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The Light Elements Be and B as Stellar Chronometers in the Early Galaxy

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Abstract. Recent detailed simulations of Galactic Chemical Evolution have shown that the heavy elements, in particular [Fe/H], are expected to exhibit a weak, or absent, correlation with stellar ages in the early Galaxy due to the lack of efficient mixing of interstellar material enriched by individual Type II supernovae. A promising alternative "chronometer" of stellar ages is suggested, based on the expectation that the light elements Be and B are formed primarily as spallation products of Galactic Cosmic Rays.

1. Introduction

It has become clear, from a number of lines of recent evidence, that the early evolution of the Galaxy is best thought of as a stochastic process. Within the first 0.5-1 Gyr following the start of the star formation process, chemical enrichment does not operate within a well-mixed uniform environment, as was assumed in the simple one-zone models that were commonly used in past treatments of this problem. Rather, the very first generations of stars are expected to have their abundances of heavy elements set by local conditions, which are likely to have been dominated by the yields from individual SNeII.

The seeds of this paradigm shift can be found in the observations, interpretations, and speculations of McWilliam et al. (1995), Audouze & Silk (1995), and Ryan, Norris, & Beers (1996). Models which attempt to incorporate these ideas into a predictive formalism have been put forward by Tsujimoto, Shigeyama, & Yoshii (1999; hereafter TSY), and Argast et al. (2000). Although they differ in the details of their implementation, and in a number of their assumptions, both of these models rely on the idea of enhanced star formation in the high-density shells of SN remnants, and the interaction of these shells of enriched material with a local ISM. The predictions which result are similar as well: (1) Both models are capable of reproducing the observed distributions of abundance (e.g., [Fe/H]) for stars in the tail of the halo metallicity distribution function (Laird et al. 1988; Ryan & Norris 1991; Beers 1999), and (2) Both models predict that the abundances of heavy elements, such as Fe, are not expected to show strong correlations with the ages of the first stars, at least up until an enrichment level on the order of [Fe/H]~ -2.0 is reached, i.e., at the time when mixing on a Galactic scale is possible (roughly 1 Gyr following the initiation of star formation).

Suzuki, Yoshii, & Kajino (1999; hereafter SYK, see also Suzuki, Yoshii, & Kajino, this volume) have extended the SN-induced chemical evolution model of TSY to include predictions of the evolution of the light element species ^{9}Be, ^{10}B, and ^{11}B, based on secondary processes involving spallative reactions with Galactic Cosmic Rays (hereafter GCRs). Recently, Suzuki, Yoshii, & Beers (2000) have considered the extension of this model to the prediction of ^{6}Li and ^{7} Li, and demonstrate that they naturally reproduce the recently detected slope in the abundance of Li in extremely metal-poor stars noted by Ryan, Norris, & Beers (1999; see also Ryan this volume). It is particularly encouraging that the same stochastic star-formation models which reproduce the observed trends of some (but not all) heavy elements, such as Eu, Fe, etc., also obtain predictions of the light element abundance distributions that match the available observations quite well, with a minimum of parameter tweaking.

In this contribution we summarize one of the more interesting predictions of the TSY/SYK class of models, that the abundances of the light elements Be and B (hereafter, BeB) might be useful as stellar chronometers in the early Galaxy (a time when the heavy element "age-metallicity" relationships are not operating due to the lack of global mixing). It appears possible that, with refinement of the modeling, and adequate testing, observations of BeB for metal-poor stars may provide a chronometer with "time resolution" on scales of tens of Myrs.

2. The Essence of the Model

In this section we would like to briefly explain our model of SN-induced star formation and chemical evolution. After formation of the very FIRST generation of (Pop. III) stars, with atmospheres containing gas of primordial abundance, the most massive of these stars exhaust their core H, and explode as SNeII. Following the explosion a shock is formed, because the velocity of the ejected material exceeds the local sound speed. Behind the shock the swept-up ambient material in the ISM accumulates to form a high-density shell. This shell cools in the later stages of the lifetime of a given SN remnant (SNR) and is a suitable site for the star formation process to occur. The SNR shells are expected to be distributed randomly throughout the early and rapidly evolving halo, and the shells do not easily merge with one another because of the large available volume. As a result, each SNR keeps its identity and the stars which form there reflect the abundances of material generated by their "parent" SN. TSY present this model, and describe the input assumptions, in more quantitative detail. Figure 1 provides a cartoon illustration of the processes which we discuss herein.

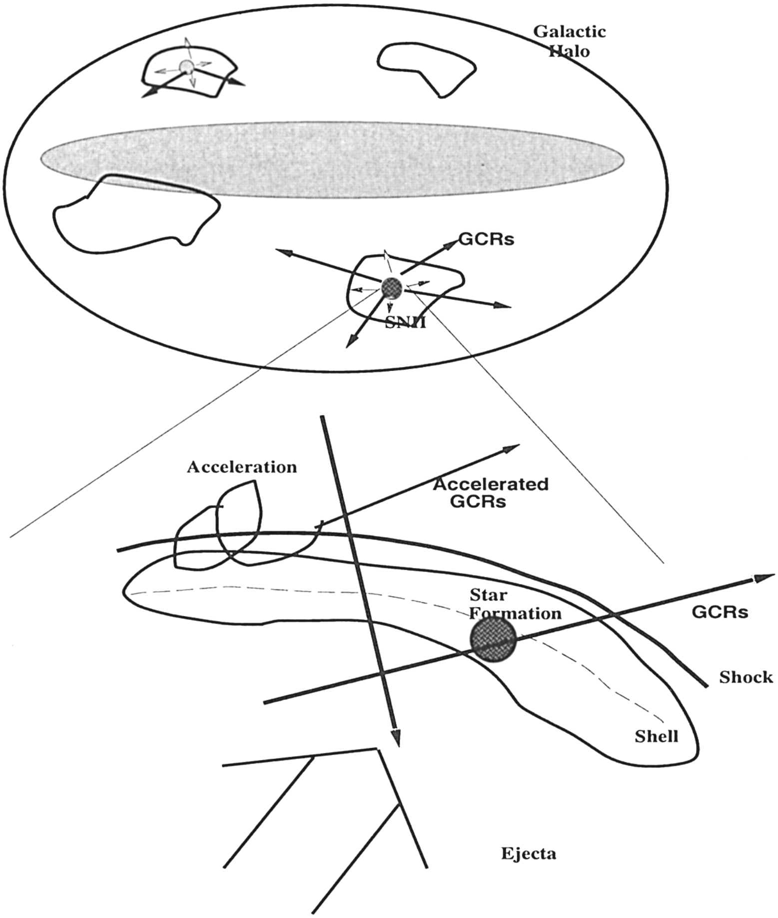

Figure 1. A simplified view of the early stages of chemical evolution in the Galactic halo. In the lower cutout we show star formation being triggered in SNR shells. See text for more detail.

One of the most important results of the TSY model is that stellar metallicity, especially [Fe/H], cannot be employed as an age indicator at these early epochs. Thus, to consider the expected elemental abundances of the metal-poor stars which form at a given time, a *distribution* of stellar abundances must be constructed, rather than adopting a global average abundance under the assumption that the gas of the ISM is well mixed. SYK constructed such a model, coupled with the model of SN-induced chemical evolution, which considers the evolution of the light elements.

SYK proposed that GCRs arise from the mixture of elements of individual SN ejecta and their swept-up ISM, with the acceleration being due to the shock formed in the SNR. GCRs originating from SNeII propagate faster than the material trapped in the clouds of gas making up the early halo. As a result, GCRs are expected to achieve uniformity throughout the halo faster than the general ISM, with its patchy structure. It follows that the abundances of BeB, which are mainly produced by spallation processes of CNO elements involving GCRs, are expected to exhibit a much tighter correlation with time than those of heavy elements, synthesized through stellar evolution and SN explosions.

We note that alternative models for the origin of spallative nucleosynthesis products have been developed which rely on the existence of *spatially correlated* SNeII in superbubbles of the early ISM (see Parizot & Drury 1999, and this volume). The superbubble model predicts a locally homogeneous production of both heavy and light elements, and the variety of stellar abundances which are observed are explained by the differing diffusion processes of metal-rich ([Fe/H] ~ -1) shells swept-up by the bubble and mixed with a metal-poor ([Fe/H] ~ -4) ISM. Tests of the "isolated" SN models vs. the superbubble models are expected to be conducted in the near future.

3. Abundance Predictions of the Model

Figure 2 shows the predicted behavior of the abundance of [Fe/H], log(Be/H), and log(B/H), as a function of time, over the first 0.6 Gyrs of the evolution of the early Galaxy, according to the model of SYK. At any given time (note that "zero time" is set by the onset of star formation, not the beginning of the Universe) the range of observed BeB is substantially less than that of Fe, owing to the global nature of light element production. For example, at time 0.2 Gyrs, the expected stellar [Fe/H] extends over a range of 50, while that of log (BeB/H) is on the order of 3–7.

During early epochs Fe is produced *only* by SNeII, and most of the Fe observed in stars formed in SNR shells originates from that contributed by the parent SN, because of uniformly low Fe abundance in the ISM at that time. Thus, the expected [Fe/H] of stars born at that time will exhibit a rather large range, reflecting differences in Fe yields associated with the different masses of the progenitor stars. On the other hand, according to the SYK model, most of the BeB is produced by spallation reactions of CNO nuclei involving globally transported GCRs. The observed abundances of BeB in metal-poor stars which formed at this time should reflect the global nature of their production, and the correlation between time and BeB abundance is expected to be much better than that found for heavier species.

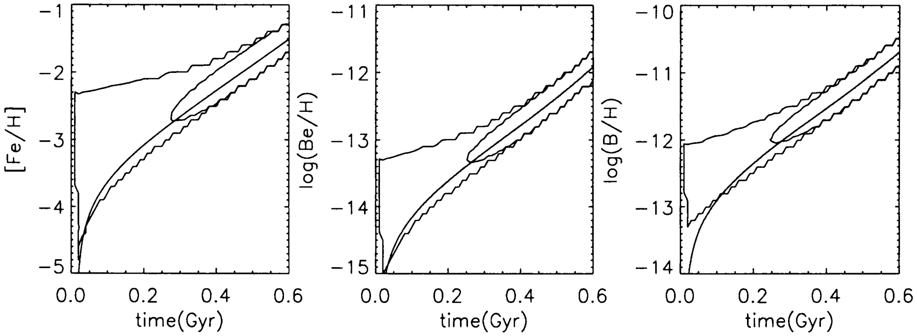

Figure 2. Predicted distribution of abundance for three elements, relative to H, for long-lived stars born at the indicated time *following* the initiation of star formation. The distributions have been convolved with Gaussians with $\sigma = 0.15$ dex to take into account expected observational errors. The two contours, from the inside to the outside, correspond to probability density 10^{-3} and 10^{-5} within the unit area $\Delta t = 10(\mathrm{Myr}) \times \Delta \log(\mathrm{element/H}) = 0.1$. The solid lines show the predicted ISM gas abundances of each element.

In Table 1, we use the predictions from SYK, and the stellar abundance data from Boesgaard et al. (1999) for Be, to put forward "bold" estimates of stellar ages (since the onset of star formation). We note that these numbers are meant to be indicative, not definitive, predictions, as further tests of the model and its underlying assumptions still remain to be carried out. We have ordered the table according to estimated (Be) time since the onset of star formation in the early Galaxy.

It is interesting to consider the implications of this strong age-abundance relationship for individual stars which have been noted in the literature as having "peculiar" BeB (or ^{7}Li for that matter) abundances, at least as compared to otherwise similar stars of the same [Fe/H], T_{eff}, and log g. The set of "twins" G64-12 and G64-37 have been noted as one example of stars with very low metallicity, and apparently similar T_{eff} and log g, which never-the-less, exhibit rather different abundances of ^{7}Li. Could this difference be accounted for by a difference in AGE of these stars ? Answering this question is of great importance, and hopefully will be resolved in the near future.

4. Can we Test This Model ?

Yes, but it will take some hard work. Obviously, if there exists an independent method with which to verify the relative age determinations predicted by this model, that would be ideal. Fortunately, there have been numerous refinements in models of stellar atmospheres, and their interpretation, which may make

Table 1. Predictions of Stellar "Ages" Based on Be Abundance

Star	[Fe/H]	log(Be/H)	Be "age" (Gyr)
BD−13:3442	−3.02	−13.49	0.22 (−0.07,+0.03)
BD+03:740	−2.89	−13.33	0.26 (−0.05,+0.03)
HD 140283	−2.56	−13.08	0.32 (−0.05,+0.02)
BD+37:1458	−2.14	−13.07	0.32 (−0.05,+0.02)
HD 84937	−2.20	−12.94	0.35 (−0.05,+0.03)
BD+26:3578	−2.32	−12.79	0.39 (−0.05,+0.03)
BD+02:3375	−2.39	−12.80	0.39 (−0.05,+0.03)
BD−04:3208	−2.35	−12.69	0.41 (−0.05,+0.03)
HD 19445	−2.10	−12.55	0.45 (−0.04,+0.03)
HD 64090	−1.77	−12.49	0.46 (−0.04,+0.03)
BD+20:3603	−2.22	−12.47	0.46 (−0.04,+0.03)
BD+17:4708	−1.81	−12.40	0.48 (−0.04,+0.03)
HD 219617	−1.58	−12.15	0.54 (−0.04,+0.02)
HD 74000	−2.05	−12.10	0.55 (−0.04,+0.02)
HD 103095	−1.37	−12.04	0.56 (−0.04,+0.02)
HD 194598	−1.25	−11.88	0.59 (−0.03,+0.01)
BD+23:3912	−1.53	−11.92	0.59 (−0.03,+0.01)
HD 94028	−1.54	−11.55	> 0.60

this feasible (see Fuhrmann 2000). In order to apply the methods described by Fuhrmann, one requires high-resolution, high-S/N spectroscopy of individual stars. It is imperative that the present-generation 8m telescopes (VLT, SUBARU, GEMINI, HET) obtain this data, so that this, and other related questions, may be addressed with the best possible information.

Another feasible test would be to compare the abundances of BeB with [Fe/H], and other heavy elements, for a large sample of stars with [Fe/H] < -2.0. If the superbubble model is the correct interpretation, with an implied locally homogeneous production of the light elements, then one might expect to find correlations between the abundances of various heavy element species (including those other than Fe and O) and BeB. Simultaneous observations of light and heavy elements for stars of extremely low abundance are planned with all the major 8m telescopes, so it should not be too long before a sufficiently large sample to carry out this test is obtained.

One can also seek, as we have, confirmatory evidence in the predicted behavior of ^{7}Li vs. [Fe/H] (Suzuki et al. 2000).

5. Other Uses for This Model

If the model we have considered here can be shown to be correct, there are several new avenues of investigation which are immediately opened. For example, if one were able to "age rank" stars on the basis of their BeB abundances, one could refine alternative production mechanisms for the light element Li which are not driven by GCR spallation, including the SN $\nu-$process and/or production via a giant-branch Cameron-Fowler mechanism (see Castilho et al. , this volume), in stellar flares, etc..

Furthermore, since BeB nuclei are more difficult to burn than Li nuclei, one could imagine a powerful test for the extent to which depletion of Li has operated in metal-poor dwarfs, with important implications for the Li constraint on Big Bang Nucleosynthesis (BBN). Realistic modeling of BeB evolution at early epochs may also help distinguish between predictions of standard BBN, non-standard BBN, and the accretion hypothesis (see Yoshii, Mathews, & Kajino 1995).

An age ranking of metal-poor stars based on their BeB abundances, in combination with measurements of their alpha, iron-peak, and neutron-capture elements, would open the door for an unraveling of the mass spectrum of the progenitors of first generation SNeIIs, and allow one to obtain direct constraints on their elemental yields as a function of mass, a key component to models of early nucleosynthesis.

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