

Abundances in Metal-Poor Stars and Chemical Evolution of the Early Galaxy

G. J. Wasserburg^{*†}

The Lunatic Asylum, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA
E-mail: gjw@gps.caltech.edu

Y.-Z. Qian[‡]

School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA
E-mail: qian@physics.umn.edu

We have attributed the elements from Sr through Ag in stars of low metallicities ($[\text{Fe}/\text{H}] \lesssim -1.5$) to charged-particle reactions (CPR) in neutrino-driven winds, which are associated with neutron star formation in low-mass and normal supernovae (SNe) from progenitors of $\sim 8\text{--}11 M_{\odot}$ and $\sim 12\text{--}25 M_{\odot}$, respectively. Using this rule and attributing all Fe production to normal SNe, we previously developed a phenomenological two-component model, which predicts that $[\text{Sr}/\text{Fe}] \geq -0.32$ for all metal-poor stars. This is in direct conflict with the high-resolution data now available, which show that there is a great shortfall of Sr relative to Fe in many stars with $[\text{Fe}/\text{H}] \lesssim -3$. The same conflict also exists for the CPR elements Y and Zr. We show that the data require a stellar source leaving behind black holes and that hypernovae (HNe) from progenitors of $\sim 25\text{--}50 M_{\odot}$ are the most plausible candidates. If we expand our previous model to include three components (low-mass and normal SNe and HNe), we find that essentially all of the data are very well described by the new model. The HN yield pattern for the low-*A* elements from Na through Zn (including Fe) is inferred from the stars deficient in Sr, Y, and Zr. We estimate that HNe contributed $\sim 24\%$ of the bulk solar Fe inventory while normal SNe contributed only $\sim 9\%$ (not the usually assumed $\sim 33\%$). This implies a greatly reduced role of normal SNe in the chemical evolution of the low-*A* elements. This work was supported in part by US DOE grants DE-FG03-88ER13851 (G.J.W.) and DE-FG02-87ER40328 (Y.Z.Q.). G.J.W. acknowledges NASA's Cosmochemistry Program for research support provided through J. Nuth at the Goddard Space Flight Center. He also appreciates the generosity of the Epsilon Foundation.

10th Symposium on Nuclei in the Cosmos
July 27 - August 1, 2008
Mackinac Island, Michigan, USA

*Speaker.

†Unable to attend the conference due to illness.

‡Spoke on behalf of G.J.W.

1. Introduction

The high-resolution (e.g., [1–5]) and medium-resolution [6] observations of elemental abundances in a large number of low-metallicity stars in the Galactic halo (and a single star in a dwarf galaxy [7]) now provide a data base for determining the stellar sources contributing to the interstellar/intergalactic medium (ISM/IGM) at metallicities of $-5.5 < [\text{Fe}/\text{H}] < -1.5$. These data taken in conjunction with stellar models appear to define the massive stars active in the early epochs. This changes our views of what may be Population III (Pop III) stars and what stellar types are continuing contributors through the present epoch. A key to our understanding is the recognition that low-mass and normal core-collapse supernovae (SNe) from progenitors of $\sim 8\text{--}11 M_{\odot}$ and $\sim 12\text{--}25 M_{\odot}$, respectively, end their lives as neutron stars and that nucleosynthesis in the neutrino-driven winds of nascent neutron stars produce a large group of elements including Sr, Y, and Zr via charged-particle reactions (CPR, e.g., [8]). This process is not the true “ r -process” with rapid neutron capture. In considering the contributions of low-mass and normal SNe that are certainly key contributors, certain rules are now established:

1. The true “ r -process” is not connected with any significant production of Fe group nuclei (or the low- A elements below Zn with mass numbers $A \sim 23\text{--}70$, e.g., [9]);
2. The CPR nuclei are not directly coupled to the true “ r -process” elements. While some workers consider that a “turn-on” of high neutron densities may be achieved in some unknown way coupled to a neutrino-driven wind, the observational data do not appear to be in support of this;
3. If one assumes that only low-mass and normal SNe were the sources, then $[\text{Sr}/\text{Fe}]$ must exceed -0.32 for all metal-poor stars.

The last rule appears to be well followed for $[\text{Fe}/\text{H}] > -3$, consistent with a two-component model of chemical evolution [10]. However, below $[\text{Fe}/\text{H}] \sim -3$ there is a gross deficiency of Sr (and other CPR elements) relative to Fe. This is shown in Figure 1a. This observation requires that there be an early stellar source of Fe that leaves behind a black hole instead of a neutron star with neutrino-driven winds producing the CPR nuclei. It further follows that a third stellar component in addition to low-mass and normal SNe is required to account for all the abundance data.

2. The third source

The effects of all three stellar sources are most clearly seen if we consider the relationship of Sr (a CPR element) in conjunction with Ba (a true “ r -process” element at low metallicities) and Fe. Using the yield ratios $(\text{Sr}/\text{Ba})_H$ of the H source (low-mass SNe) and $(\text{Sr}/\text{Fe})_L$ of the L source (normal SNe) we obtain:

$$(\text{Sr}/\text{H}) = (\text{Sr}/\text{Ba})_H (\text{Ba}/\text{H}) + (\text{Sr}/\text{Fe})_L (\text{Fe}/\text{H}) f_{\text{Fe},L}, \quad (2.1)$$

where $f_{\text{Fe},L}$ is the fraction of Fe from the L source. The above equation can be rewritten as:

$$[\text{Sr}/\text{Fe}] = \log \left(10^{[\text{Sr}/\text{Ba}]_H + [\text{Ba}/\text{Fe}]} + f_{\text{Fe},L} \times 10^{[\text{Sr}/\text{Fe}]_L} \right). \quad (2.2)$$

The evolution of $[\text{Sr}/\text{Fe}]$ with $[\text{Ba}/\text{Fe}]$ for the high-resolution data shown in Figure 1a is exhibited in Figure 1b along with the curves representing Equation (2.2) for $f_{\text{Fe},L} = 0, 0.1, 0.5,$ and 1 . Similar results are found for the medium-resolution data.

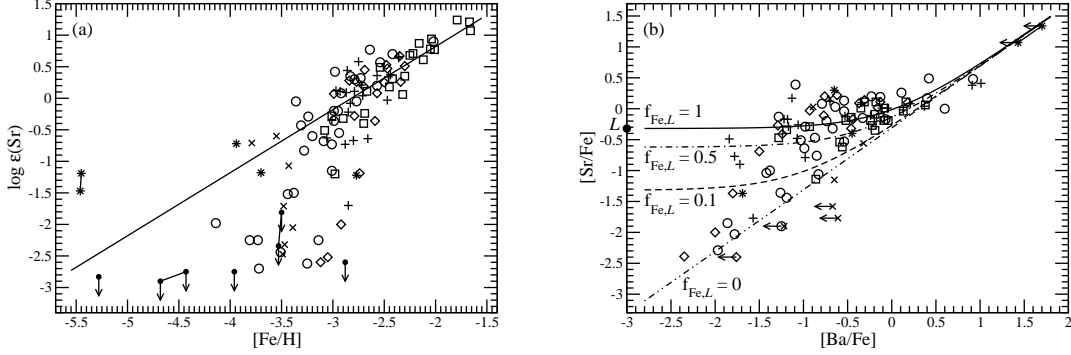


Figure 1: (a) High-resolution data on $\log \epsilon(\text{Sr})$ vs. $[\text{Fe}/\text{H}]$. The solid line is calculated from the two-component model for a well-mixed ISM/IGM. Note that there is a great deficiency of Sr for many sample stars with $[\text{Fe}/\text{H}] \lesssim -3$. It is evident that a source producing Fe and no Sr is required. (b) Evolution of $[\text{Sr}/\text{Fe}]$ with $[\text{Ba}/\text{Fe}]$ for the data shown in (a). The curves correspond to different fractions $f_{\text{Fe},L}$ of Fe due to the L source (normal SNe). Details for these and the other figures of this contribution can be found in [11].

While there appears to be a clustering of data in the neighborhood of $f_{\text{Fe},L} = 1$ corresponding to Fe contributions exclusively from the L source in Figure 1b, there is a substantial fraction of the data lying down to $f_{\text{Fe},L} = 0$. This requires an Fe source not related to normal SNe and clearly shows that the preponderance of the Fe in many sample stars is from this third source. Essentially the same results shown for $[\text{Sr}/\text{Fe}]$ vs. $[\text{Ba}/\text{Fe}]$ are found for $[\text{Y}/\text{Fe}]$ vs. $[\text{La}/\text{Fe}]$ and $[\text{Zr}/\text{Fe}]$ vs. $[\text{Ba}/\text{Fe}]$, where La and Ba are measures of the true “ r -process” contributions. These results clearly show that there are major contributions from the third source producing Fe with no CPR elements and no “ r -process” nuclei.

The matter at hand is what is the nature of this third source? Consideration of the yields of very massive stars ($\sim 140\text{--}260 M_{\odot}$) associated with pair-instability SNe (PI-SNe) show that these sources are characterized by strong deficiencies in the elements of odd atomic numbers (e.g., Na, Al, K, Sc, V, Mn, Co). Neither the data from earlier studies [12] nor the more precisely-determined data from recent studies [13] on low-metallicity halo stars exhibit these deficiencies. It follows that PI-SNe cannot be the third source. A plausible candidate is hypernovae (HNe) from progenitors of $\sim 25\text{--}50 M_{\odot}$. These stars are known to be active in the current epoch, although little attention has been paid to them in consideration of Galactic chemical evolution. They have explosion energies far above those of low-mass and normal SNe and are presumed to be associated with gamma-ray bursts. The yields of HNe are generally not well known, but the typical Fe yield inferred from observations is $\sim 0.5 M_{\odot}$, much higher than the yield of $\sim 0.07 M_{\odot}$ for normal SNe [14].

If we assume a Salpeter initial mass function (IMF) for massive stars of $\sim 8\text{--}50 M_{\odot}$, the relative rates are $R_{\text{HN}} : R_H : R_L \sim 0.36 : 0.96 : 1$ for HNe, low-mass SNe (H), and normal SNe (L), respectively. Of the Fe contributed by massive stars to the ISM/IGM, the fraction from HNe is ~ 0.72 . Thus HNe are the dominant Fe source at early epochs with contributions far exceeding those of normal SNe. This seems to explain the earlier conundrum that the yield patterns for the low- A elements below Zn in stars at very low metallicities ($[\text{Fe}/\text{H}] < -3$) appear to be indistinguishable from what was attributed to normal SNe at higher metallicities (see Figure 2) [9].

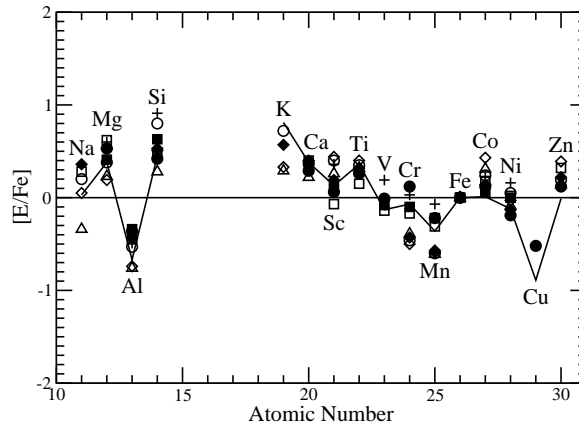


Figure 2: The abundance patterns of the low- A elements below Zn for stars with “pure” HN contributions ($f_{\text{Fe},L} = 0$ in Figure 1b). The solid curve represents the abundance pattern for a star with $[\text{Fe}/\text{H}] = -2$.

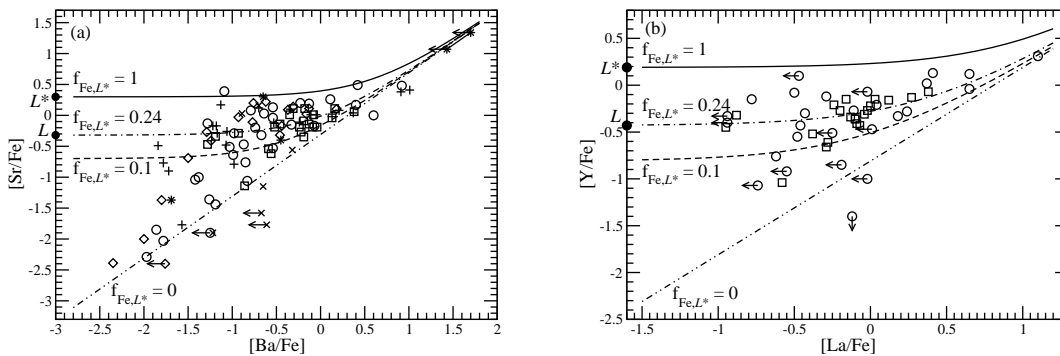


Figure 3: (a) Similar to Figure 1b but with the L source being a blend of normal SNe (L^*) and HNe. (b) Same as (a) but for $[\text{Y}/\text{Fe}]$ vs. $[\text{La}/\text{Fe}]$.

It is now evident that the inventory of the low- A elements including Fe that we had attributed to normal SNe is in fact the mixture of HN and normal SN ejecta where the preponderant contributions are from HNe. Thus the previously-designated L source is not a pure source but a blend of HNe and normal SNe: $L = L^* + \text{HNe}$, where L^* represents normal SNe. For the estimated yields and relative rates given above, it follows that the $\sim 1/3$ of the solar Fe inventory previously assigned to normal SNe is in considerable error. Taking $\sim 2/3$ of the solar Fe inventory to be from Type Ia SNe, we find that of the remaining $\sim 1/3$, $\sim 24\%$ is from HNe with only $\sim 9\%$ from normal SNe. Thus with the proper assignment of Fe contributions for the L blend with $[\text{Sr}/\text{Fe}]_L = -0.32$, we obtain $[\text{Sr}/\text{Fe}]_{L^*} = 0.3$ for the L^* source. Using the proper yield ratios for the L^* source, we obtain the results shown in Figure 3. It is seen that the data for all the elements appear to be described very well by the three-component (H , L^* , and HNe) model. We further note that the clump of data above the $f_{\text{Fe},L} = 1$ curve in Figure 1b are now absent in Figure 3a with diminished Fe contribution from normal SNe.

3. General discussion

From the results reviewed above it appears that the whole chemical evolution in the “juvenile epoch” of the first Gyr after the Big Bang may be explained by the concurrent contributions of massive stars associated with low-mass and normal SNe and HNe in a standard IMF and that this same relative contribution continues into the present epoch. The efforts to seek Pop III stars that only occur in early epochs and then stop are considered by us to be invalid as were our earlier efforts to find a “prompt inventory” in the ISM/IGM. It follows that models for the formation of the “first” stars, which has been the focus of intensive studies with due consideration of the complex condensation and cooling processes at zero to low metallicities (e.g., [15, 16]), should consider the stellar populations inferred here with HNe ($\sim 25\text{--}50M_{\odot}$) being the dominant metal source. This source is highly disruptive and certainly can disperse debris through the IGM until halos of substantial mass have formed. The apparent sudden onset of heavy “*r*-process” elements, which motivated our earlier search for a “prompt inventory”, is most plausibly related to the formation of halos of sufficient mass that remain bound following both SNe and HNe [17]. It also follows that the earlier models of Galactic chemical evolution that aimed to provide $\sim 1/3$ of the solar Fe inventory by normal SNe must now be subject to reinvestigation. The observational evidence for ongoing HNe in the current epoch cannot be ignored. There is further the fact that production of heavy (true) *r*-process nuclei is strongly decoupled from Fe production. The extent to which this presents a further challenge to stellar models is to be resolved.

References

- [1] J.A. Johnson and M. Bolte, *ApJ* **579** (2002) 616.
- [2] S. Honda et al., *ApJ* **607** (2004) 474.
- [3] W. Aoki et al., *ApJ* **632** (2005) 611.
- [4] P. François et al., *A&A* **476** (2007) 935.
- [5] J.G. Cohen et al., *ApJ* **672** (2008) 320.
- [6] P.S. Barklem et al., *A&A* **439** (2005) 129.
- [7] J.P. Fulbright, R.M. Rich and S. Castro, *ApJ* **612** (2004) 447.
- [8] S.E. Woosley and R.D. Hoffman, *ApJ* **395** (1992) 202.
- [9] Y.-Z. Qian and G.J. Wasserburg, *ApJ* **567** (2002) 515.
- [10] Y.-Z. Qian and G.J. Wasserburg, *Phys. Rep.* **442** (2007) 237.
- [11] Y.-Z. Qian and G.J. Wasserburg, *ApJ* **687** (2008) 272.
- [12] A. McWilliam et al., *AJ* **109** (1995) 2757.
- [13] R. Cayrel et al., *A&A* **416** (2004) 1117.
- [14] N. Tominaga, H. Umeda and K. Nomoto, *ApJ* **660** (2007) 516.
- [15] T. Abel, G.L. Bryan and M.L. Norman, *Science* **295** (2002) 93.
- [16] V. Bromm and R.B. Larson, *ARAA* **42** (2004) 79.
- [17] Y.-Z. Qian and G.J. Wasserburg, *ApJ* **612** (2004) 615.