THE ASTROPHYSICAL JOURNAL, 549:337–345, 2001 March 1

EVOLUTION OF O ABUNDANCE RELATIVE TO Fe

Y.-Z. QIAN[1] AND G. J. WASSERBURG[2]

Received 2000 September 7; accepted 2000 October 23

ABSTRACT

We present a three-component mixing model for the evolution of O abundance relative to Fe, taking into account the contributions of the first very massive stars (with masses of $\gtrsim 100\ M_{\odot}$) formed from Big Bang debris. We show that the observations of O and Fe abundances in metal-poor stars in the Galaxy by Israelian et al. in 1998 and by Boesgaard et al. in 1999 can be well represented both qualitatively and quantitatively by this model. We use the representation of the number ratios (O/Fe) versus 1/(Fe/H). In this representation, if there is only a single source with a fixed production ratio of O to Fe beyond a certain point, the subsequent evolution of (O/Fe) is along a straight line segment. Under the assumption of an initial Fe ([Fe/H] ~ -3) and O inventory caused by the prompt production by the first very massive stars, the data of Israelian et al. and Boesgaard et al. at $-3 \lesssim$ [Fe/H] $\lesssim -1$ are interpreted to result from the addition of O and Fe only from Type II supernovae (SNII) to the prompt inventory. At [Fe/H] $\gtrsim -1$, SNII still contribute O while both SNII and Type Ia supernovae contribute Fe. During this later stage, (O/Fe) sharply drops off to an asymptotic value of ~ 0.8 (O/Fe)$_{\odot}$. The value of (O/Fe) for the prompt inventory at [Fe/H] ~ -3 is found to be (O/Fe) ~ 20 (O/Fe)$_{\odot}$. This result suggests that protogalaxies with low "metallicities" should exhibit high values of (O/Fe). The C/O ratio produced by the first very massive stars is expected to be $\ll 1$ so that all the C should be tied up as CO and that C dust and hydrocarbon compounds should be quite rare at epochs corresponding to [Fe/H] $\lesssim -3$.

Subject headings: Galaxy: abundances — Galaxy: evolution — Galaxy: formation — stars: abundances — supernovae: general

1. INTRODUCTION

In a recent theoretical study of Fe and *r*-process abundances in the early Galaxy by Wasserburg & Qian (2000a), it was proposed that the first stars formed after the Big Bang were very massive ($\gtrsim 100\ M_{\odot}$) and enriched the interstellar medium (ISM) to [Fe/H] ~ -3, at which metallicity point formation of regular stars (with masses of ~ 1–60 $M_{\odot}$) took over. The initial Fe inventory of [Fe/H] ~ -3 could be provided over a short or rather long period prior to the onset of regular star formation; but, for convenience, we will refer to this as the "prompt inventory" hereafter. Subsequent Fe enrichment was provided initially by a subset of Type II supernovae (SNII). The interpretations of Wasserburg & Qian (2000a) were based on observations of metal-poor stars in the Galaxy by Gratton & Sneden (1994), McWilliam et al. (1995), McWilliam (1998), and Sneden et al. (1996, 1998). The critical metallicity [Fe/H] ~ -3 deduced by Wasserburg & Qian (2000a) for transition from formation of very massive stars to regular stars is in remarkable coincidence with the lower bound of [Fe/H] ~ -2.7 observed in damped Lyα systems over a wide range in redshift (e.g., Prochaska & Wolfe 2000). Furthermore, Wasserburg & Qian (2000b) showed that the [Fe/H] of damped Lyα systems can be explained in a straightforward manner by addition of Fe from SNII to the prompt inventory provided by the first very massive stars and that the evolution of [Fe/H] with redshift reflects the chronology of turn-on of protogalaxies.

The first very massive stars would certainly produce elements other than Fe. One of the issues to be resolved is the general problem of the nucleosynthetic signatures of these stars. This problem was discussed in the early work by Ezer & Cameron (1971). More recently, studies on condensation of Big Bang debris (e.g., Bromm, Coppi, & Larson 1999) indicated that protostellar aggregates of $\sim 100\ M_{\odot}$ may be formed. Evolution of zero-metallicity stars of $\gtrsim 100\ M_{\odot}$ was discussed by Fryer, Woosley, & Heger (2001). Calculations by Heger, Woosley, & Waters (2000) suggest that C, N, O, Mg, Si, and Fe are produced in large amounts by these stars. The question is how the theoretical models of nucleosynthesis in the first very massive stars formed from Big Bang debris are related to the observations. Another issue concerns the Fe enrichment by Type Ia supernovae (SNIa). It was assumed by Wasserburg & Qian (2000a, 2000b) that SNIa started to contribute Fe at [Fe/H] ~ -1 and were responsible for $\sim \frac{2}{3}$ of the solar Fe inventory. In a self-consistent Fe enrichment model, the history of SNIa Fe contribution needs to be examined more carefully based on observations.

This paper presents a phenomenological model for the evolution of O abundance relative to Fe. Our approach differs from previous studies (e.g., Timmes, Woosley, & Weaver 1995) in the following respects. Previous studies rely on many inputs such as the nucleosynthetic yields predicted by various models of SNII and SNIa and some description of star formation. In the approach here, we attempt to identify a chemical evolution model that can account for the observed evolution of O abundance relative to Fe in terms of several key parameters. We hope that this approach will give a simple yet complete interpretation of the data. The usual representation of the O and Fe data is to display [O/Fe] against [Fe/H]. Our approach here uses (O/Fe) versus 1/(Fe/H), with the parentheses indicating the number ratios. If there is only a single source with a fixed production ratio of O to Fe beyond a certain point, the subsequent evolution of (O/Fe) as a function of 1/(Fe/H) is

[1] School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455; qian@physics.umn.edu.
[2] The Lunatic Asylum, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125.

along a straight line segment. As will be shown, this representation also facilitates a simple geometric means to describe the evolution of O and Fe abundances in the general case. As the first very massive stars are thought to be a source of O and Fe (Heger et al. 2000), the value of (O/Fe) at [Fe/H] $\lesssim -3$ should serve as a nucleosynthetic signature of these stars, thus addressing the first issue raised above. Subsequent to the prompt enrichment by the very massive stars, SNII are essentially the only source of O, while Fe enrichment was provided by SNII initially and augmented by the contribution from SNIa only at a later time. Thus the evolution of O abundance relative to Fe at [Fe/H] > -3 provides a means of addressing questions concerning the onset and nature of SNIa Fe contribution.

Based on the observations of metal-poor stars in the Galaxy by Israelian, Garcia Lopez, & Rebolo (1998) and Boesgaard et al. (1999), the value of (O/Fe) resulting from the prompt production by the first very massive stars is $\sim 20\ (\mathrm{O/Fe})_\odot$. Comparison of our model with the same observations gives a history of SNIa Fe contribution that is consistent with the results of previous studies (e.g., Timmes et al. 1995) and with the assumptions of Wasserburg & Qian (2000a, 2000b). The average production of O relative to Fe for SNII is found to be $(\mathrm{O/Fe})_{\mathrm{II}} \sim 3\ (\mathrm{O/Fe})_\odot$, which is ~ 7 times lower than that for the very massive stars. While the results on the prompt O inventory are dependent on the data of Israelian et al. (1998) and Boesgaard et al. (1999), the methodology developed here is reliable in general and can be applied to any set of data. Our model is presented in § 2 and compared with observations in § 3. Discussion and conclusions are given in § 4.

2. MODEL FOR EVOLUTION OF O ABUNDANCE RELATIVE TO Fe

For the sake of simplicity, we focus on the evolution of O and Fe abundances in a closed system with a fixed mass. This mass can be stored in gas and stars. The initial state P at time $t = 0$ contains gas only. At $t > 0$, the total mass of gas $M_{\mathrm{gas}}(t)$ and that of stars $M_{\mathrm{star}}(t)$ satisfy

$$M_{\mathrm{gas}}(t) + M_{\mathrm{star}}(t) = M_{\mathrm{gas}}(0)\ . \tag{1}$$

We ignore the return of O and Fe to the gas by stars that are not related to SNII or SNIa and consider that stars sample the composition of the gas at the time of their birth. Thus the mass fraction $X_{\mathrm{E}}(t)$ of the element E in the gas is governed by

$$X_{\mathrm{E}}(t)M_{\mathrm{gas}}(t) + \int_0^t X_{\mathrm{E}}(t') \frac{dM_{\mathrm{star}}(t')}{dt'}\, dt' = \int_0^t [P_{\mathrm{E,II}}(t') + P_{\mathrm{E,I}}(t')] dt'\ , \tag{2}$$

where $P_{\mathrm{E,II}}(t)$ and $P_{\mathrm{E,I}}(t)$ are the total rates for production of the element by SNII and SNIa.

Differentiating equation (2) with respect to t gives

$$M_{\mathrm{gas}}(t) \frac{dX_{\mathrm{E}}}{dt} = P_{\mathrm{E,II}}(t) + P_{\mathrm{E,I}}(t)\ , \tag{3}$$

where equation (1) has been used. Equation (3) can be integrated to give

$$X_{\mathrm{E}}(t) = X_{\mathrm{E}}(0) + \int_0^t \frac{P_{\mathrm{E,II}}(t')}{M_{\mathrm{gas}}(t')}\, dt' + \int_0^t \frac{P_{\mathrm{E,I}}(t')}{M_{\mathrm{gas}}(t')}\, dt'\ . \tag{4}$$

Note that the integrands in equation (4) only depend on the production rates per unit mass of gas. As the mass fraction of H in the gas is nearly constant during its evolution, $X_{\mathrm{E}}(t)$ is proportional to the number ratio (E/H). So, equation (4) can be rewritten as

$$(\mathrm{E/H}) = (\mathrm{E/H})_P + (\mathrm{E/H})_{\mathrm{II}} + (\mathrm{E/H})_{\mathrm{I}}\ , \tag{5}$$

where $(\mathrm{E/H})_P$ is the inventory for the initial state P, and $(\mathrm{E/H})_{\mathrm{II}}$ and $(\mathrm{E/H})_{\mathrm{I}}$ represent the integral of the production rate per unit mass of gas over time for SNII and SNIa.

We consider that the first very massive stars (with masses of $\gtrsim 100\ M_\odot$) formed from Big Bang debris provided an inventory of Fe ([Fe/H] ~ -3) and O. Frequently we use "prompt inventory" or "prompt production" when referring to this inventory of Fe and associated elements. It is considered that only very massive stars could form until this level of Fe and associated elements was reached. The onset of formation of regular stars (with masses of ~ 1–60 $M_\odot$) corresponds to [Fe/H] ~ -3. This defines the initial state P of the system. Subsequently, SNII that are related to the formation of regular massive stars (with masses of ~ 10–60 $M_\odot$) began to contribute O and Fe. At a still later time (see § 3), SNIa also began to contribute additional Fe. It is considered (e.g., Timmes et al. 1995) that SNIa produce essentially no O. So we assume a production ratio $(\mathrm{O/Fe})_{\mathrm{I}} = 0$ for SNIa. The O and Fe yields may vary significantly between individual SNII (see § 4). However, the O or Fe contribution from all SNII may be lumped together so long as we are concerned with timescales of, e.g., $\gtrsim 10^8$ yr (see § 4). Furthermore, we will assume a constant average production ratio $(\mathrm{O/Fe})_{\mathrm{II}}$ for SNII.

The value of (O/Fe) for the initial state P resulting from the prompt production by the first very massive stars is taken to be a constant $(\mathrm{O/Fe})_P$. Thus $(\mathrm{O/Fe})_P$ represents the production ratio for the prompt source, $(\mathrm{O/Fe})_{\mathrm{II}}$ for SNII, and $(\mathrm{O/Fe})_{\mathrm{I}} = 0$ for SNIa. The whole evolution of O and Fe abundances can then be described by a three-component mixing model. In consideration of the time sequence indicated above, there is a domain where the model reduces to only two components, the prompt source and SNII (no SNIa). In this domain, the number ratio of O to Fe in the gas is

$$(\mathrm{O/Fe}) = \frac{(\mathrm{O/H})_P + (\mathrm{O/H})_{\mathrm{II}}}{(\mathrm{Fe/H})_P + (\mathrm{Fe/H})_{\mathrm{II}}} = \frac{(\mathrm{O/Fe})_P(\mathrm{Fe/H})_P + (\mathrm{O/Fe})_{\mathrm{II}}(\mathrm{Fe/H})_{\mathrm{II}}}{(\mathrm{Fe/H})}\ , \tag{6}$$

where $(\mathrm{Fe/H}) = (\mathrm{Fe/H})_P + (\mathrm{Fe/H})_{\mathrm{II}}$. Equation (6) can be rewritten as

$$(\mathrm{O/Fe}) = (\mathrm{O/Fe})_{\mathrm{II}} + [(\mathrm{O/Fe})_P - (\mathrm{O/Fe})_{\mathrm{II}}] \frac{(\mathrm{Fe/H})_P}{(\mathrm{Fe/H})}\ . \tag{7}$$

Thus the ratio (O/Fe) is a linear function of $(\mathrm{Fe/H})_P/(\mathrm{Fe/H})$ with a slope of $[(\mathrm{O/Fe})_P - (\mathrm{O/Fe})_{\mathrm{II}}]$. The evolution of (O/Fe) in this regime would be along the line segment PII in Figure 1. Point P is at $(\mathrm{O/Fe}) = (\mathrm{O/Fe})_P$ and $(\mathrm{Fe/H})_P/(\mathrm{Fe/H}) = 1$, and represents the initial state P. Point II is at $(\mathrm{O/Fe}) = (\mathrm{O/Fe})_{\mathrm{II}}$ and $(\mathrm{Fe/H})_P/(\mathrm{Fe/H}) = 0$ and represents the result after an infinite number of SNII (eq. [7]). If SNII cease to occur after contributing finite amounts of Fe and O, then the endpoint for this part of the evolution would lie somewhere on the line segment PII.

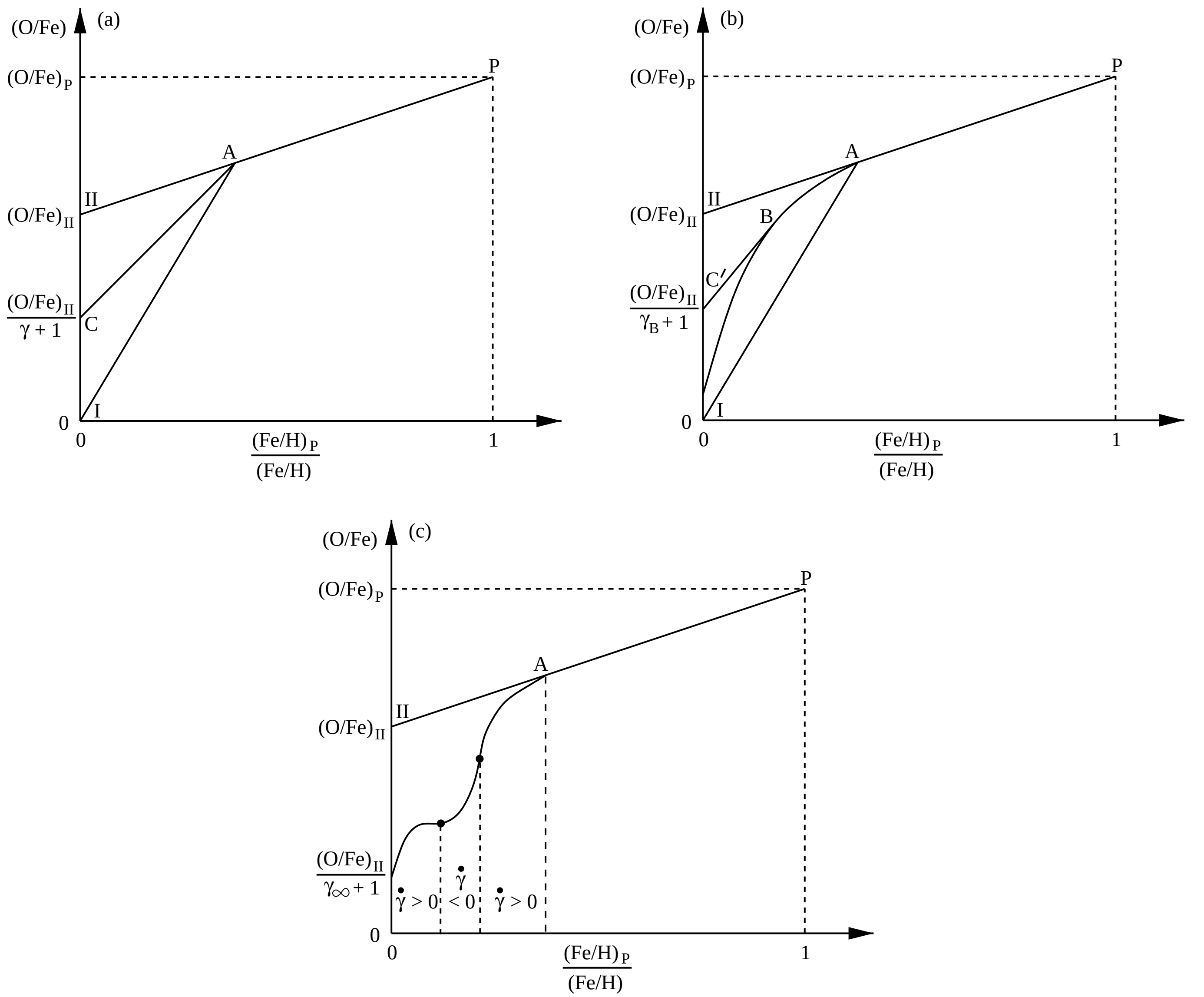

FIG. 1.—Illustration of the evolution of (O/Fe) as a function of $(\mathrm{Fe/H})_P/(\mathrm{Fe/H})$. Here $(\mathrm{O/Fe})_P$ represents the production ratio for the prompt source, $(\mathrm{O/Fe})_{\mathrm{II}}$ for SNII, and $(\mathrm{O/Fe})_{\mathrm{I}} = 0$ for SNIa. The initial state *P* results from the production by the prompt source. State *A* corresponds to the onset of SNIa Fe contribution. The general evolution is described by a three-component mixing model involving the initial state *P*, SNII, and SNIa. Prior to reaching state *A*, the evolution is along the line segment *P*II, with point II representing the state to be reached after an infinite number of SNII. (*a*) If SNII contributions were to cease at state *A*, subsequent evolution would be along the line segment *P*I, with point I representing the state to be reached after an infinite number of SNIa. On the other hand, if the rate per unit mass of gas for Fe production by SNIa relative to SNII were a constant γ, the evolution beyond state *A* would be along the line segment *AC*, with point *C* representing the state to be reached after an infinite number of SNII and SNIa. Note that the line segments *A*II and *A*I correspond to the limits $\gamma = 0$ and ∞. (*b*) In general, the rate per unit mass of gas for Fe production by SNIa relative to SNII is a function of time $\gamma(t)$. So the evolution beyond state *A* follows a curve between the line segments *A*II and *A*I. The tangent at an arbitrary point *B* on the curve is the same as the slope of the line segment *BC*′, with point *C*′ representing the state to be reached after an infinite number of SNII and SNIa for a constant γ equal to the value γ_B at point *B*. Thus if $\gamma(t)$ monotonically increases with time, the curve drops more and more steeply in approaching $(\mathrm{Fe/H})_P/(\mathrm{Fe/H}) = 0$. (*c*) In general, the curve is concave downward if $\gamma(t)$ increases with time ($\dot{\gamma} > 0$) and is concave upward if $\gamma(t)$ decreases with time ($\dot{\gamma} < 0$). In any case, the value of (O/Fe) to be reached after an infinite number of SNII and SNIa is determined by the asymptotic value γ_∞ of $\gamma(t)$.

If the SNII contributions were to cease and SNIa were to begin to contribute Fe at the state corresponding to point *A* on the line segment *P*II in Figure 1, then the evolution of (O/Fe) would again reduce to a two-component mixing model with one member being state *A* and the other being SNIa. In this simplified case (no concurrent production by SNII), the evolution of (O/Fe) beyond point *A* would be along the line segment *A*I in Figure 1 corresponding to

$$(\mathrm{O/Fe}) = (\mathrm{O/Fe})_A \frac{(\mathrm{Fe/H})_A}{(\mathrm{Fe/H})}, \qquad (8)$$

where $(\mathrm{Fe/H}) = (\mathrm{Fe/H})_A + (\mathrm{Fe/H})_{\mathrm{I}}$, and the subscript "*A*" stands for quantities at point *A*. Point *I* in Figure 1 is at $(\mathrm{O/Fe}) = (\mathrm{O/Fe})_I = 0$ and $(\mathrm{Fe/H})_P/(\mathrm{Fe/H}) = 0$ and represents the result after an infinite number of SNIa (eq. [8]).

As SNII still occur after SNIa start to contribute Fe at point *A*, the actual evolution of (O/Fe) follows a curve between the line segments *A*II and *A*I in Figure 1. This is a three-component mixing regime involving state *A*, SNII, and SNIa. An important parameter for this regime is the rate per unit mass of gas for Fe production by SNIa relative to SNII:

$$\gamma \equiv \frac{d(\mathrm{Fe/H})_{\mathrm{I}}/d\,t}{d(\mathrm{Fe/H})_{\mathrm{II}}/d\,t}\,. \qquad (9)$$

For a constant γ, we have

$$(\mathrm{O/Fe}) = \frac{(\mathrm{O/Fe})_{\mathrm{II}}}{\gamma+1} + \left[(\mathrm{O/Fe})_A - \frac{(\mathrm{O/Fe})_{\mathrm{II}}}{\gamma+1}\right]\frac{(\mathrm{Fe/H})_A}{(\mathrm{Fe/H})}\,, \qquad (10)$$

corresponding to the line segment AC in Figure 1*a*. Point C is at $(\mathrm{O/Fe}) = (\mathrm{O/Fe})_{\mathrm{II}}/(\gamma+1)$ and $(\mathrm{Fe/H})_P/(\mathrm{Fe/H}) = 0$ and represents the result after an infinite number of SNII and SNIa (eq. [10]). It can be seen that the line segments AII and AI correspond to the limits $\gamma = 0$ and ∞.

In general, γ is a function of time t. We can discuss the evolution of (O/Fe) as a function of $(\mathrm{Fe/H})_P/(\mathrm{Fe/H})$ for the case of a time-dependent γ by calculating $d(\mathrm{O/Fe})/d\,t$ and $d[(\mathrm{Fe/H})_P/(\mathrm{Fe/H})]/d\,t$. From the rates for addition to the total O and Fe inventory in the gas,

$$\frac{d(\mathrm{O/H})}{d\,t} = \frac{d(\mathrm{O/H})_{\mathrm{II}}}{d\,t} = (\mathrm{O/Fe})_{\mathrm{II}}\frac{d(\mathrm{Fe/H})_{\mathrm{II}}}{d\,t}\,, \qquad (11)$$

and

$$\frac{d(\mathrm{Fe/H})}{d\,t} = \frac{d(\mathrm{Fe/H})_{\mathrm{II}}}{d\,t} + \frac{d(\mathrm{Fe/H})_{\mathrm{I}}}{d\,t} = [\gamma(t)+1]\frac{d(\mathrm{Fe/H})_{\mathrm{II}}}{d\,t}\,, \qquad (12)$$

we obtain

$$S \equiv \frac{d(\mathrm{O/Fe})}{d[(\mathrm{Fe/H})_P/(\mathrm{Fe/H})]} = \frac{(\mathrm{O/Fe}) - \{(\mathrm{O/Fe})_{\mathrm{II}}/[\gamma(t)+1]\}}{(\mathrm{Fe/H})_P/(\mathrm{Fe/H})}\,. \qquad (13)$$

Figure 1*b* gives a simple geometric interpretation of equation (13). At an arbitrary point B beyond point A, the tangent S of the curve for (O/Fe) is the same as the slope of the line segment BC'. Point C' is at $(\mathrm{O/Fe}) = (\mathrm{O/Fe})_{\mathrm{II}}/(\gamma_B+1)$ and $(\mathrm{Fe/H})_P/(\mathrm{Fe/H}) = 0$ and represents the result after an infinite number of SNII and SNIa for a constant γ equal to the value γ_B at point B (eq. [10]).

Equation (13) also gives

$$\frac{dS}{d[(\mathrm{Fe/H})_P/(\mathrm{Fe/H})]} = \frac{1}{(\mathrm{Fe/H})_P/(\mathrm{Fe/H})} \times \frac{(\mathrm{O/Fe})_{\mathrm{II}}}{[\gamma(t)+1]^2}\frac{d\gamma}{d[(\mathrm{Fe/H})_P/(\mathrm{Fe/H})]}\,. \qquad (14)$$

According to equation (14), if $\gamma(t)$ increases with time, i.e., $d\gamma/d[(\mathrm{Fe/H})_P/(\mathrm{Fe/H})] < 0$, then $dS/d[(\mathrm{Fe/H})_P/(\mathrm{Fe/H})] < 0$ and the corresponding curve for (O/Fe) is concave downward. On the other hand, if $\gamma(t)$ decreases with time, i.e., $d\gamma/d[(\mathrm{Fe/H})_P/(\mathrm{Fe/H})] > 0$, then $dS/d[(\mathrm{Fe/H})_P/(\mathrm{Fe/H})] > 0$ and the corresponding curve for (O/Fe) is concave upward. Figure 1*c* illustrates the trend of (O/Fe) for some hypothetical time evolution of $\gamma(t)$ specified by $d\gamma/dt \equiv \dot{\gamma}$. In the simple case where $\gamma(t)$ monotonically increases with time, the curve for (O/Fe) drops more and more steeply in approaching $(\mathrm{Fe/H})_P/(\mathrm{Fe/H}) = 0$ (Fig. 1*b*). In any case, the value of (O/Fe) corresponding to $(\mathrm{Fe/H})_P/(\mathrm{Fe/H}) = 0$ is $(\mathrm{O/Fe})_{\mathrm{II}}/(\gamma_\infty+1)$, with γ_∞ being the asymptotic value of $\gamma(t)$ after an infinite amount of time. Note that in the above treatment, the evolution of (O/Fe) is directly related to the Fe inventory (Fe/H). The time t only serves as an implicit parameter that has the same sense of increase as (Fe/H).

3. COMPARISON WITH OBSERVATIONS

We now proceed to compare the phenomenological model presented in § 2 with the observational data on the evolution of O abundance relative to Fe. We take $[\mathrm{Fe/H}]_P = \log(\mathrm{Fe/H})_P - \log(\mathrm{Fe/H})_\odot = -3$ to correspond to the initial state P resulting from the prompt production by the first very massive stars. Here the subscript "$\odot$" indicates quantities pertaining to the Sun. The data from the observations of metal-poor stars (mostly unevolved halo stars) in the Galaxy by Israelian et al. (1998) and Boesgaard et al. (1999) are shown as $(\mathrm{O/Fe})/(\mathrm{O/Fe})_\odot = 10^{[\mathrm{O/Fe}]}$ versus $(\mathrm{Fe/H})_P/(\mathrm{Fe/H}) = 10^{[\mathrm{Fe/H}]_P - [\mathrm{Fe/H}]}$ in Figure 2*a*. The data at $(\mathrm{Fe/H})_P/(\mathrm{Fe/H}) < 0.066$ are shown without error bars in the inset. Note that the data of Boesgaard et al. (1999) have been modified to match the scale of stellar parameters used by Israelian et al. (1998) (see Israelian, Garcia Lopez, & Rebolo 2000). Figure 2*a* shows that the evolution of (O/Fe) follows a linear trend between the initial state P and an intermediate state at $(\mathrm{Fe/H})_P/(\mathrm{Fe/H}) \sim 0.02$. The evolution beyond the intermediate state follows a much steeper curve. These evolution trends are expected from the model, with the intermediate state corresponding to state A at the onset of SNIa Fe contribution.

For a quantitative comparison of the model trajectory with the data on the evolution of O abundance relative to Fe, we assume a time parameterization where the rate per unit mass of gas for Fe production by SNII is constant over Galactic history. This rate can be written as

$$\frac{d(\mathrm{Fe/H})_{\mathrm{II}}}{d\,t} = \frac{\alpha(\mathrm{Fe/H})_\odot}{t_{\mathrm{SSF}}}\,, \qquad (15)$$

where α is the fraction of the solar Fe inventory contributed by SNII and t_{SSF} is the time of solar system formation (with $t = 0$ corresponding to the initial state P). The occurrence of SNIa is considered to depend on the accretion of matter onto a white dwarf from its binary companion. The formation of white dwarfs requires long-term stellar evolution and thus SNIa cannot occur early in Galactic history. We assume that SNIa Fe production begins to occur at state A and then increases to a constant value relative to SNII Fe production over a timescale $\hat{\tau}$ (it will be shown that the results are not sensitive to the choice of $\hat{\tau}$). This is represented by the following expression of the rate per unit mass of gas for Fe production by SNIa relative to SNII:

$$\gamma(t) = \gamma_\infty\left[1 - \exp\left(-\frac{t-t_A}{\hat{\tau}}\right)\right]\theta(t-t_A)\,, \qquad (16)$$

where t_A is the time corresponding to state A, and $\theta(t-t_A)$ is a step function with its value being unity at $t \geq t_A$ and zero otherwise. Under the above assumptions, the O and Fe inventory in the gas is

$$(\mathrm{O/H}) = (\mathrm{O/Fe})_P(\mathrm{Fe/H})_P + \alpha(\mathrm{O/Fe})_{\mathrm{II}}(\mathrm{Fe/H})_\odot(t/t_{\mathrm{SSF}})\,, \qquad (17)$$

and

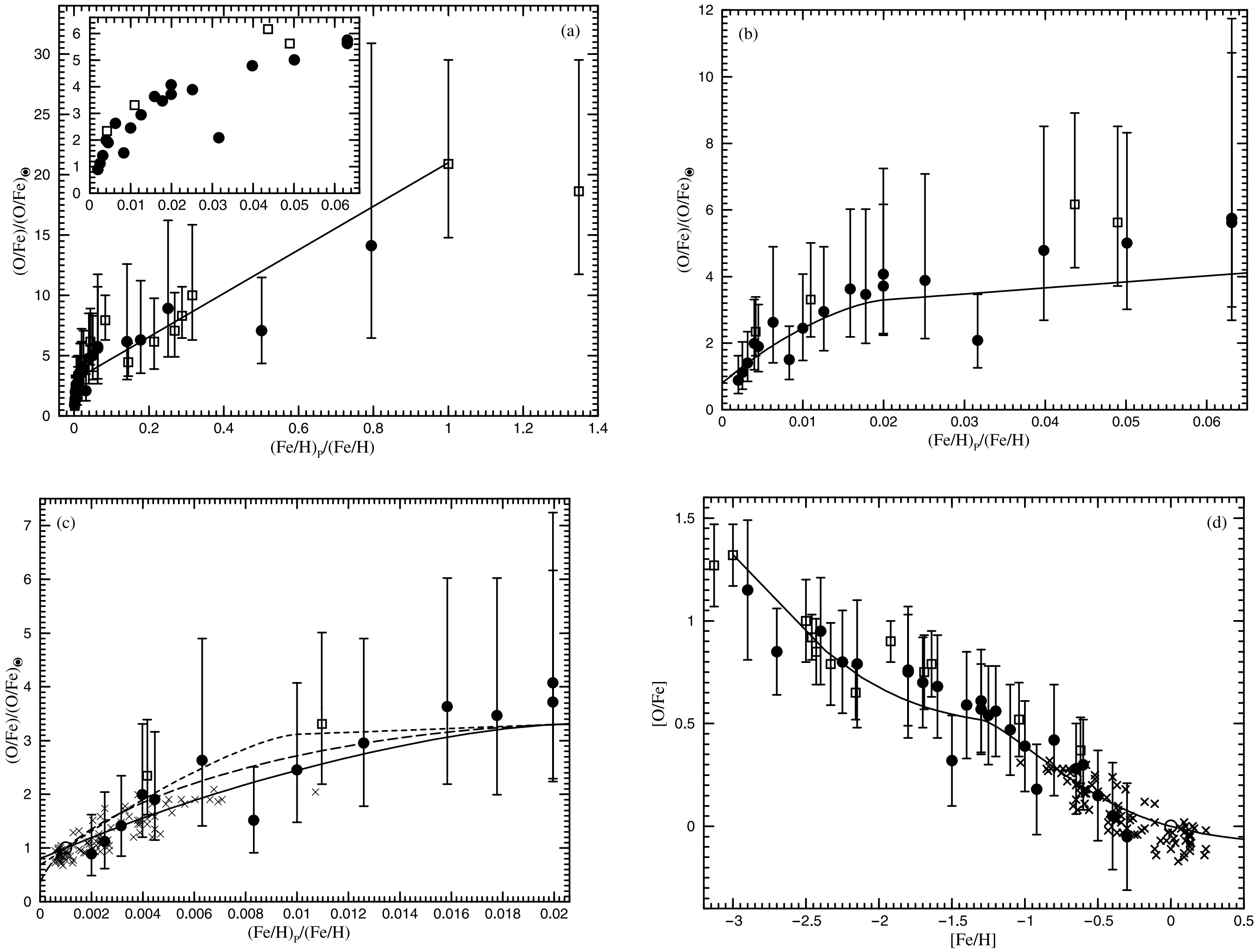

FIG. 2.—Comparison of the model for the evolution of O abundance relative to Fe with the data for metal-poor stars in the Galaxy (*filled circles:* Israelian et al. 1998; *squares:* Boesgaard et al. 1999). Note the change in the trend of the data at $(Fe/H)_P(Fe/H) \sim 0.02$ highlighted in the inset of (*a*). Data for Galactic disk stars (*crosses:* Edvardsson et al. 1993) are included in (*c*) and (*d*) to indicate the trend near and beyond the solar point (*circle*). The solid curve is obtained from the model by taking $(O/Fe)_P = 21\ (O/Fe)_\odot$, $(Fe/H)_P = 10^{-3}\ (Fe/H)_\odot$, $(Fe/H)_A = 0.05\ (Fe/H)_\odot$ $[(Fe/H)_P/(Fe/H)_A = 0.02]$, $\alpha = \frac{1}{3}$, and $\hat{\tau}/t_{SSF} = 0.1$. The long-dashed curve in (*c*) is obtained by taking $\hat{\tau}/t_{SSF} = 1$ and the short-dashed curve by taking $(Fe/H)_A = 0.1\ (Fe/H)_\odot$ $[(Fe/H)_P/(Fe/H)_A = 0.01]$ while keeping all the other parameters the same as for the solid curve.

$$(Fe/H) = (Fe/H)_P + \alpha(Fe/H)_\odot(t/t_{SSF}) + \alpha\gamma_\infty(Fe/H)_\odot \times \left\{\frac{t - t_A}{t_{SSF}} - \frac{\hat{\tau}}{t_{SSF}}\left[1 - \exp\left(-\frac{t - t_A}{\hat{\tau}}\right)\right]\right\} \times \theta(t - t_A)\,. \quad (18)$$

After choosing a set of parameters $(O/Fe)_P$, $(Fe/H)_P$, $(Fe/H)_A$, α, and $\hat{\tau}/t_{SSF}$, we can obtain (O/Fe) as a function of $(Fe/H)_P/(Fe/H)$ from equations (17) and (18). The quantities $(O/Fe)_{II}$, t_A, and γ_∞ in these equations are given by

$$(O/Fe)_{II} = \frac{1}{\alpha}\left[(O/Fe)_\odot - (O/Fe)_P\,\frac{(Fe/H)_P}{(Fe/H)_\odot}\right], \quad (19)$$

$$\frac{t_A}{t_{SSF}} = \frac{(Fe/H)_A - (Fe/H)_P}{\alpha(Fe/H)_\odot}\,, \quad (20)$$

and

$$\alpha\gamma_\infty = \frac{1 - \alpha - [(Fe/H)_P/(Fe/H)_\odot]}{1 - (t_A/t_{SSF}) - (\hat{\tau}/t_{SSF})\{1 - \exp[-(t_{SSF} - t_A)/\hat{\tau}]\}}\,. \quad (21)$$

Note again that the time t (measured in units of t_{SSF}) is introduced as an implicit parameter to be eliminated from the final results. The form of this parameterization does not significantly affect these results.

As a numerical example, we take $(O/Fe)_P = 21\ (O/Fe)_\odot$, $(Fe/H)_P = 10^{-3}\ (Fe/H)_\odot$, $(Fe/H)_A = 0.05\ (Fe/H)_\odot$ [corresponding to $(Fe/H)_P/(Fe/H)_A = 0.02$], $\alpha = \frac{1}{3}$ for the fraction of solar Fe inventory contributed by SNII, and $\hat{\tau}/t_{SSF} = 0.1$. The corresponding trajectory of (O/Fe) as a function of $(Fe/H)_P/(Fe/H)$ is shown as the solid curve in Figures 2*a*, 2*b*, and 2*c*. These figures cover a series of nested intervals in $(Fe/H)_P/(Fe/H)$ to expose the complete range of results. For reference, the same results (*solid curve*) are also shown in the conventional representation of [O/Fe] versus [Fe/H] in Figure 2*d*. The data of Edvardsson et al. (1993) for Galactic disk stars are included in Figures 2*c* and 2*d* to show the trend near and beyond the solar point (*circle*). It is evident that the model provides both a good qualitative and quantitative description of all the data. There is some scatter of the data relative to the solid curve from the model over almost the entire range of $(Fe/H)_P/(Fe/H)$, especially in the range

$0.03 \lesssim (\mathrm{Fe/H})_P/(\mathrm{Fe/H}) \lesssim 0.1$. However, we do not consider this to be critical.

To test the sensitivity of the results to the choice of parameters, we have varied $\hat{\tau}/t_{\mathrm{SSF}}$, $(\mathrm{Fe/H})_A$ or α one at a time while keeping all the other parameters the same as in the above example. The long-dashed curve in Figure 2*c* is obtained by taking $\hat{\tau}/t_{\mathrm{SSF}} = 1$ and the short-dashed curve by taking $(\mathrm{Fe/H})_A = 0.1\ (\mathrm{Fe/H})_\odot$ [corresponding to $(\mathrm{Fe/H})_P/(\mathrm{Fe/H})_A = 0.01$]. These two variations seem to have little effect on the description of the data. The only significant change is that the value of $(\mathrm{O/Fe})/(\mathrm{O/Fe})_\odot$ in the infinite future decreases from 0.8 for the solid curve to 0.36 for the long-dashed curve because of the tenfold increase in $\hat{\tau}/t_{\mathrm{SSF}}$. Changing α from $\frac{1}{3}$ to $\frac{1}{4}$ only slightly improves the agreement with the data in the range $0.03 \lesssim (\mathrm{Fe/H})_P/(\mathrm{Fe/H}) \lesssim 0.1$ (not shown). It would be difficult to obtain a fit to the data for α significantly greater than $\frac{1}{3}$.

The value of (O/Fe) for the initial state P appears to be $(\mathrm{O/Fe})_P \sim 20\ (\mathrm{O/Fe})_\odot$ from the existing data. This clearly shows that the contributors to the prompt Fe inventory have also made major contribution to O and very possibly to C, Mg, and Si. The value $(\mathrm{O/Fe})_P$ is considered here to be the result from the production by the first very massive stars (with masses of $\gtrsim 100\ M_\odot$) and not by SNII (see § 4). The results from complete models of nucleosynthesis in these stars should provide a guide as to what may be expected for the other elements. The average production of O relative to Fe for SNII is $(\mathrm{O/Fe})_{\mathrm{II}} \sim 3\ (\mathrm{O/Fe})_\odot$, which is ~ 7 times lower than $(\mathrm{O/Fe})_P$ for the very massive stars. The high value of $(\mathrm{O/Fe})_P$ required by the data implies that even after the major addition of Fe and O from SNII, the total O inventory at the onset of SNIa Fe contribution may still have a significant component from the prompt source. For example, at $(\mathrm{Fe/H})_P/(\mathrm{Fe/H}) \sim 0.02$ ([Fe/H] ~ -1.3), $\sim 10\%$ of the O inventory but only $\sim 2\%$ of the Fe inventory are from the prompt source.

We are further concerned with the possibility that prior to the formation of very massive stars with masses of $\gtrsim 100\ M_\odot$, there may have been a separate generation of supermassive stars with masses of $\gtrsim 10^3$–$10^4\ M_\odot$. Such objects may produce peculiar values of (O/Fe) in the data around $(\mathrm{Fe/H})_P/(\mathrm{Fe/H}) \sim 1$. We have sought to find an indication of this, but there does not appear to be any such indication in the data.

4. DISCUSSION AND CONCLUSIONS

We have presented a phenomenological model for the evolution of O abundance relative to Fe. In this model, the first very massive stars formed from Big Bang debris provided a prompt inventory of Fe ($[\mathrm{Fe/H}]_P \sim -3$) and O, thus defining an initial state of the ISM. Subsequent O enrichment was provided by SNII that are related to regular massive stars, while subsequent Fe enrichment was provided by SNII followed by additional contribution from SNIa. Prior to the onset of SNIa Fe contribution, the evolution of (O/Fe) as a function of 1/(Fe/H) is along a straight line segment (Fig. 1). Subsequent evolution is governed by the rate per unit mass of gas for Fe production by SNIa relative to SNII (Fig. 1). Based on the observations of Israelian et al. (1998) and Boesgaard et al. (1999), the value $(\mathrm{O/Fe})_P$ resulting from the prompt production by the first very massive stars is $\sim 20\ (\mathrm{O/Fe})_\odot$. Comparison of our model with the same observations indicate that SNIa began to contribute Fe at [Fe/H] ~ -1 and were responsible for $\sim \frac{2}{3}$ of the solar Fe inventory, which is consistent with the results of previous studies (e.g., Timmes et al. 1995) and with the assumptions of Wasserburg & Qian (2000a, 2000b). The average production of O relative to Fe for SNII is found to be $(\mathrm{O/Fe})_{\mathrm{II}} \sim 3\ (\mathrm{O/Fe})_\odot$, which is ~ 7 times lower than that for the first very massive stars.

The model developed here neither depends on nor gives numerical values of the rates per unit mass of gas for O and Fe production by SNII, $d(\mathrm{O/H})_{\mathrm{II}}/d\,t$ and $d(\mathrm{Fe/H})_{\mathrm{II}}/d\,t$. Likewise, the model only involves $\gamma(t)$, the rate per unit mass of gas for Fe production by SNIa relative to SNII. Taking the Galaxy as an example, we can obtain the numerical values of $d(\mathrm{O/H})_{\mathrm{II}}/d\,t$ and $d(\mathrm{Fe/H})_{\mathrm{II}}/d\,t$ by introducing the time for solar system formation $t_{\mathrm{SSF}} \approx 10^{10}$ yr (eqs. [11] and [15]). The absolute yields of O and Fe from each SNII can also be obtained by further introducing the SNII rate per unit mass of gas and the total mass of gas at t_{SSF}. The progenitor stars of SNII have very short lifetimes so that an equilibrium between the birth and death of these stars is established on a correspondingly short timescale. If the rate for formation of these stars is proportional to the mass of gas, then the SNII rate per unit mass of gas can be considered as constant over Galactic history. This is the justification for our earlier assumption of a constant rate per unit mass of gas for Fe production by SNII (eq. [15]). At the present time, the Galactic SNII rate is $\sim (30\ \mathrm{yr})^{-1}$, corresponding to a total gas mass of $\sim 10^{10}\ M_\odot$. Assuming that all SNII have the same O yield, we find that each SNII must produce $\sim 0.3\ M_\odot$ of O in order to enrich the gas with a solar O mass fraction ($\approx 9.6 \times 10^{-3}$) at $t_{\mathrm{SSF}} \approx 10^{10}$ yr (eq. [4]).

In the model presented here, we have assigned the O and Fe abundances at [Fe/H] ~ -3 to the prompt production by the first very massive stars formed from Big Bang debris and have rejected the possibility that these could be produced by SNII. Indeed, although the value of $(\mathrm{O/Fe})_P$ found here is ~ 7 times larger than the average relative production of O to Fe that we associate with SNII, it is still possible to attribute the large (O/Fe) value at [Fe/H] ~ -3 to contributions from a subset of SNII that produce O but little Fe. The key argument that we have used in rejecting this possibility comes from the results on the production of *r*-process elements and Fe by SNII that were obtained from meteoritic data and observations of metal-poor stars. We give a short summary of these results below as they will be used to place bounds on the O and Fe enrichment to be expected from the early occurrence of SNII in comparison with the prompt inventory $(\mathrm{O/H})_P$ and $(\mathrm{Fe/H})_P$.

Meteoritic data on the inventory of radioactive ^{129}I and ^{182}Hf in the early solar system require at least two distinct kinds of SNII as sources for the *r*-process (Wasserburg, Busso, & Gallino 1996; Qian, Vogel, & Wasserburg 1998; Qian & Wasserburg 2000). These are the high-frequency SNIIH events responsible for heavy *r*-process elements with mass numbers $A > 130$ (e.g., Ba and Eu; "H" for "high-frequency" and "heavy *r*-process elements") and the low-frequency SNIIL events dominantly producing light *r*-process elements with $A \leq 130$ (e.g., Ag; "L" for "low-frequency" and "light *r*-process elements"). The timescales required for replenishment of the appropriate radioactive nuclei in an average ISM by the SNIIH and SNIIL events are $\sim 10^7$ and $\sim 10^8$ yr, respectively. These timescales can be explained by considering the mixing of the ejecta from an individual SNII with the ISM. The amount of ISM to mix the SNII ejecta is the mass swept up by a supernova remnant (SNR). The expansion of an SNR can be roughly described by an energy-conserving phase followed by a momentum-conserving one (e.g., Thornton et al. 1998). This expansion results in a total swept-up mass of $\sim 2E_{SN}/(v_{tr} v_f) \sim 3 \times 10^4\ M_\odot$, where $E_{SN} \sim 10^{51}$ ergs is the supernova explosion energy, $v_{tr} \sim 200$ km s^{-1} is the velocity at the transition between the two phases of expansion, and $v_f \sim 15$ km s^{-1} is the final velocity typical of the random motion in the ISM. For Galactic rates of $\sim(30\ \mathrm{yr})^{-1}$ for H events and $\sim(300\ \mathrm{yr})^{-1}$ for L events in a total gas mass of $\sim 10^{10}\ M_\odot$, we obtain that the rates of SNIIH and SNIIL events in an ISM of $\sim 3 \times 10^4\ M_\odot$ are $\sim(10^7\ \mathrm{yr})^{-1}$ and $\sim(10^8\ \mathrm{yr})^{-1}$, respectively, as required by replenishment of the appropriate radioactive nuclei in this ISM.

Observations of metal-poor stars in the Galactic halo (McWilliam et al. 1995; McWilliam 1998; Sneden et al. 1996, 1998) show that there is wide dispersion in the Ba abundance $\log \epsilon(\mathrm{Ba}) \equiv \log (\mathrm{Ba/H}) + 12$ at $[\mathrm{Fe/H}] \sim -3$ (region "b" in Fig. 3). This dispersion in the Ba abundance (~ 2 dex) at a nearly constant [Fe/H] led Wasserburg & Qian (2000a) to conclude that the SNIIH events cannot produce a significant amount of Fe. The Ba abundance becomes extremely low for $[\mathrm{Fe/H}] < -3$ and there is no correlation with Fe in this region (region a in Fig. 3), indicating that there was some Fe production prior to the occurrence of SNII. Observations (Gratton & Sneden 1994; see also McWilliam et al. 1995) also show that there is a correlation between the abundances of Ba and Fe at $[\mathrm{Fe/H}] \gtrsim -2.5$ (region "c" in Fig. 3).

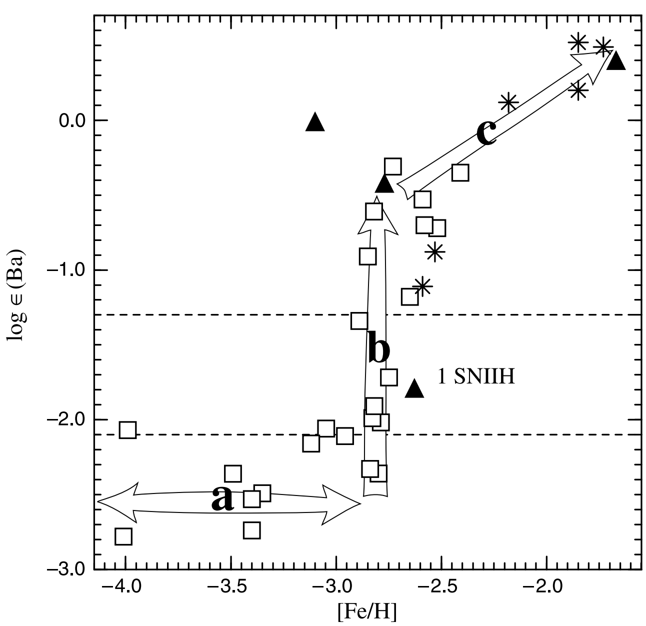

FIG. 3.—Data (*asterisks:* Gratton & Sneden 1994; *squares:* McWilliam et al. 1995, McWilliam 1998; *triangles:* Sneden et al. 1996, 1998) on $\log \epsilon(\mathrm{Ba})$ vs. [Fe/H] for metal-poor stars in the Galaxy. The band labeled "1 SNIIH" shows estimates of the $\log \epsilon(\mathrm{Ba})$ value resulting from a single SNIIH event. The wide dispersion in $\log \epsilon(\mathrm{Ba})$ at $[\mathrm{Fe/H}] \sim -3$ (region "b") indicates that the SNIIH events cannot produce a significant amount of Fe. The correlation between the abundances of Ba and Fe at $[\mathrm{Fe/H}] \gtrsim -2.5$ (region "c") results from the mixture of the SNIIH and the Fe-producing SNIIL events. The low Ba abundances in stars with $-4 \lesssim [\mathrm{Fe/H}] \lesssim -3$ (region "a") compared with the contribution from a single SNIIH event and the sharp increase of $\log \epsilon(\mathrm{Ba})$ at $[\mathrm{Fe/H}] \sim -3$ (region "b") suggest that a prompt source other than SNII must exist to produce Fe (along with other elements such as C, N, O, Mg, and Si) at $[\mathrm{Fe/H}] \lesssim -3$.

Estimates of the Ba abundance resulting from a single SNIIH event (Qian & Wasserburg 2000; Wasserburg & Qian 2000a) are shown as the band labeled "1 SNIIH" in Figure 3. The low Ba abundances in stars with $[\mathrm{Fe/H}] \sim -4$ to -3 (region "a" in Fig. 3) compared with this band and the sharp increase in the Ba abundance at $[\mathrm{Fe/H}] \sim -3$ led Wasserburg & Qian (2000a) to conclude that a source other than SNII must exist to produce Fe (along with other elements such as C, N, O, Mg, and Si) at $[\mathrm{Fe/H}] \lesssim -3$. They attributed this source to the first very massive stars (with masses of $\gtrsim 100\ M_\odot$) formed from Big Bang debris. They further argued that formation of regular stars (with masses of $\sim$1–60 $M_\odot$) could not occur until later when $[\mathrm{Fe/H}] \sim -3$ was reached. In this later regime, regular stars with masses of $\gtrsim 10\ M_\odot$ explode as SNII. The more frequent occurrence of SNIIH events with no Fe production over a period of $\lesssim 10^8$ yr gives rise to the sharp increase in the Ba abundance at $[\mathrm{Fe/H}] \sim -3$. This is followed by the occurrence of low-frequency Fe-producing SNIIL events. Contribution to Fe from SNIa only takes place at $[\mathrm{Fe/H}] \gtrsim -1$. Enrichment in Fe of metal-poor stars with $-1 \gtrsim [\mathrm{Fe/H}] \gtrsim -2.5$ must be provided by the SNIIL events. For a Galactic rate of $\sim(300\ \mathrm{yr})^{-1}$ corresponding to a total gas mass of $\sim 10^{10}\ M_\odot$, each SNIIL must produce $\sim 0.1\ M_\odot$ of Fe in order to enrich the gas with $\sim \frac{1}{3}$ of a solar Fe mass fraction ($\approx 1.2 \times 10^{-3}$) at $t_{SSF} \approx 10^{10}$ yr (eq. [4]). Diluting this amount of Fe in an ISM of $\sim 3 \times 10^4\ M_\odot$ that mixes with the ejecta of a single SNII event results in $[\mathrm{Fe/H}] \sim -2.5$. Thus the correlation between the abundances of Ba and Fe at $[\mathrm{Fe/H}] \gtrsim -2.5$ shows that the variation of Fe yields between SNIIH and SNIIL events is smoothed out over a timescale of $\gtrsim 10^8$ yr.

While the SNIIH events would produce oxygen, they will not be sufficient to provide the large O inventory at $[\mathrm{Fe/H}] \sim -3$. Diluting the O yield of $\sim 0.3\ M_\odot$ from an SNIIH event into an ISM of $\sim 3 \times 10^4\ M_\odot$ would result in $(\mathrm{O/H}) \sim 10^{-3}\ (\mathrm{O/H})_\odot$ in this mixture. We note that two stars with Ba abundances close to our estimate for a single SNIIH event and with essentially the same values of $[\mathrm{Fe/H}] \sim -3$ are both observed to have $(\mathrm{O/H}) \approx 10^{-2}\ (\mathrm{O/H})_\odot$, which is a factor of ~ 10 greater than our estimate for a single SNIIH event (HD 122563 has $\log \epsilon(\mathrm{Ba}) = -1.54$ and $[\mathrm{Fe/H}] = -2.74$, and BD $-18°5550$ has $\log \epsilon(\mathrm{Ba}) = -1.72$ and $[\mathrm{Fe/H}] = -2.91$; Westin et al. 2000; McWilliam 1998; Cavallo, Pilachowski, & Rebolo 1997).

We also note that the prompt value $(\mathrm{O/Fe})_P \sim 20\ (\mathrm{O/Fe})_\odot$ at $[\mathrm{Fe/H}] \sim -3$ assigned by us is based on the observations of BD $+23°3130$ with $[\mathrm{Fe/H}] = -2.9$ (Israelian et al. 1998), BD $+03°740$ with $[\mathrm{Fe/H}] = -3$, and BD $-13°3442$ with $[\mathrm{Fe/H}] = -3.13$ (Boesgaard et al. 1999; Israelian et al. 2000) but there are no relevant Ba data. This value of $(\mathrm{O/Fe})_P$ corresponds to $(\mathrm{O/H})_P \sim 2 \times 10^{-2}\ (\mathrm{O/H})_\odot$, which could be explained by the O contribution from ~ 20 SNIIH events at $\sim 0.3\ M_\odot$ of O per event. If this were the case, then the relevant stars should have high $\log \epsilon(\mathrm{Ba})$ values. Future measurements of Ba abundances in these stars are needed to identify possible SNIIH contribution to the observed O abundances and to determine the prompt O inventory more accurately. However, from the above arguments based on the observations of HD 122563 and BD $-18°5550$, we conclude that the origin of the O inventory at [Fe/H] $\lesssim -3$ must be assigned to the prompt source.

Based on the assignment of $(\mathrm{O/Fe})_P \sim 20\ (\mathrm{O/Fe})_\odot$, the average production ratio of O to Fe for the first very massive stars is ~ 560 by number $[(\mathrm{O/Fe})_\odot \approx 28]$. As the amount of O production is much less than the mass of the star, this means that the typical Fe yield from a zero-metallicity star of mass M must be $\ll (56/16)(M/560) \approx 0.6\ M_\odot \times (M/100\ M_\odot)$. In considering the prompt enrichment of the ISM by the very massive stars, it is necessary to take several effects into account. The universe at the epoch for formation of these stars was probably dominated by gas. We do not know how many very massive stars contributed to the prompt inventory. Explosions of these stars are likely to be much more energetic than supernova explosions. So the mass of ISM for diluting the ejecta from the explosion of a very massive star is expected to be $\gg 3 \times 10^4\ M_\odot$. With an O yield of $\sim 0.1\ M$ for a very massive star of mass M and with the number N_{VMS} of such stars contributing to the prompt O inventory of $(\mathrm{O/H})_P \sim 2 \times 10^{-2}\ (\mathrm{O/H})_\odot$, this dilution mass can be estimated as $\sim 5 \times 10^4\ M_\odot(M/100\ M_\odot) \times N_{\mathrm{VMS}}$. The expectation that this mass should be $\gg 3 \times 10^4\ M_\odot$ leads us to conclude that the prompt inventory must have been provided by $N_{\mathrm{VMS}} \gg 1$ very massive stars. That is, many very massive stars are required to provide $(\mathrm{O/H})_P$. Clearly, further studies are needed to understand the formation, evolution, nucleosynthesis, and explosion of these stars.

To determine the relationship between (O/Fe) and (Fe/H) in the Galaxy, Israelian et al. (1998) and Boesgaard et al. (1999) used the OH lines of metal-poor stars with a wide range of (Fe/H). Their results represent the most complete and self-consistent data set available. There is some disagreement between different workers on the evolution of O abundance relative to Fe, in part because of the choice of spectral lines used to determine the O abundance (e.g., Barbuy 1988). While the general model developed here must stand on its own, the numerical value of $(\mathrm{O/Fe})_P$ for the prompt inventory is dependent on the observational results of Israelian et al. (1998) and Boesgaard et al. (1999).

To this point, we have assumed that the ISM consists of gas only and that the abundances in an individual star are representative of the average gas at the birth of the star. In fact, the Galactic ISM consists of both gas and dust, with dust making up $\sim 1\%$ of the total mass at present. Certain elements, such as Fe, in the ISM are greatly depleted in the gas phase and are considered to be condensed into dust. So long as stars sample the composition of the bulk ISM including both gas and dust, we can still interpret stellar observations in terms of Galactic chemical evolution as done here because dust is converted into gas in stars. In contrast, when applying the model developed here to damped Lyα systems, it must be further assumed that Fe and O are not substantially fractionated relative to each other in the protogalactic ISM of such systems. If, for example, Fe were dominantly in dust and O in gas in the ISM of damped Lyα systems (as is the case in many galaxies of about the present epoch), then a straightforward application of the model to such systems would give completely misleading interpretation of the data, which only sample elements in the gas phase.

The most accurate measurement of O abundance in a damped Lyα system so far was reported by Molaro et al. (2000). They gave $[\mathrm{O/H}] = -1.85 \pm 0.1$ corresponding to $[\mathrm{O/Fe}] = 0.19 \pm 0.14$ for a damped Lyα system with $[\mathrm{Fe/H}] = -2.04 \pm 0.1$ at a redshift $z = 3.39$. These data do not fit the trend exhibited by the Galactic data shown in Figure 2*d* as the Galactic value of [O/Fe] for the same [Fe/H] is substantially higher. The data on other elements (e.g., Cr and Zn) in the above damped Lyα system also suggest that there is no effect of dust depletion (Molaro et al. 2000). We note that the observed value of [O/H] in this system is close to the prompt O inventory assigned here based on the Galactic data while the value of [Fe/H] is ~ 10 times higher than the prompt Fe inventory. We cannot offer a simple explanation for these O and Fe abundances.

Substantial efforts have been made to establish the dust-to-gas ratio for damped Lyα systems at redshifts $z \gtrsim 1$. Estimates have been made for the possible dust depletion of condensable elements (e.g., Si, Cr, and Fe) relative to more volatile ones (e.g., Zn) that are considered to remain in the gas phase. Pettini et al. (1997) have argued that there is some significant dust depletion of condensable elements (by a factor of ~ 2) in the damped Lyα systems at very early epochs. However, there is strong disagreement between various workers (e.g., Lu et al. 1996; Prochaska & Wolfe 2000) regarding the degree of dust depletion in these systems. Wasserburg & Qian (2000b) assumed that dust depletion is not a dominant effect on the chemical evolution of damped Lyα systems at $z \gtrsim 1$. There is clear evidence for large amounts of dust in a variety of galaxies at high z. We cannot reconcile the assumption of low dust-to-gas ratios for damped Lyα systems with these observations. The cause of the transition to the high dust content for galaxies of about the present epoch is not understood unless the later dust contribution of asymptotic giant branch (AGB) stars plays a major role.

It is expected that the first very massive stars formed from Big Bang debris produce C/O ratios of $\ll 1$ (Heger et al. 2000). The dominance of O over C should cause all the C to be converted into CO, leaving an excess of O in the ISM. This would prevent the formation of C grains and also the formation of polyaromatic hydrocarbon (PAH) as well as other hydrocarbon molecules. A strict upper limit to the dust content of the ISM at $[\mathrm{Fe/H}] \sim -3$ can be estimated by taking the total abundance of the major condensable elements Mg, Si, and Fe to be ~ 10 times the Fe abundance (see below). As no C dust should be formed, dust would constitute at most $\sim 10^{-5}$ of the total mass of the ISM at $[\mathrm{Fe/H}] \sim -3$. For a typical dust size d, the obscuration caused by this presence of dust is at most at the level of $\sim 10^{-3}(0.1\ \mu\mathrm{m}/d)[N(\mathrm{H\ I})/10^{21}\ \mathrm{cm}^{-2}]$ in a system of neutral H column density $N(\mathrm{H\ I})$.

By attributing the O inventory at $[\mathrm{Fe/H}] \sim -3$ to the prompt production by the first very massive stars formed from Big Bang debris, the model presented here also predicts that the Mg and Si abundances in stars with $(\mathrm{O/Fe}) \sim (\mathrm{O/Fe})_P$ and $[\mathrm{Fe/H}] \sim -3$ should—to a large extent—reflect the prompt inventory of Mg and Si. Based on the observations of McWilliam et al. (1995), we obtain $(\mathrm{Mg/H})_P \sim 3 \times 10^{-3}\ (\mathrm{Mg/H})_\odot$ and $(\mathrm{Si/H})_P \sim 10^{-2}\ (\mathrm{Si/H})_\odot$, corresponding to $(\mathrm{Mg/Fe}) \sim 3(\mathrm{Mg/Fe})_\odot$ and $(\mathrm{Si/Fe}) \sim 10(\mathrm{Si/Fe})_\odot$ for stars with $[\mathrm{Fe/H}] \sim -3$. We also consider that the abundances in the prompt inventory represent the critical condition for transition from formation of very massive stars to regular ones. Taking into account the radiative properties of H, O, Mg, Si, and Fe, we predict that the abundances $(\mathrm{O/H}) \sim 2 \times 10^{-2}\ (\mathrm{O/H})_\odot$, $(\mathrm{Mg/H}) \sim 3$

$\times 10^{-3}$ (Mg/H)$_\odot$, (Si/H) $\sim 10^{-2}$ (Si/H)$_\odot$, and (Fe/H) $\sim 10^{-3}$ (Fe/H)$_\odot$ in the prompt inventory should give sufficient "metals" to permit cooling and fragmentation of large condensing gas clouds to form stars with masses of $\sim$1–60 $M_\odot$.

We would like to thank Garik Israelian for supplying the data of Israelian et al. (1998) and Boesgaard et al. (1999) on the same scale of stellar parameters. Comments by the referee, F. X. Timmes, were very helpful in improving the presentation. This work was supported in part by the Department of Energy under grant DE-FG02-87ER40328 to Y.-Z. Q. and by NASA under grant NAG5-4083 to G. J. W., Caltech Division Contribution No. 8732(1063).

REFERENCES

Barbuy, B. 1988, A&A, 191, 121
Boesgaard, A. M., King, J. R., Deliyannis, C. P., & Vogt, S. S. 1999, AJ, 117, 492
Bromm, V., Coppi, P. S., & Larson, R. B. 1999, ApJ, 527, L5
Cavallo, R. M., Pilachowski, C. A., & Rebolo, R. 1997, PASP, 109, 226
Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, A&A, 275, 101
Ezer, D., & Cameron, A. G. W. 1971, Ap&SS, 14, 399
Fryer, C. L., Woosley, S. E., & Heger, A. 2001, ApJ, in press
Gratton, R. G., & Sneden, C. 1994, A&A, 287, 927
Heger, A., Woosley, S. E., & Waters, R. 2000, in The First Stars, ed. A. Weiss, T. Abel, & V. Hill (Berlin: Springer), in press
Israelian, G., Garcia Lopez, R. J., & Rebolo, R. 1998, ApJ, 507, 805
———. 2000, preprint (astro-ph/0001426)
Lu, L., Sargent, W. L. W., Barlow, T. A., Churchill, C. W., & Vogt, S. S. 1996, ApJS, 107, 475
McWilliam, A. 1998, AJ, 115, 1640
McWilliam, A., Preston, G. W., Sneden, C., & Searle, L. 1995, AJ, 109, 2757
Molaro, P., Bonifacio, P., Centurión, M., D'Odorico, S., Vladilo, G., Santin, P., & Marcantonio, P. D. 2000, ApJ, 541, 54
Pettini, M., King, D. L., Smith, L. J., & Hunstead, R. W. 1997, ApJ, 478, 536
Prochaska, J. X., & Wolfe, A. M. 2000, ApJ, 533, L5
Qian, Y.-Z., Vogel, P., & Wasserburg, G. J. 1998, ApJ, 494, 285
Qian, Y.-Z., & Wasserburg, G. J. 2000, Phys. Rep., 333, 77
Sneden, C., Cowan, J. J., Burris, D. L., & Truran, J. W. 1998, ApJ, 496, 235
Sneden, C., McWilliam, A., Preston, G. W., Cowan, J. J., Burris, D. L., & Armosky, B. J. 1996, ApJ, 467, 819
Thornton, K., Gaudlitz, M., Janka, H.-Th., & Steinmetz, M. 1998, ApJ, 500, 95
Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1995, ApJS, 98, 617
Wasserburg, G. J., Busso, M., & Gallino, R. 1996, ApJ, 466, L109
Wasserburg, G. J., & Qian, Y.-Z. 2000a, ApJ, 529, L21
———. 2000b, ApJ, 538, L99
Westin, J., Sneden, C., Gustafsson, B., & Cowan, J. J. 2000, ApJ, 530, 783