 is added. We are free to normalize the suprathermal component, i.e., the production per supernova, in any 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 ^{7}Li/^{6}Li ~ 10.

4) *AT-2.* This case is supposed to account for the somewhat unlikly possibility that B/H ~ 10^{-8}. To produce this amount of boron along with the necessary ^{7}Li, we select the case where there is a large flux of suprathermal protons and α-particles with 16–30 MeV (in total energy). A GCR contribution given by MAR-1 is added, to account only for ^{6}Li and ^{9}Be.

5) *AT-3.* Finally, we consider the possibility that the actual B abundance is B/H ~ 2×10^{-9}, the upper limit determined from the *Copernicus* interstellar data by ALR. The production rates in this case are a combination of MAR-1 and suprathermal contribution 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 enevelopes by thermonuclear reactions, at rates which increase in the order ^{3}He, B, 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. Deuterium, ^{6}Li, and ^{7}Li are assumed to be totally destroyed before ejection from any star. For ^{3}He, TC's prescription is: "for masses $m > 25\ M_{\odot}$, ^{3}He is completely destroyed; for masses $10 \leq m \leq 25\ M_{\odot}$, ^{3}He survives only in the outer 10 percent by mass of the star; for masses $3 \leq m \leq 10\ M_{\odot}$, ^{3}He survives only in the outer 25 percent by mass of the star; for masses $m < 3\ M_{\odot}$, ^{3}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 $f_L(m)$ to be used in equation (1).

V. RESULTS

Relative abundances by mass, $X_L(t)$, 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 2*a* and 2*b*, respectively. In model QT, D is initially transformed rapidly into ^{3}He during the first 10^9 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 (§ IV*a*). 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 infall 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 supernovae, EACs are shown in figures 2*c* and 2*d*; the production rate chosen is 10^{54} 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 ($\sim 6 \times 10^9$ 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, if as suggested by Reeves (1973) 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 astration be ruled out if there is infalling gas with sufficient big-bang D.

b) Helium 3

Figures 2*a* and 2*b* show the EACs in the case where ^{3}He is produced in the big bang and in the D-burning zones of stellar envelopes (§ IV*a*), and with standard fractions surviving in these envelopes (§ IV*c*). In model QT, ^{3}He is at first enriched by D burning, but later depleted by astration and the infall of gas with less ^{3}He. In model TC, in which astration is less

TABLE 3

COMPUTED EVOLUTION OF ABUNDANCES, BY MASS, OF D AND ^{3}He* (numbers in parentheses are powers of 10)

ELEMENT	BIG-BANG ABUNDANCE	OTHER PRODUCTION	SURVIVAL†	GALACTIC MODEL	TIME (10^9 yr)			
					1	3	6	10
D.........	1.0 (−4)	...	0	QT	1.7(−5)	2.3(−5)	3.6(−5)	5.7(−5)
^{3}He.......	2.43(−5)	D burning	1	QT	6.9(−5)	1.3(−4)	1.0(−4)	7.4(−5)
^{3}He.......	2.43(−5)	D burning	0.5	QT	3.5(−5)	5.7(−5)	4.6(−5)	3.6(−5)
D.........	...	Supernovae	0	QT	4.7(−5)	8.2(−6)	8.8(−6)	1.6(−5)
^{3}He.......	...	Burning of D from supernovae	1	QT	3.3(−5)	8.0(−5)	7.0(−5)	4.3(−5)
D.........	8.5 (−5)	...	0	TC	7.8(−5)	5.7(−5)	3.5(−5)	2.3(−5)
^{3}He.......	2.20(−5)	D burning	1	TC	2.3(−5)	3.3(−5)	4.6(−5)	5.7(−5)
^{3}He.......	2.20(−5)	D burning	0.5	TC	2.2(−5)	2.5(−5)	2.8(−5)	3.0(−5)
D.........	...	Supernovae	0	TC	1.2(−5)	2.8(−5)	3.7(−5)	3.9(−5)
^{3}He.......	...	Burning of D from supernovae	1	TC	1.4(−7)	2.7(−6)	1.1(−5)	1.9(−5)

* Adopted solar-system abundances: $X_2 = (3.5 \pm 1.4)(-5)$, $X_3 = (2.0 \pm 1.0)(-5)$.

‡ Fraction of stellar envelopes in which the element is not destroyed during astration, normalized to unity for the fractions given by TC for ^{3}He.

TABLE 4

COMPUTED EVOLUTION OF ABUNDANCES, BY MASS, OF ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, AND ^{11}B

ELEMENT AND SOLAR-SYSTEM ABUNDANCE	PRODUCTION CASE†	SURVIVAL‡	MODEL QT, TIME (10^9 yr)				MODEL TC, TIME (10^9 yr)			
			1	3	6	10	1	3	6	10
^{6}Li: 3.5(+3.5, −1.8)(−10)	MAR-1	0	6.3	1.6	1.2	1.0	12	22	20	15
	MAR-2	0	110	27	20	17	210	380	340	260
	AT-1 (SN and IS)	0	6.3	1.6	1.2	1.0	12	22	20	15
	AT-2 (SN)	0	7.1	2.0	1.6	1.5	13	23	22	18
	AT-2 (IS)	0	9.2	2.3	1.7	1.5	18	32	29	22
	AT-3 (SN and IS)	0	6.9	1.7	1.3	1.1	13	24	22	17
^{7}Li: 5.0(+5.0, −2.5)(−9)	MAR-1	0	1.1	0.28	0.21	0.18	2.2	3.9	3.6	2.8
	MAR-2	0	23	5.6	4.2	3.7	43	78	72	55
	AT-1 (SN)	0	2.6	1.5	1.5	1.5	1.5	4.6	6.9	7.1
	AT-1 (IS)	0	9.4	2.3	1.8	1.5	18	32	30	23
	AT-2 (SN)	0	6.9	4.1	3.9	3.9	4.0	12	18	19
	AT-2 (IS)	0	25	6.1	4.6	4.0	47	86	79	60
	AT-3 (SN)	0	1.2	0.89	0.79	0.76	2.8	5.7	6.3	5.5
	AT-3 (IS)	0	4.9	1.2	0.90	0.77	9.2	17	15	12
^{9}Be: 1.0(+0.6, −0.4)(−10)	MAR-1	0	2.4	0.59	0.45	0.39	4.6	8.3	7.6	5.9
	MAR-1	1	4.1	4.3	3.4	2.6	4.6	8.7	9.4	8.7
	MAR-2	0	7.2	1.8	1.3	1.2	14	25	23	18
	MAR-2	1	12	13	10	7.9	14	26	28	26
	AT-1 (SN and IS)	0	2.4	0.59	0.45	0.39	4.6	8.3	7.6	5.9
	AT-1 (SN and IS)	1	4.1	4.3	3.4	2.6	4.6	8.7	9.4	8.7
	AT-2 (SN)	0	3.1	0.99	0.83	0.77	5.0	9.5	9.4	7.6
	AT-2 (SN)	1	5.2	5.4	4.4	3.4	5.0	10	11	11
	AT-2 (IS)	0	4.8	1.2	0.90	0.77	9.2	17	15	12
	AT-2 (IS)	1	8.3	8.6	6.8	5.2	9.2	18	19	17
	AT-3 (SN and IS)	0	2.8	0.68	0.51	0.44	5.2	9.5	8.7	6.7
	AT-3 (SN and IS)	1	4.8	4.9	3.9	3.0	5.3	10	11	9.9
^{10}B: 0.72(+0.72, −0.36)(−9) ...	MAR-1	0	1.2	0.28	0.21	0.18	2.2	4.0	3.6	2.8
	MAR-1	1	2.0	2.0	1.6	1.3	2.2	4.2	4.5	4.1
	MAR-2	0	2.7	0.66	0.50	0.43	5.1	9.2	8.5	6.5
	MAR-2	1	4.6	4.8	3.8	2.9	5.1	9.7	10	9.6
	AT-1 (SN and IS)	0	1.2	0.28	0.21	0.18	2.2	4.0	3.6	2.8
	AT-1 (SN and IS)	1	2.0	2.0	1.6	1.3	2.2	4.2	4.5	4.1
	AT-2 (SN)	0	9.3	5.5	5.3	5.3	5.5	16	24	25
	AT-2 (SN)	1	15	16	14	11	5.6	17	28	32
	AT-2 (IS)	0	33	8.2	6.2	5.3	64	115	106	81
	AT-2 (IS)	1	58	10	47	36	64	120	130	120
	AT-3 (SN)	0	2.5	1.1	0.99	0.96	3.0	6.4	7.3	6.6
	AT-3 (SN)	1	4.2	4.4	3.7	2.8	3.0	6.7	8.5	9.0
	AT-3 (IS)	0	6.1	1.5	1.1	0.98	12	21	19	15
	AT-3 (IS)	1	11	11	8.6	6.7	12	22	24	22
^{11}B: 0.32(+0.32, −0.16)(−8) ...	MAR-1	0	0.30	0.072	0.055	0.047	0.56	1.0	0.93	0.72
	MAR-1	1	0.51	0.52	0.42	0.32	0.56	1.1	1.1	1.1
	MAR-2	0	1.1	0.26	0.20	0.17	2.0	3.6	3.3	2.6
	MAR-2	1	1.8	1.9	1.5	1.1	2.0	3.8	4.1	3.8
	AT-1 (SN and IS)	0	0.32	0.078	0.059	0.050	0.60	1.1	1.0	0.77
	AT-1 (SN and IS)	1	0.54	0.56	0.45	0.34	0.60	1.1	1.2	1.1
	AT-2 (SN)	0	4.1	2.4	2.3	2.3	2.4	7.2	11	11
	AT-2 (SN)	1	6.5	7.0	6.1	4.7	2.4	7.5	12	14
	AT-2 (IS)	0	15	3.6	2.7	2.4	28	51	47	36
	AT-2 (IS)	1	25	26	21	16	28	54	57	53
	AT-3 (SN)	0	0.68	0.42	0.40	0.40	0.41	1.2	1.8	1.9
	AT-3 (SN)	1	1.1	1.2	1.0	0.80	0.42	1.3	2.1	2.4
	AT-3 (IS)	0	2.5	0.60	0.47	0.40	4.8	8.7	8.0	6.1
	AT-3 (IS)	1	4.4	4.3	3.6	2.7	4.8	9.2	9.8	9.0

* 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 suprathermal particles react *in* the supernova envelopes, and IS refers to the case where the suprathermal component is produced in the interstellar medium *near* the supernovae.

‡ Fraction of each stellar envelope in which the element is not destroyed by astration, normalized to unity for the fractions given by TC for ^{3}He.

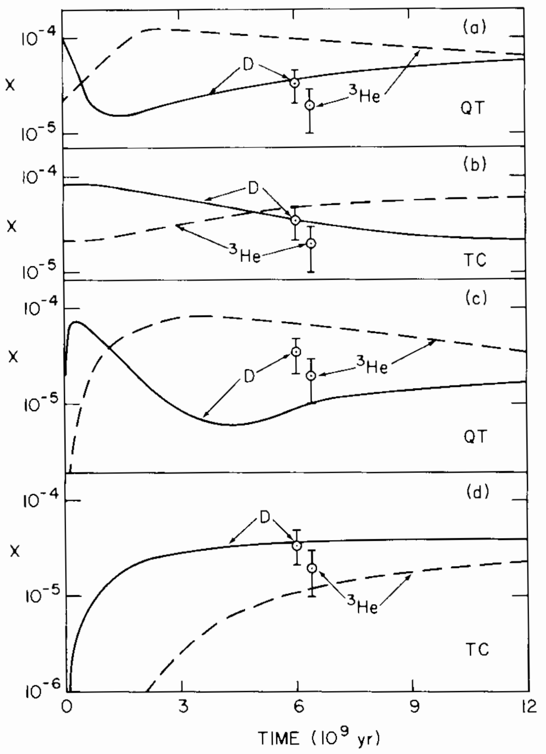

FIG. 2.—EACs of D and ^{3}He. In all cases, no D survives astration, and the standard fractions of ^{3}He survive. (*a*) Both elements are produced in the big bang, and ^{3}He also by D-burning in stellar envelopes. Model QT. (*b*) As (*a*), model TC. (*c*) D is produced only in supernovae (10^{54} atoms per SN), and ^{3}He only in stellar envelopes during burning of this D. Model QT. (*d*) As for (*c*), model TC. Big-bang abundances were chosen to reproduce D/H; ^{3}He production would be less excessive if the correct D abundance is smaller or if more ^{3}He is destroyed by astration.

important, the abundance increases steadily by D burning.

It is seen that in both models these most straightforward 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 ^{3}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 near 6×10^9 years is still about twice too large in model QT, but it agrees within the uncertainties in model TC. Best agreement in both models is obtained with survival in 0.2 times the standard fractions, but the results for Be and B below suggest that ^{3}He is unlikely to be destroyed to that extent. Considering the uncertainties in the abundances of D and ^{3}He, it is possible to adjust the big-bang production so that D is near its lower limit and ^{3}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 Rogerson and York [1973], which was published after the present calculations were completed.) Because of the uncertainties in D/H and ^{3}He/H, evolutionary studies cannot be used to determine the destruction rate of ^{3}He in stellar envelopes.

Independently of these uncertainties, we can conclude that if D is produced in the big bang, and ^{3}He in corresponding proportions there and later by D burning in stars, any contribution to the galactic ^{3}He from production in red giants must be minor.

If D is produced in supernovae as discussed in § V*a* above, substantial ^{3}He abundances may result from burning of that D. Figures 2*c* and 2*d* show the EACs derived in the case where that is the only source of ^{3}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 ^{3}He abundances in an evolutionary model without very much astration.

However, in model QT, too much ^{3}He is produced, as a direct result of the large degree of astration which led to too little D. If the production rate of D is assumed to be ~4 times greater, the discrepancy with ^{3}He is even worse. A significant reduction of the ^{3}He abundance would require that very much less ^{3}He survives astration than the amount estimated by TC. The supernova origin for D, and subsequently ^{3}He, thus has more difficulties in the context of an evolutionary model in which a large fraction of the matter is astrated early in time.

c) *Lithium 6*

This element is produced almost entirely by the GCR impinging on the interstellar gas; there is an appreciable suprathermal 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 ^{6}Li by astration; the fall is more drastic than for D, because there is no ^{6}Li in the infalling gas. In model TC, both the initial rise and the loss through astration are less. The resulting overabundance in QT and underabundance in TC are probably not outside the range of uncertainty in the solar-system value.

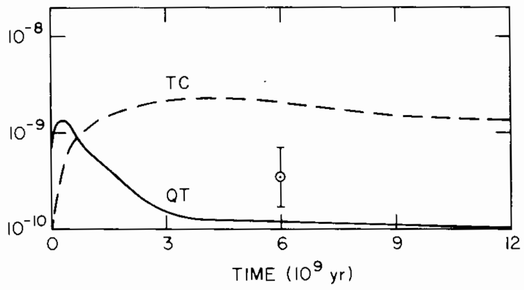

FIG. 3.—EACs of ^{6}Li for each evolutionary model (QT and TC). Production is by GCR, according to AT-1, and no ^{6}Li survives astration. The solar-system abundance is shown at an indicative time of 6×10^9 years.

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 suprathermal production: "SN" if it occurs in the supernova envelopes, and "IS" if it occurs in the nearby interstellar medium. Similar results are obtained in cases MAR-1, AT-1, AT-2, and AT-3. MAR-2 produces rather more ^{6}Li, which is clearly too much in a model with as little astration as TC.

d) *Lithium 7*

The origin of this element is less certain than that of ^{6}Li (§ II), but we explore here the possibility that ^{7}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 ^{3}He in a universe with zero leptonic number (Wagoner 1973), i.e., $X_{p7} \sim 3.5 \times 10^{-10}$, its contribution is negligible after a few 10^8 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 cases MAR-1 and MAR-2, and by suprathermal 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 in 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 ^{8}Li (probably within the uncertainties), while AT-3 and especially MAR-1 give too little ^{7}Li. In model TC, the small astration results in too much ^{7}Li except in cases MAR-1 and AT-1 and AT-3 (each for production in supernova only). The isotope ratio ^{7}Li/^{6}Li rules out MAR-1 and MAR-2 in any model, as mentioned in § IV*b*. It has the value nearest to that observed in case AT-1. Thus the best choice for the origin of Li seems to be given by AT-1, where ^{6}Li is produced by GCR and ^{7}Li by suprathermal particles; either site (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.

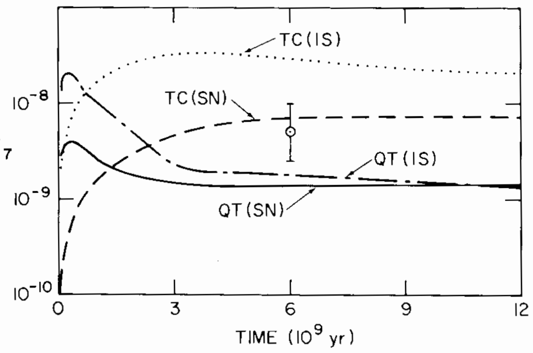

FIG. 4.—EACs of ^{7}Li for each evolutionary model (QT and TC). Production is according to AT-1, i.e., nearly all due to suprathermal particles, either in supernova envelopes (SN) or in their vicinity (IS). The solar-system abundance is indicated as in fig. 3.

Specific calculations for ^{7}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 ^{3}He according to the results in § V*b*. If ^{7}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 $X_{p7} = 1.3 \times 10^{-8}$ would account for all the ^{7}Li. According to Reeves (1972*a*), this is possible in a universe of low baryon density and slightly negative electron leptonic number.

e) *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 ^{3}He 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 $\sim$0.3 of the standard fractions of stars do not destroy ^{9}Be. These are in accord with the different reaction rates of ^{9}Be and ^{3}He. But in model TC, the abundances are too great even if no ^{9}Be survives in the stars.

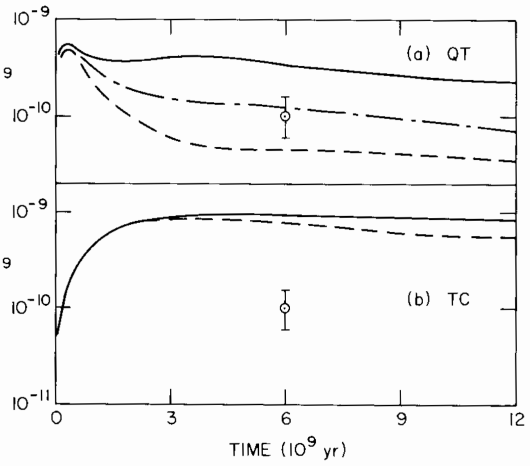

FIG. 5.—EACs of ^{9}Be, (*a*) in model QT, (*b*) in model TC. Production is according to AT-1, i.e., nearly all by GCR. The three curves in (*a*) correspond to a survival of ^{9}Be in fractions of stellar envelopes given by the standard prescription, 0.3 times the standard fractions, and no survival, respectively. The solar-system abundance is indicated as in fig. 3. For TC only the curves corresponding to the standard prescription (*upper curve*) and to no survival (*lower curve*) have been presented.

From these results, we find that the abundance of ^{9}Be, and particularly its ratio to ^{6}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 ^{9}Be in model QT is that astration and infall cause the abundance to decrease by a factor up to 5 over the last $\sim 9 \times 10^9$ years. This type of model may thus partially explain the puzzling increase of surface Be abundance with age in field stars (Wallerstein 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 cases 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 suprathermal 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 suprathermal production sites (supernovae or interstellar medium, cf. § V*d*).

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 ^{11}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 ^{3}He. 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.

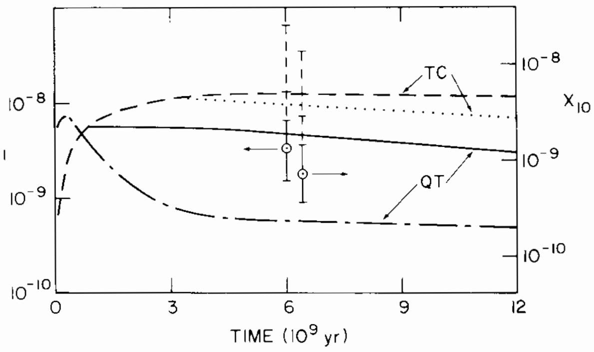

FIG. 6.—EACs of ^{10}B (*right ordinate scale*) and ^{11}B (*left scale*) with production rates AT-1, i.e., nearly all by GCR. For each model the upper curve is for survival in the standard fractions of stellar envelopes, and the lower curve is for no survival after astration. The empirical abundance estimates are shown for each isotope, with arrows indicating the corresponding scale, as follows: the ○ symbol with solid error bars gives the abundance supported by ALR; the dashed error bar is marked by a cross line at the upper limit to the present interstellar abundance derived by ALR; and the top of the dashed error bar is at the value proposed by Cameron *et al.* (1973).

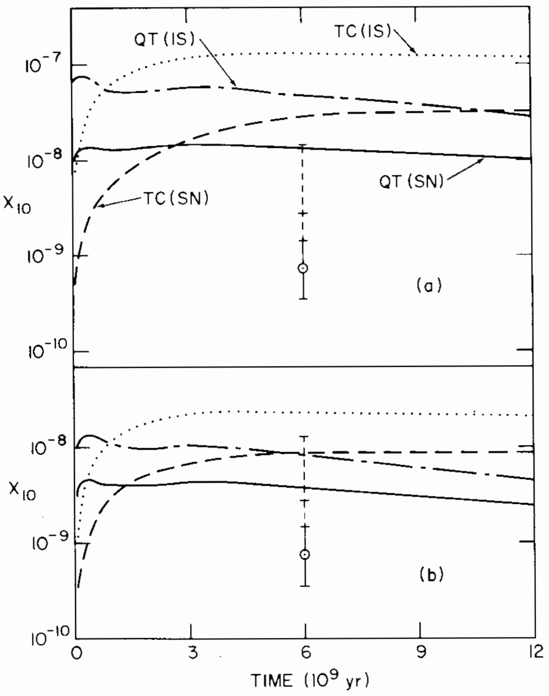

FIG. 7.—EACs of ^{10}B, with production rates (*a*) AT-2, (*b*) AT-3 and a standard survival after astration. Separate EACs are shown for the cases where the suprathermal component is produced in supernova envelopes (SN) or nearby (IS), as labeled in (*a*) and indicated by corresponding lines in (*b*).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

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

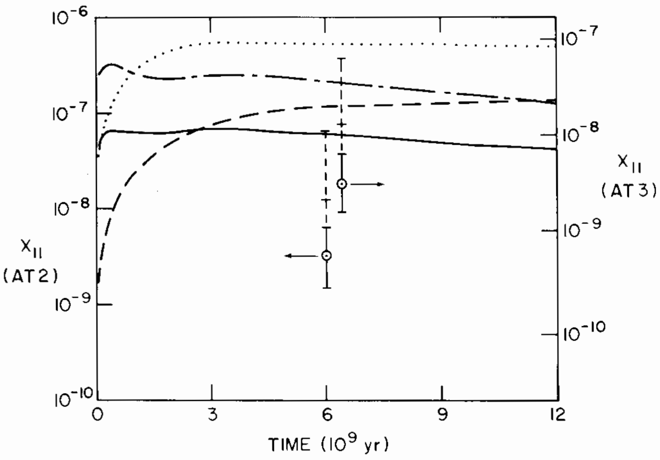

FIG. 8.—EACs of ^{11}B, with production rates AT-2 (*left ordinate scale*) and AT-3 (*right scale*), i.e., essentially all suprathermal in both cases, for a standard survival after astration. The alternative galactic models and production sites are distinguished by different lines as in fig. 7*a*, and the various abundance estimates are indicated as in fig. 6.

effects of astration and infall lead to different conclusions regarding the possible boron abundances.

1. In model QT, MAR-2 and AT-3 can give the adopted low abundances if 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 $B/H = 2 \times 10^{-9}$ ($X_{10} = 2.8 \times 10^{-9}$, $X_{11} = 1.3 \times 10^{-8}$), i.e., to the upper limit from the *Copernicus* data (ALR), which motivated case AT-3. MAR-2 has been invalidated by the lithium isotope ratio (§ V*d*). The EACs for AT-3 are shown in figures 7*b* and 8 (*right-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 10^{-8} proposed by Cameron *et al.* (1973).

Case AT-2 was chosen to give $B/H \sim 10^{-8}$ in the solar system ($X_{10} \sim 1.4 \times 10^{-8}$, $X_{11} \sim 6 \times 10^{-8}$), as proposed by Cameron *et al.* (1973), although ALR have found this hypothesis difficult to support. The EACs for standard surviving fractions are shown in figures 7*a* and 8 (*left-hand scale*), and other numerical results are given in table 4. Since nearly all the B is suprathermal in this case, the production rates could be normalized to give the desired abundances for any choice of surviving fractions; the choice in AT-2 gives $B/H \sim 10^{-8}$ with survival slightly less than standard. The decrease shown by the EAC for this case over the last few 10^9 years is not sufficient to make a meteoritic $B/H \sim 10^{-8}$ compatible with a present interstellar limit of 2×10^{-9}.

2. In model TC, all cases give more B than the low abundance favored by ALR. This result is independent of the destruction rate and cannot be altered by renormalization since it holds for the MAR-1 GCR production which is tied to the observed cosmic-ray spectrum. Thus, a low B abundance requires a model with considerable astration and/or infall of gas with no B, a conclusion similar to that for Be. However, both MAR-1 and AT-1 are consistent with the *Copernicus* upper limit, $B/H \sim 2 \times 10^{-9}$, while MAR-2 and AT-3 are consistent with $B/H \sim 10^{-8}$. It follows that in a model like TC, it is possible to choose suprathermal production rates in order to account for $B/H \sim 10^{-8}$, while GCR production alone is consistent with $B/H \sim 2 \times 10^{-9}$. There is no significant decrease with time over the past few 10^9 years in such a model.

VI. 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 big-bang 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 ^{7}Li, up to $^7Li/H \sim 10^{-9}$, in supernova envelopes, since spallation on ^{4}He and CNO induced by suprathermal protons and α-particles need not be as complete as for D production.) Evolutionary models are consistent with big-bang production if the interstellar $D/H \sim 2.5 \times 10^{-5}$, provided that if a large fraction of the matter is astrated early in the galactic history there is an inflow of primordial gas containing D; infall may cause D/H to increase somewhat over the last few 10^9 years, but observations cannot yet be used to test this.

2. If D is produced in the big bang, ^{3}He must be destroyed in stellar envelopes at least to the extent suggested by TC, and there need not be a significant contribution from production in red giants. This is because big-bang production of ^{3}He and its formation as a product of D burning are sufficient to account for the solar-system ^{3}He. However, the uncertainties in the abundances are such that stellar production of ^{3}He might not be negligible.

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

4. Beryllium-9 is overproduced by GCR, (*a*) relative to the solar-system abundance unless there is considerable astration and/or infall during galactic evolution, and (*b*) relative to ^{6}Li unless ^{9}Be is destroyed in stellar envelopes considerably faster than ^{3}He. These conclusions depend on our assumption that the rate of production of GCR is proportional to the supernova rate. The same results would follow as long as their production varies as the birth rate of massive stars ($M \geqslant 3\, M_\odot$). Infall and astration also cause a decline in interstellar Be/H over all but the first 10^9 years, which may help to provide an explanation for the trend to greater stellar Be abundances at later spectral types.

5. Lithium-6 is entirely produced by GCR, but this process gives relatively too little ^{7}Li, independently of the galactic model and of a possible large flux of low-energy cosmic rays. Low-energy (~10 MeV) particles in or near supernova envelopes can explain the ^{7}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 nonzero leptonic number is consistent with the galactic models.

6. Since it seems now likely that the cosmic boron abundance is as low as $B/H \sim 5 \times 10^{-10}$, GCR are adequate to produce boron, and a suprathermal component is needed to account for ^{7}Li only.

A galactic model with large initial astration and continued infall of primordial gas (e.g., model QT with AT-1 rates) can reproduce satisfactorily the observed abundances (within the uncertainties) of LiBeB. On the other hand, too much Be and B are produced in a model without these features.

7. If the cosmic B/H is $\sim 10^{-9}$ or 10^{-8}, as discussed

TABLE 4

COMPUTED EVOLUTION OF ABUNDANCES, BY MASS, OF ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, AND ^{11}B

ELEMENT AND SOLAR-SYSTEM ABUNDANCE	PRODUCTION CASE†	SURVIVAL‡	MODEL QT, TIME (10^9 yr)				MODEL TC, TIME (10^9 yr)			
			1	3	6	10	1	3	6	10
^{6}Li: 3.5(+3.5, −1.8)(−10)	MAR-1	0	6.3	1.6	1.2	1.0	12	22	20	15
	MAR-2	0	110	27	20	17	210	380	340	260
	AT-1 (SN and IS)	0	6.3	1.6	1.2	1.0	12	22	20	15
	AT-2 (SN)	0	7.1	2.0	1.6	1.5	13	23	22	18
	AT-2 (IS)	0	9.2	2.3	1.7	1.5	18	32	29	22
	AT-3 (SN and IS)	0	6.9	1.7	1.3	1.1	13	24	22	17
^{7}Li: 5.0(+5.0, −2.5)(−9)	MAR-1	0	1.1	0.28	0.21	0.18	2.2	3.9	3.6	2.8
	MAR-2	0	23	5.6	4.2	3.7	43	78	72	55
	AT-1 (SN)	0	2.6	1.5	1.5	1.5	1.5	4.6	6.9	7.1
	AT-1 (IS)	0	9.4	2.3	1.8	1.5	18	32	30	23
	AT-2 (SN)	0	6.9	4.1	3.9	3.9	4.0	12	18	19
	AT-2 (IS)	0	25	6.1	4.6	4.0	47	86	79	60
	AT-3 (SN)	0	1.2	0.89	0.79	0.76	2.8	5.7	6.3	5.5
	AT-3 (IS)	0	4.9	1.2	0.90	0.77	9.2	17	15	12
^{9}Be: 1.0(+0.6, −0.4)(−10).....	MAR-1	0	2.4	0.59	0.45	0.39	4.6	8.3	7.6	5.9
	MAR-1	1	4.1	4.3	3.4	2.6	4.6	8.7	9.4	8.7
	MAR-2	0	7.2	1.8	1.3	1.2	14	25	23	18
	MAR-2	1	12	13	10	7.9	14	26	28	26
	AT-1 (SN and IS)	0	2.4	0.59	0.45	0.39	4.6	8.3	7.6	5.9
	AT-1 (SN and IS)	1	4.1	4.3	3.4	2.6	4.6	8.7	9.4	8.7
	AT-2 (SN)	0	3.1	0.99	0.83	0.77	5.0	9.5	9.4	7.6
	AT-2 (SN)	1	5.2	5.4	4.4	3.4	5.0	10	11	11
	AT-2 (IS)	0	4.8	1.2	0.90	0.77	9.2	17	15	12
	AT-2 (IS)	1	8.3	8.6	6.8	5.2	9.2	18	19	17
	AT-3 (SN and IS)	0	2.8	0.68	0.51	0.44	5.2	9.5	8.7	6.7
	AT-3 (SN and IS)	1	4.8	4.9	3.9	3.0	5.3	10	11	9.9
^{10}B: 0.72(+0.72, −0.36)(−9)...	MAR-1	0	1.2	0.28	0.21	0.18	2.2	4.0	3.6	2.8
	MAR-1	1	2.0	2.0	1.6	1.3	2.2	4.2	4.5	4.1
	MAR-2	0	2.7	0.66	0.50	0.43	5.1	9.2	8.5	6.5
	MAR-2	1	4.6	4.8	3.8	2.9	5.1	9.7	10	9.6
	AT-1 (SN and IS)	0	1.2	0.28	0.21	0.18	2.2	4.0	3.6	2.8
	AT-1 (SN and IS)	1	2.0	2.0	1.6	1.3	2.2	4.2	4.5	4.1
	AT-2 (SN)	0	9.3	5.5	5.3	5.3	5.5	16	24	25
	AT-2 (SN)	1	15	16	14	11	5.6	17	28	32
	AT-2 (IS)	0	33	8.2	6.2	5.3	64	115	106	81
	AT-2 (IS)	1	58	10	47	36	64	120	130	120
	AT-3 (SN)	0	2.5	1.1	0.99	0.96	3.0	6.4	7.3	6.6
	AT-3 (SN)	1	4.2	4.4	3.7	2.8	3.0	6.7	8.5	9.0
	AT-3 (IS)	0	6.1	1.5	1.1	0.98	12	21	19	15
	AT-3 (IS)	1	11	11	8.6	6.7	12	22	24	22
^{11}B: 0.32(+0.32, −0.16)(−8)...	MAR-1	0	0.30	0.072	0.055	0.047	0.56	1.0	0.93	0.72
	MAR-1	1	0.51	0.52	0.42	0.32	0.56	1.1	1.1	1.1
	MAR-2	0	1.1	0.26	0.20	0.17	2.0	3.6	3.3	2.6
	MAR-2	1	1.8	1.9	1.5	1.1	2.0	3.8	4.1	3.8
	AT-1 (SN and IS)	0	0.32	0.078	0.059	0.050	0.60	1.1	1.0	0.77
	AT-1 (SN and IS)	1	0.54	0.56	0.45	0.34	0.60	1.1	1.2	1.1
	AT-2 (SN)	0	4.1	2.4	2.3	2.3	2.4	7.2	11	11
	AT-2 (SN)	1	6.5	7.0	6.1	4.7	2.4	7.5	12	14
	AT-2 (IS)	0	15	3.6	2.7	2.4	28	51	47	36
	AT-2 (IS)	1	25	26	21	16	28	54	57	53
	AT-3 (SN)	0	0.68	0.42	0.40	0.40	0.41	1.2	1.8	1.9
	AT-3 (SN)	1	1.1	1.2	1.0	0.80	0.42	1.3	2.1	2.4
	AT-3 (IS)	0	2.5	0.60	0.47	0.40	4.8	8.7	8.0	6.1
	AT-3 (IS)	1	4.4	4.3	3.6	2.7	4.8	9.2	9.8	9.0

* 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 suprathermal particles react *in* the supernova envelopes, and IS refers to the case where the suprathermal component is produced in the interstellar medium *near* the supernovae.

‡ Fraction of each stellar envelope in which the element is not destroyed by astration, normalized to unity for the fractions given by TC for ^{3}He.

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JEAN AUDOUZE
Department de Radio Astronomie, Observatoire de Meudon, Place Jenssen, 92190 Meudon, France

BEATRICE M. TINSLEY
Department of Astronomy, The University of Texas at Austin, Austin, TX 78712