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Inferences on Aspects of Stellar Evolution and the Evolution of Galaxies

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1. INTRODUCTION

In this report we will try to summarize some key observations on isotopic abundances of radioactive nuclei in meteorites and their relationship to stellar sources. We will also cover the transition from the first generation of supermassive stars to the "normal" stellar population (including supernovae) in a galaxy. Two distinctive approaches are presented. The first is to utilize the observations on meteorites to infer the sources of radioactive nuclei in the solar system. We will show that some radioactive nuclides are clearly related to production in AGB stars, while others are produced in r-processes in SNII. We will show that there must be at least two distinct types of SNII sites with very different time scales for replenishing the ISM with different r-nuclides. This model leads us to a means of identifying the first generation of supernovae that contribute to the galactic inventory of r-process nuclei and of Fe. This is then related to observations of low metallicity stars and connects/disconnects more general r-process abundance patterns with/from Fe production and points to a first generation of stars having distinct characteristics. This approach is the view backward in time. The second approach uses the phenomenological model derived from the above considerations and applies it to the chronology evolving from Big Bang toward the present epoch. The latter approach proclaims an "absolute" time scale and what the evolutionary path of condensing, star-forming, baryonic matter should be. I am obviously going beyond my own capability in this approach, but it is at least interesting and may contain some seeds of truth. The assumption of a universal r-process that produces both Fe and r-nuclei in a coupled manner is in violation of the observations that the correlation of r-elements with Fe breaks down at $[\mathrm{Fe/H}] \lesssim -3$ as observed in halo stars. Furthermore, the *ab initio* approaches to early star formation, chemical evolution, and the early universe, have not proven very successful so far. There has been no real success in establishing the relationship between the condensation of cold dark matter early in the universe ($z \gtrsim 10?$) with the aggregation of baryonic matter and the formation of the first generation of stars.

2. THE BACKWARD VIEW

The basic time scale for the last addition of fresh r-process nuclei to the ISM from which the solar system formed is governed by the observation that $^{129}\mathrm{I}/^{127}\mathrm{I} \cong 1.0 \times 10^{-4}$ (Reynolds, 1960). The nuclide $^{129}\mathrm{I}$ ($\bar{\tau} = 2.3 \times 10^{7}$ yr) was found to be widespread in

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many meteorites with the abundance indicated above. As was early recognized by A. G. W. Cameron (see Cameron, 1993), ^{129}I can only be produced in an r-process. From any plausible assumption of the relative production rates of ^{129}I and ^{127}I it was found that the last time the r-process event that salted the protosolar ISM was $\sim 10^8$ years prior to the formation of the solar system (see Wasserburg, Fowler & Hoyle, 1960; and Schramm & Wasserburg, 1970). With this time scale, there should not be any remaining ^{107}Pd $\bar{\tau} = 9.4 \times 10^6$ yr) which is produced in an r-process from the r-event that produced ^{129}I. The discovery of ^{107}Pd (Kelly & Wasserburg, 1978) in a wide variety of iron meteorites with an abundance of $^{107}\mathrm{Pd}/^{108}\mathrm{Pd} \approx 2 \times 10^{-5}$ thus required another source. As ^{107}Pd can also be produced by an s-process, this discovery required further study in order to explain the observed ^{107}Pd abundance. As a result of the extensive work of R. Gallino with M. Busso on the s-process, based on the thorough and detailed stellar evolution models of O. Straniero and A. Chieffi, a collaboration was started during the Nuclei in the Cosmos meeting hosted by F. Käppeler in Karlsruhe in (1992) (see Figure 1). It was found that ^{107}Pd could be produced abundantly in AGB stars and many other short-lived nuclei could also be produced. It was found that using a self-consistent AGB model, ^{107}Pd, ^{60}Fe, and ^{26}Al could be produced in appropriate quantities to provide the estimated solar inventory of these nuclides by a mixture of fresh AGB debris into the protosolar cloud with $M_{AGB}/M_{PSC} \sim 10^{-2}$. This model also predicted that $^{182}\mathrm{Hf}/^{180}\mathrm{Hf} \sim 2 \times 10^{-6}$. It further confirmed that ^{129}I was not produced during the s-process. When ^{41}Ca was discovered in an inclusion in Allende (Srinivasan et al, 1994; Sahijpal et al., 1998) with $^{41}\mathrm{Ca}/^{40}\mathrm{Ca} \sim 1.5 \times 10^{-8}$, the calculated nuclear reaction output for the model was reviewed. It was found that ^{41}Ca was adequately produced if the time scale for collapse was $5 \times 10^5 - 7 \times 10^5$ years, about a factor of two shorter than calculated from the $^{26}\mathrm{Al}/^{27}\mathrm{Al}$ results, a time that my friend A. G. W. Cameron finds too short from a dynamical point of view. It follows that a model of AGB contamination of the protosolar cloud could provide several short-lived radioactive nuclei including ^{107}Pd, thus eliminating the conflict with ^{129}I.

An example of AGB contributions can be seen in a direct comparison between the calculated composition of the ejecta from an AGB star and actual debris from a star. This is seen in the results found by Choi et al. (1999) for a circumstellar dust grain in a hibonite grain ($\mathrm{CaAl_{12}O_{19}}$) found in the Semarkona meteorite (Figure 2a,b). This grain has a depletion in $^{18}\mathrm{O}/^{16}\mathrm{O}$ and increase in $^{17}\mathrm{O}/^{16}\mathrm{O}$ (see Figure 3) in agreement with what is expected for an AGB star after first dredge-up (Boothroyd, Sackmann and Wasserburg, 1994; Boothroyd and Sackmann, 1999). The oxygen results justify assigning this grain to a formation in the winds of an AGB star with C/O < 1. The grain shows ($^{26}\mathrm{Al}/^{27}\mathrm{Al}$) $= 4.7 \times 10^{-3}$ and ($^{41}\mathrm{Ca}/^{40}\mathrm{Ca}$) $= 1.5 \times 10^{-4}$. These are precisely the values calculated for an AGB model (Wasserburg et al., 1994; Busso et al., 1999). The results by Choi et al. (1999) demonstrated a quantitative self-consistency between the theoretical AGB model for production of these rare radioactive nuclei. They are also a necessary (but not sufficient) demonstration of the possibility of an AGB contamination model as shown schematically in Fig. 4.

A major conflict arises from the discovery of ^{182}Hf ($\bar{\tau} = 1.3 \times 10^7$ yr). The predicted yield from an AGB model s-process would only be $^{182}\mathrm{Hf}/^{180}\mathrm{Hf} = 2.4 \times 10^{-6}$ (Wasserburg et al., 1994). However, the observed value is $^{182}\mathrm{Hf}/^{180}\mathrm{Hf} = 3.4 \times 10^{-4}$ (Jacobsen and Harper, 1996; Lee and Halliday, 1995, 2000). The s-process yields of ^{182}Hf from an AGB star are thus a factor of 100 too low to explain the data. However, an r-process could produce the required abundance if the last r contributions continued to $\sim 10^7$ yr before the solar system was formed. The Hf data then requires an r-process contribution much closer in time to the formation of the solar system than is allowed by the ^{129}I data. A summary of all the r-nuclei abundances relative to ^{232}Th is shown in Fig. 5. It can be seen that the measured values (M) and the values calculated for uniform production (UP) over the history of the galaxy up until solar sytem formation are in quite reasonable agreement for the r-process nuclei ^{232}Th, ^{238}U, ^{235}U, ^{244}Pa, and ^{182}Hf, as well as for the p or (γ,n) nuclide ^{146}Sm. The clear exceptions for r-process nuclei are ^{107}Pd and ^{129}I (see recent review by Busso et al., 1999).

Based on this evidence, Wasserburg, Busso and Gallino (1996) proposed that there had to be two distinctive sites for the r-process: those producing heavy r-nuclei (Ba and above) and those producing lighter r-nuclei. They further argued that the frequency of these events attributed to SNII are $\sim 10^7$ yr for the high frequency (H) events and $\sim 10^8$ yr for the low frequency (L) ones. This is the time scale for replenishment of a standard mass of hydrogen in the ISM by the H and L events respectively. They also suggested that the very first SNII in the galaxy would show an excess of heavy r-nuclei as compared to light r-nuclei. Evidence in favor of this suggestion has been found by Sneden et al. (2000) who discovered that there is an excess of heavy r-nuclei compared to lighter ones in a low-metallicity halo star (see Figure 6). The approach of two SNII r-process sites has been explored by Qian et al. (1998) and Qian & Wasserburg (2000a). In examining the abundance of Ba and Eu as a function of metallicity, it was found that the correlation of Ba/H (represented by $\log\epsilon(\mathrm{Ba}) = \log(\mathrm{Ba/H}) + 12$) with [Fe/H] breaks down at $[\mathrm{Fe/H}] < -3$ (see Fig. 7). It is of considerable value to use the representation of the number of atoms of a species X relative to hydrogen (X/H) as this does not assume any relationship between production of different nuclides. The representation X/Fe can lead to some confusion if X and Fe are from different sources. The rapid rise in Ba at $[\mathrm{Fe/H}] \approx -3$ is associated with SNII(H) events and leads to the conclusion that the SNII(H) events do not produce Fe. The SNII(H) presumably collapse into a black hole. Only SNII(L) events are inferred to produce Fe. The near absence of Ba (and Eu) for $[\mathrm{Fe/H}] < -3$ thus requires that prior to the onset of SNII events there must be an Fe inventory in the ISM that is not related to SNII production, but must be due to a different class of early stars that preceded the onset of SNII (Wasserburg & Qian, 2000). This "prompt inventory" of Fe was attributed to the "first" generation of stars. These authors argued that: 1) these first generation stars were very massive ($M \gtrsim 100 M_\odot$); and 2) that the normal population of stars ($50 M_\odot > M \gtrsim 1 M_\odot$) could not form until a sufficient abundance of "metals" was present to permit cooling of masses of gas with the composition of Big Bang debris. It has long been recognized (c.f. Ezer and Cameron, 1971; Bromm et al., 1999) that condensing stars (particularly lower mass stars) from a gas of almost pure H and He is extremely difficult.

In a recent report by Qian & Wasserburg (2000b), it was shown that the observed relationship between [Fe/H] and [O/H] (Israelian et al., 2000) can be readily explained by a model where the first generation of very massive stars would produce large amounts of O, and excesses of Mg and Si, relative to Fe as compared to the solar abundances. It was proposed that the effective "metallicity" with all of these elements considered, as represented by [Fe/H] $\sim$ -3, is the level necessary to permit the onset of normal astration. The O and Fe evolution subsequent to achieving the level of the prompt inventory then changes regularly due to additions from SNII(H and L) and later from SNI.

3. THE FORWARD VIEW

The solar inventory of Fe is the result of any initial Fe produced by the first generation of stars, followed by that produced by SNII(L) and SNIa. The SNIa contribute at a much later time, sufficient for advanced stages of normal stellar evolution (Timmes et al., 1995). This time for SNIa corresponds to [Fe/H] $\approx$ -1. Using the estimated contribution of SNII(L) to the solar inventory of Fe to be about 1/3 of the total. This establishes the rate of Fe production of SNII(L) to be $\frac{d}{dt}(\mathrm{Fe/H}) = 10^{-2.5}(\mathrm{Fe/H})_\odot$ per 10^8 years in a standard mixing mass of H.

The abundances of Fe in early epochs has been studied using high resolution absorption spectra from protogalaxies. These protogalaxies are illuminated by QSO that are far behind them. The QSOs are, of course, also galaxies but of extremely high luminosity. The damped Lyman α studies show clear evidence of Fe lines back to red shifts (z) of $z = 4.5$ and the abundances relative to hydrogen have been determined (cf. Lu et al., 1996; Pettinni et al., 1997; Prochaska and Wolfe, 2000). It was noted by Prochaska and Wolfe (2000) that for any red shift z, there is a very large dispersion of [Fe/H] but that the lowest values found (for $1 \leq z \leq 4.5$) was [Fe/H] ≈ -2.7. We consider this in relationship to the cutoff in [Fe/H] $= -3$ that was earlier attributed to the onset of normal astration. If most of the Fe is in the gas phase (not in dust, but see Pettini et al., 1997), then this data can be used to establish a universal chronology for a galaxy from the arguments and rates given in the previous section.

We now consider the chronology relative to Big Bang. The relationship of the time scale to z can be adequately approximated by the following equation. We take the redshift z to correspond to a time

$$t(z) \approx \frac{2}{3} H_0^{-1} \Omega_\mathrm{m}^{-1/2} (1+z)^{-3/2} \tag{1}$$

after the Big Bang. We take the Hubble constant $H_0 = 65$ km s^{-1} Mpc^{-1} and the matter contribution to the critical density $\Omega_\mathrm{m} = 0.3$. This gives the maximum time available for any nucleosynthesis at a given z. The set of all observations at a given z then represents a sampling of the evolution of different protogalaxies up until that time. If we now assume that [Fe/H] $= -3$ is the baseline for starting regular astration, then the increase in iron above that level must, for a prolonged time, come from SNII(L) (until SNIa begin).

If a given protogalaxy first achieves a level of [Fe/H] $= -3$ at time $t^\star$ after Big Bang, then the subsequent iron abundances is given by:

$$(\mathrm{Fe/H}) = (\mathrm{Fe/H})_\mathrm{p} + \left(\frac{d(\mathrm{Fe/H})}{dt}\right)_\mathrm{L} (t(z) - t^\star), \tag{2}$$

where (Fe/H) is the number ratio and $t - t^\star$ is the total "cooking" time.

A frequency distribution of turn on of galaxies (i.e., ignition of normal astration) relative to Big Bang can be found from the observational data of [Fe/H] at a given z using this model (Fig. 8). It is seen that the rate of turn on is very low close to Big Bang and increases approximately like t^3. While there is inadequate data to establish any turnover in the turn on rate from the damped Lyman α data, it is evident that the turning on of galaxies appears to be dominantly at or near $z \approx 1.5$, a time 3 Æ after Big Bang. From the point of view of "normal" protogalactic and galactic nucleosynthesis, there is then typically a long delay between $t = 0$ and the development of "normal" stellar populations. The very early stages of chemical evolution of a galaxy are governed by the inventory of chemical abundances from the Big Bang debris and the product of the first generation of massive stars (what was called the "prompt" inventory) which was universally available before normal astration started. This approach was presented by Wasserburg & Qian (2000).

It is interesting to pursue this further and to consider the rate of production of QSOs. These are extremely active galaxies, short-lived, but QSOs are nonetheless galaxies. In a study of available data by Schmidt et al. (1995), it was found that the rate of QSO formation starts out low and reaches a peak at $z \sim 1.5$ and then declines. The slopes of the production rate curve between $z = 3$ to 4 for QSOs and those obtained for galaxy ignition for damped Lyman α galaxies from the above model for Fe are the same. It is most plausible that the rate of production of ignited galaxies and QSOs should be the same. After all, it is necessary to have lit up a galaxy if one is to have a QSO.

Among the questions that must be addressed are the following: Where is the evidence for the superstars ($M \gtrsim 100M_\odot$)? and; What is the basis for the gradual and then rapid turn on of galaxies? It is indeed possible that Gamma Ray Bursters (GRB) represent the superstars. The condition that the turn on of galaxies increases rapidly about 3 Æ after Big Bang would require that the superstars cannot provide the necessary metallicity in a random fashion, but that when the first superstar explodes, then it becomes (locally) sufficient to achieve [Fe/H] ≈ -3 or easier to "locally" initiate a second or third GRB. Thus, if GRBs are the hypothesized superstellar sources, they should tend to cluster in a local region, but spread over possibly several times 10^8 years. The frequency of GRBs would then, in either case, be the same as that found for the protogalaxies and QSOs as discussed above. The reason for this increased rate is not obvious but may be related to the late condensation (or re-condensation) of baryonic matter in the dark matter potential wells. The matter of the time scale for condensation of dark matter is then also important. If that is the governing parameter, then the time for major dark matter aggregation must be long and go like t^3. A possible scenario is that the superstars have provided the universe with [Fe/H] ~ -3 which destroyed most early baryonic matter concentrations. The increase in galaxy turn-on then reflects later condensation of baryonic matter (with [Fe/H] ~ -3) into the later developed, deeper dark matter potential wells. A further question that requires attention is: What are the changes in astration and stellar nucleosynthesis characteristics that lead to or produce active galactic nuclei with high Fe abundances and very large quantitites of dust (e.g., Seifert galaxies and QSOs)?

The problems of chemical evolution in galaxies over the first few Aeons of their existence cannot be understood without consideration of early stellar sources. These sources are distinct from those assumed for our galaxy using the normal mass function. These early sources provide the initial (prompt) chemical inventory on which normal chemical evolution of a galaxy proceeds. The implication of this early evolution is directly related to cosmological problems and cannot be disconnected from them.

In conclusion, I hope that this sophisticated audience will excuse the cosmic peregrinations and speculations of an aged mass spectrometrist who is mostly interested in rocks.

Caltech Division Contribution 8734(1065).

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prerogative per la forma, autorità, e facoltà del Consiglio
di essa Supernovae, e per l'amministrazione della
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IN PASADENA
& IN TORINO

NELLA STAMPERIA REALE.

Figure 1. Authorization for the Torino-Pasadena axis to study supernovae as well as AGB stars (original issue 1776, reissued and modified to include supernovae in 1996).

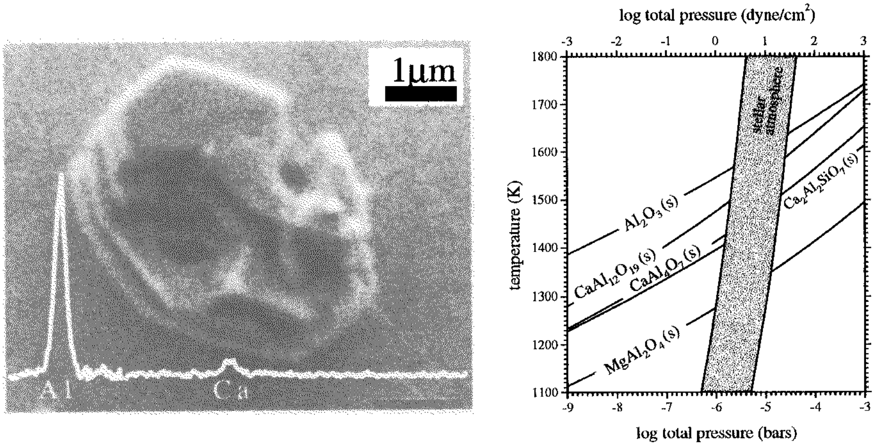

Figure 2. (a) SEM image of the first circumstellar hibonite ($CaAl_{12}O_{19}$) grain S-H5323 found in a meteorite (Choi et al., 1999). (b) Phase diagram showing stability fields of major oxides in a circumstellar envelope.

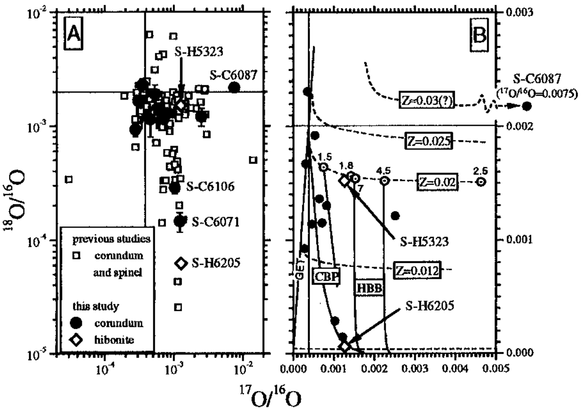

Figure 3. Compilation of oxygen isotopic compositions of circumstellar oxide grains recovered from meteorites. Note the position of hibonite S-H5323 relative to normal stellar evolution of a 1.8 $M_{\odot}$ star of solar ($z = 0.02$) composition in A. Offsets to very low $^{18}O/^{16}O$ due to cool bottom processing in B. (After Choi et al., 1999).

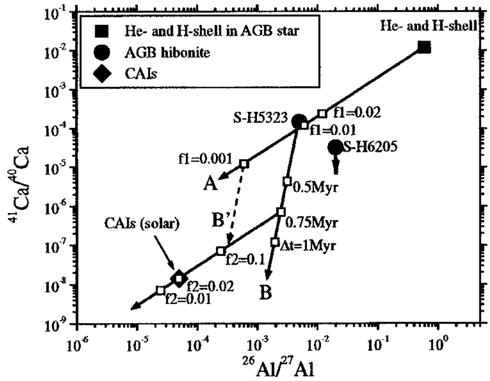

Figure 4. Abundance of ^{41}Ca and ^{26}Al measured in S-H5323. Line A: The He-H shell shows different dilution factors of $f1 = M_{He}/M_{ENV}$ for possible AGB models. Point f1 = 0.01 is the typical value in the general AGB model calculations. Trajectory down toward B is due to radioactive decay of ejecta. Trajectory to CAIs (solar) is dilution (f2) of % of AGB ejecta with the local protosolar ISM. Mixing model gives f2 ≈ 0.02 (Wasserburg et al., 1994). CAI point is from Srinivasan et al., (1994).

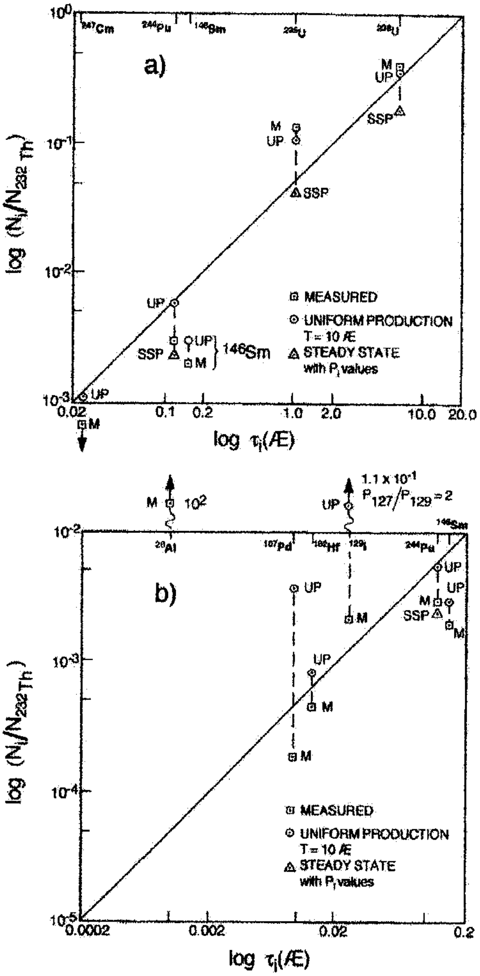

Figure 5. *a*. Graph of the log of the measured ratios (M) of the actinides (r-process) relative to ^{232}Th and of ^{146}Sm (p-process) relative to ^{232}Th in the early solar system as a function of their mean lifetimes ($\bar{\tau}_i$) for continuous nucleosynthesis up to the time of solar system formation. The straight line is a reference line corresponding to unit production ratios for all species. UP are the calculated values using best estimates of the relative production rates (P_i) for $T = 10$ Æ (1 Æ $= 10^9$ years). *SSP* corresponds to the steady-state case using (P_i) values. The ^{247}Cm is an upperbound (Wasserburg et al. 1996). *b*. Same as *a* but for mean lives $< 2 \times 10^8$ years; these include the r-process nuclei ^{182}Hf, ^{129}I, and ^{107}Pd, as well as ^{26}Al. Note that ^{129}I and ^{107}Pd for UP are far above the measured points (Busso, Gallino & Wasserburg, 1999).

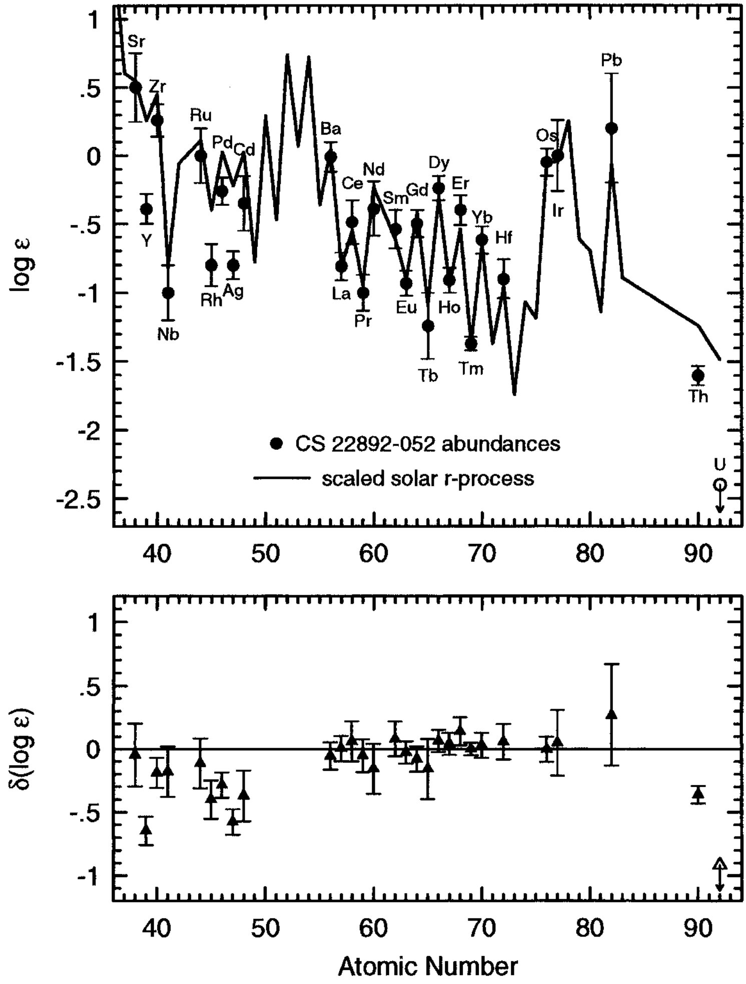

Figure 6. Abundances in the low metallicity halo star CS22892-052 plotted as filled circles with error bars, along with a scaled solar system curve plotted as a line. Lower figure shows deviations of log ϵ below the scaled solar line. Note deficiencies in the low mass region. (Sneden et al., 2000)

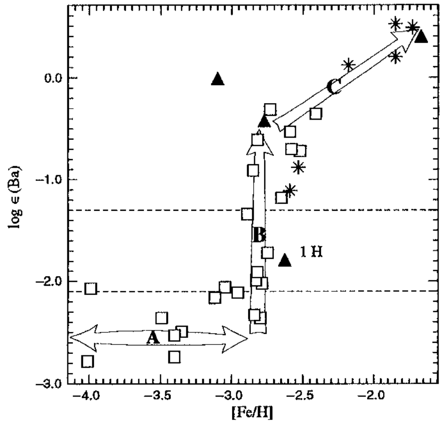

Figure 7. Compilation of data on log ϵ(Ba) vs [Fe/H] for low metallicity stars. Three regions of abundance evolution are schematically shown: the production by the initial/prompt Fe source (A), the addition of high-frequency non-Fe-producing H events (B), and the mixture of H and low-frequency Fe-producing L events (C). (Wasserburg & Qian, 2000)

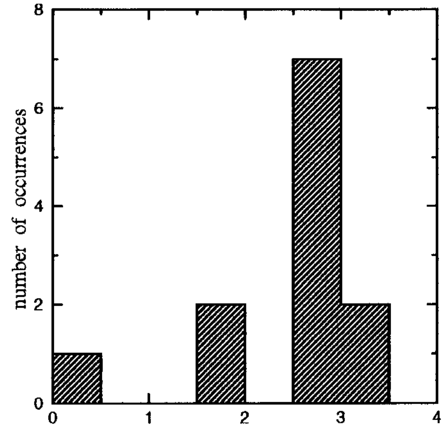

Figure 8. Histogram of t^* on damped Lyman α galaxies calculated from the Fe data summarized by Prochaska & Wolfe (2000) for z in the range $2.0 \leq z \leq 2.4$. This exhibits a peak at $t^* \approx 2.5$ Gyr when $t(z = 2.2) \approx 3.2$ Gyr. This shows that the rate of turn-on of protogalaxies starts from a low value close to the big bang and increases until at least $z \approx 2$.