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Early Chemical Evolution of The Galaxy

By

Lamya A. Saleh

A DISSERTATION

Submitted to Michigan State University
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ABSTRACT

Early Chemical Evolution of The Galaxy

By

LAMYA A. SALEH

We perform a numerical simulation to describe the evolution of pre-Galactic clouds in a manner similar to that suggested by the cold dark matter scenario of hierarchical galaxy formation, and adopting a SN-induced star-formation mechanism. The model includes chemical enrichment of the clouds by SN of type II and type Ia, and their associated energy input. It utilizes metallicity-dependent yields for all elements at all times, and takes into consideration the lifetimes of stars.

The model calculates the metallicity distribution functions for stars in the clouds, their age-metallicity relation, and relative elemental abundances for several alpha- and Fe-group elements. The stability of these clouds against destruction is discussed, and results are compared for different initial mass functions.

We find that the dispersion of the metallicity distribution function observed in the outer halo is reproduced by evolving many clouds with different initial conditions. The scatter in metallicity as a function of age for these stars is very large, implying that no age-metallicity relation exists in the early stages of galaxy formation.

Clouds with initial masses similar to presently observed globular clusters were found to be destroyed within the first 0.1 Gyr from the onset of star formation, suggesting that these systems could not have been responsible for the formation of the first stars, and were probably not self-enriched. More massive clouds are only stable when one assumes an initial mass function that is not biased towards massive stars, indicating that even if the first stars were formed according to a top-heavy mass function, subsequent star formation was likely to have proceeded with a present-day mass function, or happened in an episodic manner.

The predicted relative abundances of alpha- and Fe-group elements compared to iron show good agreement with the observed values down to a metallicity [Fe/H] = − 4. The observed scatter is reproduced fairly well for most elements but the model shows larger deviations for some elements. The contributions to the abundances from SN with different progenitor masses and metallicity are discussed. The results suggest that the low-mass end of SN of type-II was probably absent at the very lowest metallicities, and that the high-mass limit for the first stars that contributed to nucleosynthesis may be less than $40M_\odot$.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Introduction

1.1 Overview

Understanding the origin of the Milky Way has been the fascination of astronomers for many decades, and much work has been devoted to this field of science, both observational or theoretical. On the observational front, the search for stars that provide clues to the nature of galaxy formation has been going on for the past fifty years. Today, better observational techniques make it possible to obtain reasonably accurate determinations of the basic information required to understand the formation of our Galaxy, for instance, stellar kinematics, metallicities, and the relative abundances of chemical elements in individual stars. Such information not only sheds light on the formation processes of these stars, but also on the environments in which they formed. With even larger and more powerful ground-based telescopes, and with the enormous technological achievement of launching the first large telescope into space, the Hubble Space Telescope, the search for understanding the process of galaxy formation has extended not only deeper into the Milky Way, but now includes other galaxies at redshifts as high as z = 5. By studying galaxies at high redshifts one is actually looking back in time, hence one witnesses the formation of galaxies billions of years ago, providing insight on what processes might have been in play in the case of our own galaxy.

The wealth of information provided by ground- and space-based observations is growing rapidly, and is raising new questions, in addition to providing at least partial answers to old issues. Theoreticians have addressed the subject of galaxy evolution for decades, and have had many successes. Recent years have witnessed great advances in our understanding of the origin of structure in the universe and the apparent connection with the formation of galaxies. Today, chemical and chemo-dynamical evolution models are being performed with improving success, due to the leap in computational power (leading to much larger numbers of test particles that might be included in the simiulations), increased reliability of nucleosynthesis calculations, and the addition of new chemical abundance data for many more stars than was not available even in the recent past.

The first attempts to model the evolution of the Milky Way (Hartwick 1976; Tinsley & Larson 1979; Matteucci & Francios 1989; Pagel 1989a) were strongly inspired by the work of Eggen, Lynden-Bell, and Sandage (1962), who found a correlation between kinematics and chemical properties of a sample of nearby stars. This led them to suggest that the Galaxy formed by a dissipative, monolithic collapse of a spherical proto-Galactic cloud, with a free-fall timescale of $\sim 10^8$ yrs. In 1978, Searle

& Zinn (hereafter, SZ) compared the metallicities and inferred ages of a small sample of outer-halo globular clusters in the Galaxy, but found no evidence of the predicted correlations. As an alternative, they proposed that the halo formed by accretion of metal-poor fragments (similar in size to presently observed nearby dwarf galaxies) over a much longer timescale, up to several times 10^9 yrs.

Since then it has been a matter of debate as to which of these two scenarios, if either, is more likely to account for the formation of the Milky Way, and other large spirals like it. Aspects of the SZ scenario are supported by a great deal of observational evidence. The most direct is the observed tidal disturbance of the Sagittarius dwarf galaxy caused by the Milky Way (Ibata, Gilmore, & Irwin 1994; Ibata et al. 2000). Furthermore, field stars in the outer and the inner halo seem to exhibit differences in their kinematic properties (Majewski 1992; Carney et al. 1996; Sommer-Larsen et al. 1997) and possibly also in their ages, with the outer-halo stars appearing several Gyrs younger than those of the inner halo (Lance 1988; Preston et. al. 1991; Preston et. al. 1994; Lee, & Carney 1999). In addition to supporting the SZ scenario, this duality in the kinematics and the ages of the halo field stars has been taken to suggest that the inner part of the halo may have undergone a coherent contraction in the manner suggested by ELS (Carney et al. 1996; Sommer-Larsen et al. 1997; Chiba & Beers 2000).

Further support of the SZ scenario is provided by the observed apparent clustering of field horizontal-branch (FHB) stars, and the possible detection of kinematic substructure in the halo (Doinidis & Beers 1989; Majewski, Munn, & Hawley 1994, 1996; Helmi et al. 1999) that has been explained as the result of the later merging of smaller systems (perhaps similar to dwarf galaxies) with the Milky Way. Chiba & Beers (2000) studied the kinematic and chemical properties of a large sample (N ~ 1200) of non-kinematically selected metal-poor stars with full space motions available, and re-identified the 'clumps' in angular-momentum space of stars previously identified by Helmi et al. (1999). They also reported an observed elongated feature in angular-momentum space extending from the clump to regions with higher azimuthal rotation, which they referred to as a 'trail'.

The results of the Chiba & Beers study could not all be explained with either of the ELS or the SZ scenario alone. For example, they reported no observed correlation between the overall metallicity of their sample stars (quantified as [Fe/H], a logarithmic measure of the difference between the abundance of heavy metals in the star as compared with the sun) and their orbital eccentricity, and no change in the average rotational velocity of stars with abundances [Fe/H] < -1.7. This result is inconsistent with a monolithic collapse from the halo to the disk of a homogeneous spheroid. In such a scenario, stars born from the infalling gas would be expected to show a continuous increase in their average orbital rotational velocities (hence a continuous decrease in e) with increasing [Fe/H] as the spheroid spins up in order to conserve angular momentum. The SZ scenario, on the other hand, fails to explain the observed vertical gradient of rotational velocity found in the inner halo by the Chiba & Beers analysis.

Another interesting observation is that some halo stars have been found to exhibit rather low alpha-element (e.g., Ca and Mg) abundances relative to iron (King 1997; Carney et al. 1997; Preston & Sneden 2000) as compared to the majority of low-metallicity stars, which exhibit an over-abundance in alpha elements with respect to iron. This suggests that these stars may have experienced a nucleosynthesis history that differs from the bulk of the halo stars, perhaps occurring in smaller systems such as proto-galactic fragments or dwarf galaxies (Gilmore & Wyse 1998).

Taken as a whole, the extent data suggests a halo formation scenario in which the outer halo is assembled by the merging of sub-galactic clumps, while a dissipative collapse forms the inner halo on a shorter timescale (Norris 1994; Freeman 1996; Carney et al. 1996; Sommer-Larson et al. 1997; Chiba & Beers 2000). This picture is also qualitatively consistent with the present favored theory of galaxy formation, the hierarchical clustering scenario. According to this scenario, the Galaxy is initially assembled by formation of cold dark matter dominated mini-halos (Peacock 1999) that subsequently accrete primordial gas from their surroundings. Density perturbations in the early universe are believed to be the origin of these sub-galactic clumps, which eventually merge to form larger structures, and finally build up the Galaxy. Smaller clumps are more susceptible to destruction by tidal interactions and merging during the collapse of the Galaxy, in addition to the energy feedback from SN events as soon as they begin to form stars. Therefore, the stars formed in these small clouds are believed to reside in the outer halo of the Galaxy, and have no net rotational velocity, since the clouds they come from must have a distribution of velocities with no specific bias . This is in full agreement with the results of Chiba & Beers. More massive clouds, on the other hand, are less likely to be destroyed by interactions, and therefore experience multiple merging events while moving towards the central region of the proto-Galaxy. Because these clouds grow in mass and gain a large amount of orbital angular momentum, they experience a very violent and dissipative destruction, forming the observed flattened inner halo with prograde rotation

It should be noted that the details of the parameters required by cold dark matter models to reproduce the observed kinematic and chemical properties of the Galactic halo, in addition to the origins of the different populations residing in the Galaxy today, are questions that require further testing before they might be answered with confidence.

1.2 This Thesis

It is most likely that the history of the Milky Way may combine aspects of both the ELS and the SZ scenarios, occurring on different timescales, and that halo stars did not all form at the same time and did not all come from the same source. The older stars occupying the inner halo today were likely to have formed previously in the first clouds that merged to form the early halo, whereas the younger stars observed in the outer halo were accreted later from smaller nearby systems that may have gone through slower enrichment scenarios. There is a growing consensus that the halo of our Galaxy formed in a hierarchical manner, although a fully developed picture of how it occurred has not yet been developed.

In this thesis we are specifically interested in these early stages of the Galaxy's evolution, which astronomers have only recently been able to tackle due to the many poorly understood factors believed to be involved, and the scarcity of data that was available from the Galaxy's older component, the halo population.

We have performed a numerical simulation based on a chemical evolution model for individual sub-Galactic clouds, the aim of which is to test the bottom-up galaxy formation scenario and impose constraints on the early phases of galaxy evolution. We believe this study will be one of the first steps in understanding this period of galaxy evolution, and will be a stepping stone for future attempts.

Chapter 2

Approaches to Galactic Chemical Evolution

2.1 Observational Approach: Extremely Metal-Poor Stars

Since the surface elemental abundances of (non-evolved) stars are expected not to differ from those of the gas from which they formed, stars showing similar chemical and kinematic properties are believed to share the same history, and even may have had the same origin. Stellar populations in the Galaxy are commonly divided into the halo, bulge, and the thick and thin-disk populations.

It is among the field population in the halo of our Galaxy that the oldest and most metal-deficient stars are found. These stars contain in their elemental and isotopic abundances the fossil record of nucleosynthesis processes that took place in the first epochs of galaxy formation, and also reflect the inhomogeneity of the interstellar medium (ISM) during halo formation (McWilliam 1997). For this reason, astronomers today consider the search for metal-poor stars a main focus of their research efforts to understand the beginning of structure in the universe, with the halo of our Galaxy as the best available laboratory.

The first stars to form out of primordial gas that emerged from the big bang are especially significant since, if still detectable, they would contain within their chemical composition answers to many questions regarding big-bang nucleosynthesis and the early universe. Number counts of at least the low-mass stars in this population might be used as probes of the primordial Initial Mass Function (IMF), an essential parameter in hierarchical models. These stars, often referred to as Pop-III stars, are believed to have metallicities ranging anywhere between the primordial abundances, $Z \sim 10^{-10}\ Z_\odot$ (Applegate et al. 1988), and the lowest observed abundances in Pop-II stars ($Z \sim 10^{-4}\ Z_\odot$). Unfortunately, in spite of the long history of search for Pop-III stars, only a few stars of metallicity near [Fe/H] = -4 have been found, and no star has been found with a significantly lower abundance (Beers 1999). Perhaps this result should not be surprising, since the only ultra metal-poor stars that could have survived until today are the low-mass stars with main-sequence lifetimes exceeding the Hubble time (~ 10 Gyrs) If the IMF of Pop-III stars favored the formation of massive stars, as predicted by Larson (1998), then there are probably none left behind today because of their proportionately shorter lifetimes. Even if some low-mass ultra metal-poor stars are still to be found, it may be possible that that the surface abundances of these stars could have changed during their long lifetimes. Two scenarios have been suggested: extrinsic pollution -- the accretion of heavy elements onto their atmospheres while passing through the more metal- rich ISM of the Galactic disk (Yoshii 1981; Iben 1983), and intrinsic pollution --

as suggested by new stellar-evolution models for extremely metal-poor stars of Fujimoto et. al. (1999) and others, since a low-mass metal-deficient star can be converted into a carbon- and nitrogen-enhanced star due to passing through a period of intense internal mixing during late stages of evolution on the giant branch (at the time of the so-called helium shell flash). This idea gains some support by the fact that up to 25% of the stars in the HK survey (see the description below) with [Fe/H] < –3 exhibit strong carbon and nitrogen features in their spectra (Rossi, Beers, & Sneden 1999). Perhaps it is the case that all Pop-III stars with [Fe/H] < –4 do indeed undergo this conversion, and hence are not detected in normal surveys. Clearly, the origin of the metal-deficient carbon stars is of great interest, and requires a detailed understanding in the future.

In most of the surveys for metal-deficient stars carried out to date, the majority of the stars identified are located within a distance less than 10 kpc from the sun. It is not yet clear, however, whether lower metallicity stars will be found by conducting surveys of the more distant regions in the Galaxy. The scenario of galaxy formation favored by Chiba & Beers (2000), for example, suggests that the largest fraction of the oldest (and most metal-deficient) stars might be presently found in the inner-halo population (up to 20 kpc from the center of the Galaxy) rather than in the outer halo (see Beers & Chiba 2001 for a discussion).

There are a number of current projects aimed at the discovery of extremely metal-poor stars based on wide-field objective-prism surveys. The HK survey of Beers and collaborators (Beers et al 1985; Beers et al 1992; Beers 1999), for example, has identified some 1000 stars with [Fe/.H] < –2 that comprise the bulk of the low-metallicity targets for high-resolution spectroscopic studies with 8m-10m class telescopes, such as the VLT, SUBARU, and KECK.

One recent project holds particular promise. The Hamburg/ESO objective-prism survey (HES) covers the full southern sky at Galactic latitude |b| > 30 degrees (Christlieb et al 2000). The great advantage of this survey is its use of automated scans, rather than the visual scanning used in the HK survey. The HES is capable of detecting stars down to apparent magnitudes B ~ 17.0, and at distances up to 25 kpc from the Sun. The next generation of astrometric satellites (e.g., FAME, SIM, GAIA), in addition to ongoing ground-based astrometric programs (e.g., SPM, NPM, USNO) and full-sky (or nearly so) photometry programs (e.g., 2MASS, and SDSS) should dramatically improve the amount and detail of information that will be obtained from Galactic stars in the near future. These promising efforts are expected to increase the number of known extremely metal-poor stars considerably, and could perhaps lead to the discovery of Pop-III stars in the near future.

2.2 The Theoretical Approach: Galactic Chemical-Evolution Models

Modeling the evolution of our Galaxy may be seen as a first step towards understanding the formation and evolution of galaxies in general. The direction in which these modeling efforts are focused is governed by the availability of data, and by the status of theoretical approaches to the various physical processes involved.

A complete model of the formation and evolution of a galaxy must include both chemical and dynamical aspects. Chemical processes include the production of heavy elements and their re-distribution into the ISM, which includes star formation, stellar evolution and nucleosynthesis, and supernova events. Dynamical effects include merging of subsystems to form larger structures, heating and cooling processes, and gas dynamics.

Since the Milky Way is the best-studied individual galaxy, a fair amount of observational data for its constituent stars and clusters has been available for decades, leading to many efforts aimed at understanding its evolution. The first attempts (ELS, SZ) were mostly dynamical in nature due to the poor understanding of the physical processes governing chemical evolution, and the lack of detailed elemental abundance measurements for most halo stars. The Solar System abundances were established and tabulated by Andres & Grevesse in 1989. As a result, many chemical-evolution models were developed in attempts to reproduce the abundance patterns observed in the Galactic disk (Wyse & Silk 1989; Pagel 1989; Matteucci & Francois 1992; Edvardson 1993; Wang & Silk 1994; Pardi 1995; Timmes et al. 1995).

Most of these disk models divided the disk into radial zones, and as an unavoidable approximation, treated each zone as a "closed box," allowing no gas exchange to take place except for the gas accreted into each zone either from the halo or the extragalactic medium. In order to simulate the observed change in density with Galactocentric distance, the accretion rate of gas was varied in these models along the disk plane. This necessarily led to a variable Star Formation Rate (SFR) in the models that used density-dependent SFRs. Although reasonable agreement was reached between the theoretical results of these studies and the extant observations, these studies generally were forced to focus on a very limited set of observables. This indicates the need for more inclusive models that consider additional physical processes, including the dynamics of the gas. Still, our understanding of these processes is relatively limited, and in many models they were (and are) ignored. The importance of dynamical processes in chemical evolution can be realized from the correlation between a galaxy's morphology and its chemical composition, and from the systematic changes of chemical composition with position in our own Galaxy. In order to account for all of these observed trends it is necessary to treat the whole Galaxy with self-consistent models that follow its evolution, including Galactic dynamics and chemistry, in addition to the heating and cooling of the ISM (Burkert & Hensler 1987a;1987b ; Hensler et al 1992; Theis, Burkert & Hensler 1992; Sommer-Larsen et al. 1997; Samland 1998). In addition, the importance of energetic processes in the evolution of galaxies has been demonstrated through several studies (Blumenthal et al 1984; Silk 1985; Burkert & Hensler 1989; Burkert, Truran, & Hensler 1992). Their inclusion is necessary in order to create a multi-component ISM in which several gas phases can co-exist. Although these chemo-dynamical models treated the Galaxy as one whole system, and were successful in reproducing many observables. such as stellar kinematics, stellar and gas density distributions, SN rates, and the observed abundance gradients in the ISM, their treatment of the early stages of the Galaxy's evolution was brief and incomplete.

The lack of basic data, and the need for higher accuracies of the extant measurements, in addition to the complicated dynamical, nuclear, and atomic processes involved (many of which are still poorly understood), has made it impossible to formulate a complete evolution model of the Galaxy from a set of simple assumptions. Thus, most chemical-evolution models have been strongly focused on one or another aspect of the Galaxy's history. This can be seen as a necessary step, since the Galactic disk, halo and bulge do show unique abundance patterns (McWilliam 1997), suggestive of different enrichment histories. At present, complete evolution models for the Galaxy are achieved by evolving each of these populations in isolation. However, the manner in which the different populations found in the present Galaxy are related to one another is still unclear, making it difficult to combine the partial descriptions into a coherent whole.

For example, the question of whether the halo and disk populations evolved separately, or were strongly interacting with one another on similar timescales, has not yet been answered. In some models, it was assumed that the major part of the gas in the disk originally came from the subsystems that formed the halo and were disrupted by the energetics of massive stars (Sommer-Larsen et al. 1997; Pardi et al. 1995; Travaglio et al 1999a). Others excluded this scenario, and claimed that the disk accreted the majority of its gas from the extragalactic medium and evolved separately from the halo (Chiappini et al. 1997; Goswami & Prantzos 2000). In the majority of disk models, infall of gas was assumed without any specification of its origin (Timmes et al. 1995; Prantzos & Aubert 1995; Prantzos & Silk 1998).

2.3 Towards a Chemical Evolution Model of the Halo

There seems to be an urgent need for better understanding of the earliest stages of the Galaxy's evolution. The stars that formed at these earlier times, and the subsequent dynamical interactions that shaped the Galaxy, probably played a role in the nature of all of the various populations observed today.

Understanding the early epochs of the Galaxy's evolution is also crucial to the development of other branches of astronomy. Examples include high-redshift galaxies and damped Lyman-α systems, where astronomers hope to explain details of the heavy-element abundance distributions associated with these objects (Pettini et. al. 1997) . In addition to the important role the first stars are believed to play in the early evolution of galaxies, they are believed to contribute to the formation of early generations of black holes (Ostriker & Gnedin 1996; Haiman et al. 1996; Tegmark et al. 1997).

Nucleosynthesis calculations in stars is a rapidly evolving area of research, and one that is expected to benefit greatly from detailed studies of extremely metal-poor stars. By comparing the observed elemental abundances of extremely metal-poor stars with the predictions of chemical-evolution models, one can impose constraints on the theoretical nucleosynthesis calculations in massive stars. One can also predict the abundance patterns expected in metal poor stars from theoretical SN models, starting with specific assumptions about the formation processes of these stars. By comparing the predictions with the observed abundances, one can gain some insight about the validity of the assumptions made, and add to the understanding of the formation processes and the efficiency of mixing of the ejected elements into the surrounding ISM.

Most pictures for the formation of the first structures suppose that they are the result of gravitational amplification of primordial fluctuations. The halos of galaxies would then form by the merging of smaller sub-structures. The mass of these sub-structures has been estimated by hierarchical clustering models to be of the order of present-day dwarf galaxies, or large globular clusters ($\sim 10^6$ to 10^8 $M_\odot$) . These models predict that the first systems to collapse under their own gravity (and presumably that went on to form stars), are of this mass range (Blumenthal et. al. 1984, Peebles 1985; Peebles 1993; Haiman, Thoul, & Loeb 1996; Tegmark et al. 1997; Nishi & Susa 1999; Miralda-Escude 2000).

Monolithic collapse scenarios also predict fragmentation via gravitational and/or thermal instabilities into subsystems of the same mass range (Fall & Rees 1985). The stellar halo population would then originate, in this view, from disrupted subsystems. Later, the remaining gas would settle and form the disk (Katz 1992; Steinmetz & Muller 1994,1995). This scenario was also suggested by Sommer-Larsen et al. (1997), as the result of their analysis of the kinematics and dynamics of blue horizontal-branch stars in the Galactic halo. These authors found that there appears to exist a rapid decrease in the radial component of the halo's stellar velocity ellipsoid, associated with an increase in tangential velocity dispersion with Galactocentric distance. This, together with the observed abundance gradient in the inner halo that is absent in the outer halo, led them to suggest that the outer halo formed by accretion and merging processes, while the inner halo arose from a more dissipative and coherent collapse on a shorter timescale. In this picture, the more compact subsystems of the halo would survive to form the globular clusters observed today, whereas the more diffuse and probably lower-metallicity subsystems would break up due to the energetics of massive stars, tidal destruction, and dynamical friction. The majority of the gas from these systems, left in a dilute state after their destruction, would gradually settle in the disk. This galaxy formation scenario has also been supported by observations of the Sagittarius dwarf galaxy, which is presently being disrupted by the Milky Way, as well as a group of small galaxies at high redshift, possibly in the process of merging into a larger galaxy (Pascarelle et al. 1996).

Our ability to ask specific, detailed questions about the process of halo formation and evolution is being greatly expanded by the large amount of spectroscopic information now becoming available from high-resolution studies of metal-poor stars. As the result of efforts by Beers and his collaborators (Beers, Preston, & Shectman 1985, 1992; see Beers 1999 for a summary), the number of known metal-poor stars has increased dramatically in the last few years. The abundance trends of individual elements observed in these stars appear to be in agreement with the simple existing models of Galactic evolution.

Earlier, Gilroy et. al. (1988) showed that a real star-to-star abundance scatter of heavy elements exists amongst metal-poor stars, indicating that the proto-halo was not well mixed when these stars formed. This was also confirmed by Ryan, Norris, & Beers.

(1996), who performed an abundance analysis for 19 very metal-poor stars with [Fe/H] < −2.5, and found a dispersion in their measured abundances greater than the observational uncertainties. This study also confirmed similar results by McWilliam et al. (1995a), who found that the abundance ratios of several iron-group elements (such as Co and Ni) relative to iron showed a shift in slope at [Fe/H] ~ −2.5, indicating that different processes must have dominated before this "chemical time" than later in the evolution of the Galaxy. McWilliam et al. suggested that metallicity-dependent yields of type-II SN may have been responsible for the observed shift in slope for a number of elements observed below [Fe/H] = −2.5.

Ryan et. al. (1996) also proposed an explanation for the observed abundance patterns at extremely low metallicity. They noticed that, in spite of the existence of a large scatter in neutron-capture element abundances relative to iron, the iron-group elements themselves show rather well-defined trends. Adopting the supernova remnant evolution model of Cioffi, McKee & Bertschinger (1988), they offered the explanation that the mass of the ISM that mixes with the SN ejecta, though being only weakly dependent on the cloud conditions (e.g., density and metallicity), depends linearly on the SN explosion energy. Since iron-group elements are thought to form near the collapsing proto-remnant of most Type-II SN explosions, it seems reasonable that two SN producing the same amount of these elements should impart the same kinetic energy to their envelopes, allowing the ejecta to mix with the same amount of mass in the ISM, thereby producing similar enrichment. This picture would allow the proto-halo to include a combination of many clouds, evolving separately at different times and places, and still produce the well-defined chemical patterns observed for iron-group elements.

In the same paper, Ryan et al. calculated the mass of ISM that would be polluted by a SN with energy of the order ~ 10^{51} ergs, and found it to be of the order ~ 10^5 solar masses. They deduced that enrichment by a typical SN event in the proto-halo could produce a metallicity [Fe/H] ~ −2.7 when its ejecta are expelled into a bubble of primordial gas. This value coincides with the observed lower limit to the metallicity of Galactic globular clusters, and with the metallicity for field halo stars below which larger scatter in abundance ratios is seen, in addition to the observed shift in iron-group element abundance patterns. This is also consistent with the idea that field halo stars formed in less tightly-bound systems than those in which the globular clusters (GCs) formed. More massive clouds would survive one or more SN events, whose cumulative enrichment would set the lower limit on the metallicity of the clusters they form.

The idea that halo field stars formed originally in globular clusters that were later disrupted has been considered by several groups. Brown et al. (1995), for example, developed a dynamical evolution model for GCs, including self-enrichment, and showed that SN explosions of the first-generation stars trigger the formation of an expanding shell, which would be decelerated by the surrounding hot ISM, and can then form second generation stars. They also studied the conditions under which a GC can survive. Recently, Jehin et al. (1998), based on their analysis of abundances of 21 metal-poor stars, suggested a scenario for the formation of metal-poor stars based on two phases of chemical enrichment. The first is during the explosions of massive stars as SN of type-II events, the second is where enrichment is provided by stellar winds from intermediate-mass stars. In this view, all halo and thick-disk stars are assumed to be formed in GCs, from which they escaped either during an early disruption of the cluster, or later, through an evaporation process. There is also evidence in the halo of later accretion of stars from nearby systems such as dwarf galaxies.

This thesis is intended to test this early galaxy evolution scenario, by evolving individual clouds with different initial conditions, and following their chemical evolution. These clouds are intended to represent the first systems that formed stars, whether they were proto-Galactic and contributed directly to the formation of the halo, or extra-Galactic systems from which the Galaxy later accreted material. One major strength of our calculation is the use of metallicity-dependent yields, which is specifically crucial during these early times when the first enrichment events took place. Several studies used only metallicity-independent yields and followed the evolution of specific elements .(Pagel & Trautvaisiene 1995; Chiappini et al. 1997; Chiappini & Matteucci 1999).

2.4 Chemical Evolution and the r-process

There have been a number of recent studies that follow the chemical evolution of neutron-capture elements in the halo. Almost all of these models were able to reproduce the inhomogeneties observed for elemental abundances through a stochastic evolution scenario, but were generally limited to the study of a single neutron-capture element (Raiteri et al. 1999; Tsujimoto et al. 1999; McWilliam & Searle 1999; Travaglio et al 2000). Since the production processes of neutron-capture elements are still rather uncertain, we believe that the best approach to the problem of halo evolution would be to follow the evolution of elements with better understood origins, such as the alpha and Fe-group elements. The results of such models can then be used to set constraints on the evolution process, and shed more light on the neutron-capture production sites.

The only group that followed the evolution of several alpha and Fe-group elements at extremely low metallicities is Argast et al. (1999). However, this study, which made use of metallicity-independent SN yields, was unable to reproduce the observed trends at very low metallicity for some elements, and also lacked any mechanism to include accretion events that are believed to contribute greatly to the halo population.

A complete chemical evolution model that follows the production of multiple elements during the halo phase, within a framework that includes SN events and mixing processes, is absolutely necessary at this stage. If the observed trends for these elements in metal-poor stars can be reproduced fully under a given set of assumptions about the formation processes of second- and third-generation stars, then one could attempt to set limits on the formation sites of neutron-capture elements.

Truran (1981) suggested that r-process elements are produced by type-II SN events on timescales comparable to the halo formation timescale, while s-process elements require longer timescales. This is consistent with the observation of some very low-metallicity stars that show large overabundances (relative to solar) of r-process elements (e.g., the well-known metal-poor star CS 22892-052, Sneden et al. 1996, 2000; also the recently discovered giant CS 31082-001, in which uranium was detected for the first time, Cayrel et al. 2001). Some theoretical calculations were also able to reproduce the solar system r-process abundances through the action of the "neutrino wind" expected to occur in the first few seconds following SN explosions (Takahashi et al. 1994; Woosley et al. 1994). Although it has been suggested that other astrophysical sites for the source of the r-process elements might exist (Cowan et al. 1999; Freiburghaus et al. 1999), it is still believed that there must be a single dominant source for at least the heavy r-process elements. This can be deduced from the observations of halo stars which show r-process abundance patterns in full agreement with the scaled solar system r-process abundance pattern (Cowan et al. 1998).

Since the neutron-capture elements show the greatest dispersion at low metallicities, they are the best representatives of the inhomogeneities that existed in the halo at early times. Therefore, understanding the production mechanisms of these elements and their inclusion into stars is crucial for understanding this era of our Galaxy's history.

2.5 Overview of the Model

Since models that adopted a canonical one-zone approach to the chemical evolution of the Galaxy, where mixing of SN ejecta into the ISM is assumed to be complete and homogeneous, failed to reproduce the scatter observed in metal-poor stars (Primas et al. 1994; McWilliam 1995), we attempt a more realistic approach to the problem that treats the dynamics of the gas and the enrichment process in more detail.

Complete mixing of the ejecta of type-II SN with the ISM would imply the existence of an age metallicity relationship, where the metal abundances of stars would reflect those of the ISM at the time the star formed, and therefore would increase with time. Such a relationship was shown to be broken by extremely metal-poor stars with [Fe/H] < -2.5 (McWilliam et al. 1995; Ryan et al. 1996). In fact, the abundance patterns of these stars resemble those calculated for first-generation SN events, which led to the idea that very low-metallicity stars must have formed from individual, or at most, a few, SN explosions (Audouze & Silk 1995).

Tsujimoto et. al (1999) proposed a model of Galactic evolution based on SN-induced star formation, where the elemental abundances of the next-generation stars are the result of mixing of the ejecta of a SN with the gas swept up by the explosion forming a shell in which star formation is induced. This scenario takes into consideration the stochastic nature of early star formation when yields are used that depend on the initial mass and metallicity of the progenitor. It also allows for the testing of the idea that the elemental abundances in extremely metal-poor stars are the products of one or several SN events. We adopt this theory of star formation in our model. The first-generation stars are assumed to form in the cores of primordial clouds by some unspecified process.

Our chemical-evolution model includes enrichment of the ISM with several alpha and Fe-group elements, taking into consideration the lifetimes of different mass stars. It also includes dynamical processes through the mixing of the ejecta with their surroundings and through the effects of the energetics caused by SN events. Merging and tidal interactions among the different clouds are not considered in this model. Since such interactions are sure to take place, we must consider the ensemble average of our predictions for individual clouds.

The third chapter presents a detailed description of the model and the technical methods used in our code. A detailed comparison between the current results and observational data is given in chapters four and five. Finally, concluding remarks, as well as future directions, are presented in chapter six.

Chapter 3
The Chemical Evolution Model

3.1 Introduction

There is a general consensus that early evolution of our Galaxy took place in a manner consistent with the hierarchical clustering scenario. Many details of this evolution can only be explored by constraining galaxy-evolution models with the observed properties of stellar populations. The elemental abundances observed in stars of our Galaxy reflect a complex chemical evolution process. This is particularly clear in the halo population, where a large scatter is observed in the abundances of some of the heavy elements (mostly the neutron-capture species), indicating a chaotic early history. Even in the solar neighborhood, where stars exhibit a much lower star-to-star scatter in their elemental abundances, there is evidence that suggests a fairly non-uniform enrichment history (Rocha-Pinto et al. 2000).

On a larger scale, galaxies in general show non-uniformities in their chemical evolution, where more massive galaxies reflect richer enrichment histories, and individual galaxies show higher metal abundances towards their centers. This all suggests that the early evolution of galaxies may have been dominated by the subsequent evolution of gravitationaly amplified primordial fluctuations.

The main purpose of the present study is to test the bottom-up theory for galaxy formation, where primordial fluctuations resulted in the gravitational collapse of subsystems forming sub-galactic halos. Such subsystems would then merge and accrete diffuse matter to form mini-halos. We follow the chemical evolution of individual clouds, assuming all stars formed initially in proto-Galactic clouds, adopting the SN-induced star formation model of Tsujimoto et al. (1999). We follow the evolution of several alpha elements and Fe-group elements and compare to the observed abundances of individual stars in the halo and thick disk of our galaxy.

3.2 Methods of Modeling Chemical Evolution

A Galactic chemical-evolution model is concerned with the time evolution of the chemical content in the Galaxy, including stellar metallicities, abundance gradients in the ISM, and variations in the relative abundances of heavy elements. Since there are many physical processes involved in the production and distribution of heavy elements, chemical evolution models can be very complex unless certain approximations and assumptions are made regarding processes such as star formation, nucleosynthesis, gas flow, as well as the production sites and mechanisms for the re-distribution of heavy elements. The set of assumptions made give a model its identity, and defines the set of equations to be solved that represent the system. By solving these equations numerically or analytically one can trace the abundance gradients in the ISM as a function of time and position and follow the predicted elemental abundance distribution in stars.

The classical chemical-evolution equations for a one-zone model, which considers the entire ISM of the Galaxy as a medium of uniform composition at any given time, were first derived by Tinsley (1980), and have been the basis for chemical-evolution models since then. In this approach, the total mass of the system is divided into gas mass and star mass, and these constituents are followed as a function of time, allowing for infall and outflow of gas into and out of the system.

Before we present the details of our chemical evolution equations we introduce a few important definitions.

3.2.1 The Star Formation Rate (SFR)

The SFR is defined as the rate at which mass is converted into stars, and is given in units of $M_{\odot}$ Gyr^{-1}. The present-day SFR has been estimated empirically for the solar neighborhood (Miller & Scalo 1979) from the total surface density of the Galactic disk and from star counts in a number of local regions. For estimates of the SFR in more remote regions, counts of the most massive and brightest stars were used and a total SFR was obtained by assuming an IMF for the region (often taken as the local initial mass function), in addition to several other methods that were used to estimate its value (see Searle et. al. 1973; Larson & Tinsley 1974). These studies suggest that the star formation rate is different from galaxy to galaxy, and from place to place in a given galaxy, which has made it impossible to assign to it a universal function that can be used in Galactic evolution models. Although the function suggested by Schmidt (1959) assumes that the star formation rate is proportional to a power 'n' of the gas density, attempts to assign a value for 'n' that applies everywhere have failed. This suggests that the SFR depends on other properties of the environment in addition to the gas density. In fact, it has been pointed out by Lynden-Bell (1977) that this function may depend on so many other parameters of the gas that it would become too complicated to use in evolution models. Therefore, the best approach for models would be to use simple expressions for the SFR with a limited number of parameters to be tested.

Other parameterizations and modes of star formation have been suggested, such as the exponentially time-dependent SFR :

$$\Psi(t) = \Psi_o \, e^{-\lambda t}$$

Still others include self-propagating star formation, self-regulated star formation, density thresholds, and bursts of star formation triggered by interactions or mergers.

In our model we adopt the SFR suggested by Tsujimoto et. al (1999), in which star formation is triggered by a SN event, thus its value depends on the frequency of type-II SN explosions in the early Galaxy, a parameter which must be estimated.

3.2.2 The Initial Mass Function (IMF)

The initial mass function (IMF) describes the distribution of stellar masses that result when a generation of stars is born. The important role this function plays in chemical evolution comes from the fact that stellar mass affects greatly the other properties of stars, such as main-sequence lifetimes, mass loss, nucleosynthesis, and the type of death a given star will eventually experience. Thus, knowledge of the nature of the IMF is crucial for determining the properties of stellar populations and their evolution with time.

The IMF has been studied in the solar neighborhood intensively, both empirically and theoretically, since its introduction by Salpeter (1955). Based on observational data of the counts of stars per unit volume, he first obtained the luminosity function for the local region. A mass-luminosity relationship was then used to convert this to a mass function for the solar neighborhood. The Salpeter mass function takes the form:

$$\varphi_{sal} \, \alpha \, m^{-1.35}$$

It is still not clear whether the IMF is a universal function, or if it varies with space and time. There have been many studies of the IMF in different environments, and other functional forms have been suggested (Kroupa et al 1993; Adams & Fatuzzo 1996; Padoan et al. 1997, Larson 1998). It is generally thought that the IMF at early times was different from what is observed today. In particular, a number of recent studies

(Elmegreen 2000; Nakamura & Umemura 1999; Kroupa 2001) have presented evidence that the early IMF was quite likely to have been biased towards massive stars. As noted above, this might help to explain the present lack of "metal-free" stars observed today. Such a top-heavy IMF would also be able to explain the deficiency of metal-poor stars in the solar neighborhood when compared to simple chemical-evolution models (the so-called "G dwarf problem").

Analytically, the IMF has been treated with different definitions and notations in the literature. Therefore, we will introduce here the definition we adopted for our calculation. If $\Psi(t)$ is the star formation rate (SFR), and $\varphi(m)$ is the IMF, then the rate at which mass goes into forming stars in the mass range [m, $m + dm$] is:

$$\Psi(t) \cdot \varphi(m) \cdot dt \cdot dm$$

So the number of stars formed in that mass range will be:

$$\Psi(t) \cdot (\varphi(m) / m) \cdot dt \cdot dm$$

In order for $\varphi(m)$ to represent correctly the relative birth rates of stars, it must be normalized to unity over the whole allowed range of stellar masses,

$$\int_{m_l}^{m_u} \varphi(m)\, dm = 1$$

where m_u is the upper mass limit for stars, and m_l is the lower mass limit. This function allows the calculation of many quantities that vary with stellar mass. One example is the yields of different elements. If Y_i, is the total yield of element i from all stars, it can be calculated by the integral

$$Y_i = \int_{m_t}^{m_u} y_i(m) . (\varphi(m) / m) \Psi(t - t_m) . dm$$

where $y_i(m)$ is the yield of element i from a star with mass m, and m_t is the mass cut-off at time t, representing the lowest mass stars that will contribute to the enrichment process at that time. The time t_m is the lifetime of the star with mass m.

3.2.3 The Metallicity-Dependent Yields

For intermediate stellar masses, we adopt the standard nucleosynthesis yields of Renzini and Voli (1981). This study covers stars of masses in the range 1 $M_\odot$< mass < 8 $M_\odot$. They calculate the yields for two different metallicities, $Z = 0.004$, and $Z = 0.02$. In the current model, we interpolated between these two values and used $Z = .004$ yields for lower metallicities. The need to make use of predicted yields from rather high-metallicity intermediate-mass stars has been relieved only very recently (Abia et al. 2001), unfortunately too late to be incorporated into our present calculation. Intermediate-mass stars mainly eject H, He, C, and N into the ISM at the end of their lives, affecting greatly the value of the metal/H ratio. These stars end their lives as carbon-oxygen rich white dwarfs. If they are members of a binary system these dwarfs may accrete mass from the remaining member to the point where their mass exceeds the Chandrasekhar limit. At this point, the star becomes unstable causing a thermonuclear explosion and expelling its thermonuclear products into the ISM. These events are referred to as Type-Ia SN. For these events we use the yields calculated by Thielemann et al. (1986). The time between the formation of a white dwarf and its evolution into a SN is referred to as the 'delay time'. This time is taken in our model to be 1 Gyr, which provides a good fit to the observed age-metallicity curve. Therefore, these events will only have a significant effect on clouds that evolve and self-enrich for more than 1 Gyr. This can be the case for clouds that are at least as massive as dwarf galaxies. Less massive structures are expected to be destroyed due to energy input from SN of Type-II events during the first Gyr of the onset of star formation. Stars less massive than 1 $M_\odot$ serve in this model only as reservoirs of gas mass, since they do not evolve significantly during the considered time.

For massive stars we adopt the metallicity-dependent stellar yields of Woosley & Weaver 1995 (Hereafter, WW95) who were the first to include stars with progenitor masses ranging from 11 to 40 $M_{\odot}$, and metallicities from zero to solar, and to calculate yields for elements from H to Zn. This permits more solid limits to be set on Galactic chemical evolution models, and enables comparisons between the results of simulations and the empirical data from high-resolution spectral measurements in stars.

While the yields presented by WW95 cover stars up to 40 $M_{\odot}$, other studies, such as Thielemann, Nomoto & Hashimoto (1996) obtain yields for stars up to 70 $M_{\odot}$. Although the fate of stars more massive than 40 $M_{\odot}$ is still uncertain, a study by Heger, Woosley, & Waters (2000) suggests that metal-free stars with masses between 35-100 $M_{\odot}$ are expected to collapse into black holes, while stars with masses between 10-35 $M_{\odot}$ can explode as type-II SN, and contribute to the enrichment process. In addition, including such massive stars will have very little effect on the results of a chemical-evolution calculation when adopting a Salpeter IMF, since very few stars will form that are more massive than 40 $M_{\odot}$. Therefore, we believe that the stellar mass range covered by the calculation of WW95 is a reasonable range for a realistic model. This is also consistent with the findings of Samland (1998), that the mass range of stars to form Type-II SN is 11 to 30-40 $M_{\odot}$.

In contrast to the stellar yields calculated by Thielemann et al. (1996), in which they use a constant solar progenitor metallicity, the Woosley & Weaver yields have the advantage of covering the whole metallicity range from zero to solar for the progenitor stars. Although their predicted yields of heavy elements are not affected greatly by small changes in the initial metallicity of the progenitor for $Z/Z_{\odot} > 0$, there are large differences between the predicted yields for stars with metallicity $Z/Z_{\odot} > 0$ and those for stars with $Z/Z_{\odot} = 0$. This will have a great effect on the metallicity distribution of extremely metal-poor stars, and on the stars of the next generation that will form in their shells. Therefore such a detailed study has made models of the earliest stages of galaxy evolution possible for the first time.

WW95 also considered the energy of the explosion an important parameter in determining the yields of a SN event, in addition to the initial mass and metallicity. Depending on the energy of the explosion, part of the synthesized elements will be ejected, whereas elements in the deeper layers will fall down onto the core after the explosion. For stars more massive than 25 $M_{\odot}$, they distinguish different models A, B, and C, corresponding to three increasingly different values for the initial kinetic energy of the "piston" (a theoretical construct used to simulate a real explosion). The larger this energy, the more heavy elements escape from the explosion. We adopt model B, an intermediate value for the energy.

Figure 3.1 shows the yields of stars from this calculation for three different elements, Fe, Mg, and Mn, as a function of the metallicity of the progenitor. The yields are shown for progenitor masses of 40, 30, 20 and 15 $M_{\odot}$. It is clear from the figure that as metallicity goes down, a wider range of yields is produced. This will allow, in part, for the production of increased star-to-star scatter observed in elemental distributions of metal-poor stars.

The only models that used the metallicity-dependent yields of WW95 are Timmes et al. (1995), Samland (1998), and Goswami & Prantzos (2000). Timmes et al. (1995) is a chemical-evolution model of the Galaxy in which they followed the evolution of all elements from H to Zn and compared their results to the observed stellar abundances in the solar neighborhood. They discuss the strengths and weaknesses of the WW95 yields, suggesting that the main weakness is that the Fe yields are too high, and may need to be revised. But this study failed to treat the halo evolution with much detail, and did not follow the trends of elemental ratios to metallicities less than [Fe/H] = –3, where stellar abundance data now exist. Goswami & Prantzos (2000) treated the disk and halo separately, and followed the evolution of elements from C to Zn using the WW95 yields. This study also failed to follow the earliest stages of the Galaxy's evolution, and did not attempt to reproduce the scatter observed in stellar abundances at very low metallicities, as the classical model they employ assumes complete mixing of SN ejecta with the ISM.

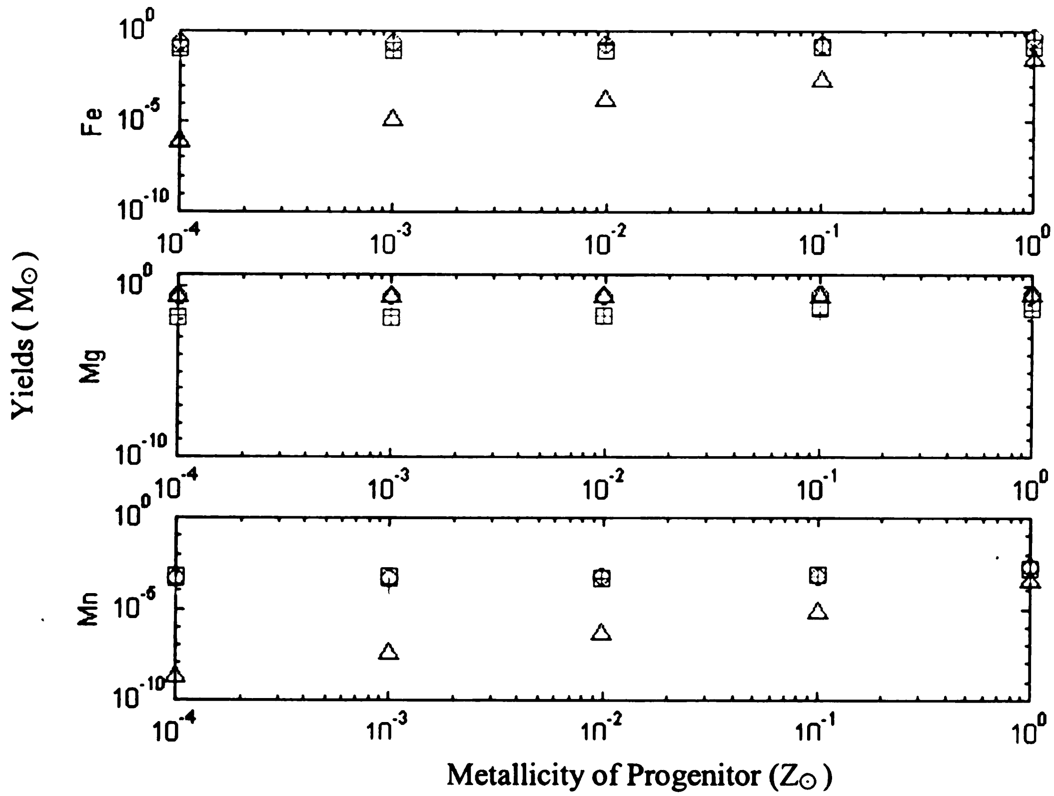

Fig. 3.1 The metallicity-dependent yields of Fe, Mg, and Mn. Each is shown for four different progenitor masses, 40 M⊙ (triangles), 30 M⊙ (circles), 20 M⊙ (squares), and 15 M⊙ (plus sign).

Samland (1998) is a chemo-dynamical model that attempts to model the collapse of the Galaxy from which both the halo and disk form. This study also treats the early evolution with little detail, and makes several approximations regarding the metallicity-dependent yields of WW95, and the stellar lifetimes.

The model I have explored utilizes the stellar yields calculated by WW95 in a more detailed discussion of early halo evolution. We use finely spaced mass and metallicity grids in our simulation, and linearly interpolate the yields in both dimensions. The yields of every SN event are mass- and metallicity- dependent, and the metallicities are calculated for all stars at the time of their formation and stored for use at later times.

3.3 Formulation of the Problem

3.3.1 Introduction

It has been predicted that the first gravitationally bound systems capable of forming stars appeared during the first 10^8 years of the history of the universe, and had masses between about 10^5 and 10^8 $M_\odot$ (Peebles 1993; Haiman at al. 1996; Tegmark et al. 1997; Nishi & Susa 1999; Ciardi et al. 2000; Hernandez & Ferrara 2000; Miralda-Escude 2000). It is also believed that these subsystems might be proto-globular cluster clouds (Fall & Rees 1985; Cayrel 1986; Brown et al. 1995; Jehin et al. 1998) with masses in the same range, and that these clouds formed stars only under certain conditions. Most of these clouds would have been disrupted by energetic processes, and their stars now form the observed halo population.

Therefore, we perform our model by evolving individual clouds of the mass range 10^5–10^8 $M_\odot$, and following the chemical evolution of each cloud based on a one-zone closed box model up to a metallicity of [Fe/H] = –2.5. We assume that all halo field stars were formed originally in these proto-Galactic clouds. By varying the total masses and the star formation histories of these clouds, one can attempt to reproduce the trends and scatter in elemental abundances observed in metal-poor stars of the halo and thick-.disk populations.

3.3.2 The First Stars

Although some predictions have been made about the formation processes of the first stars born in these clouds, their nature is not known due to the lack of direct observational data from Pop-III stars. Simulations show that once these clouds cool, mostly via molecular hydrogen, they become self-gravitating and form central cores (Abel et al 1999; Norman et al., 2000) which are believed to form stars at their centers, the type of which is still uncertain (Silk 1983; Carr et al. 1984). Nakamura & Umemura (1999) studied the gravitational contraction and fragmentation of filamentary primordial gas clouds and found that the masses of the first stars could range between 1-2 $M_\odot$ and ~ 1000 $M_\odot$.

It seems likely that the IMF of early star formation favored much more massive stars than the standard present-day IMF (Larson 1998; Hernandez & Ferrara 2000). This is due to the fact that the Jeans mass was much larger at early times than it is today because of the initially much higher temperature of the primordial material. Although the predicted size and mass of the first star-forming systems is not very different from those of today's molecular clouds, their temperatures were an order of magnitude larger, leading to a calculated Jeans mass of around 10^3 $M_\odot$ compared to a present-day Jeans mass of 1 $M_\odot$. Another reason one might expect the first stars to have formed from a high- mass biased IMF is the presence of r-process elements in metal-poor stars, which is indicative of the Galaxy being enriched by early generations of massive stars, as suggested by Truran (1981). As for the lower mass limit, Uehara et al. (1996) suggested that stars smaller than a solar mass cannot form under primordial conditions because the onset of high opacity to the H_2 cooling radiation sets a minimum fragment mass that is approximately the Chandrasekhar mass, somewhat above 1 solar mass.

The low metallicity of these clouds is expected to lower their efficiency of star formation. It has been shown that if metallicity is lower than about 0.01 solar, the host cloud depletes its main coolant, H_2, by the explosion of one O5 type star (Tashiro &

Nishi 1999). This implies that when the metallicity is lower than this value, stars can only be formed by SN-induced star-formation processes. (Nishi, Susa, & Omukai 2000).

3.3.3 The Star Formation Method

We assume that each cloud starts with primordial material, and forms one massive star at its center by some unspecified process. This Pop-III star later explodes as a SN event, triggering the formation of Pop-II stars in its high-density shell. Subsequent star formation progresses in the shells of later SN events. Such a SN-induced star formation scenario was suggested by Tsujimoto et al. (1999), and was shown to fit the observed relative abundances at early times better than models where SN ejecta mix completely with all the gas in the ISM (Nakamura et al. 1999). Thus, the trends of elemental relative abundances observed in metal-poor stars is consistent with this theory of star formation. A dispersion in heavy elements, varying from less than 10-fold for alpha and iron-group elements, to about 300-fold for n-capture elements, implies that these lowest-metallicity stars were the result of mixing of the ejecta from single, or at most a few SN, with a limited amount of gas in the parent cloud (Audouse & Silk 1995; Ryan et al. 1996; McWilliam 1997; 1998). This will result in a difference between the abundances observed in stars and those of the ISM at the time they were formed, as opposed to what has been assumed in previous Galactic chemical-evolution models, where the stellar and gas abundances were assumed to be identical.

In the Tsujimoto et al.(1999) scenario, the material from which the generation of stars that forms following a given SN explosion is the result of complete mixing of the SN ejecta with the gas swept up from the ISM by the explosion. This star formation scenario will produce low metallicity stars with elemental abundances resembling those of high mass SN ejecta.

Our model utilized metallicity-dependent yields, and follows the evolution of the gas ratio in the cloud and the evolution of individual elements as a function of time. It also follows the chemical evolution of stars and compares them to the observed distribution function for halo stars.

3.3.4 The Calculation

We perform a numerical computation of the chemical-evolution equations in each cloud, expressing the evolution of gas mass, M_g, and the evolution of the mass of individual elements, M_i, as differences in finite steps of time. At each time step, the equations are integrated over a grid of stellar masses, ranging from 0.09 to 40 $M_\odot$. The length of the time step, Δt, is chosen such that it is longer than the time required for a SN shell to form and disperse, and also short enough to be sensitive to the short lifetimes of massive stars. The expansion time of a SN event is of the order of 0.01 Myr (Binney & Tremaine 1987), while the lifetime of the most massive stars included in our model is ~ 6 Myrs. Since the sensitivity to the lifetimes is very crucial at the earliest times, the time step was taken to be 1 Myr up to the point when the least-massive SN have contributed, at 20 Myrs. Thereafter, Δt was given a larger value of 25 Myrs.

We also take into consideration the lifetimes of these stars, relaxing the instantaneous recycling approximation. This is of fundamental importance when dealing with timescales as short as the halo formation time, and when treating elements, such as Fe, that are mostly produced by long-lived stars. We adopt the mass-dependent lifetimes used by Timmes et al. 1995, where the lifetimes of Schaller et al. (1992) were used for stars less massive than 11 $M_{\odot}$. For massive stars, the lifetimes given by the stellar evolution calculations of Weaver & Woosley (1994) were adopted.

For a given cloud, the time of formation of the first shell is taken as $t = 0$, and the star formation rate in the cloud at that time is

$$\Psi(t=0) = \varepsilon \cdot M_{sh}(m_i, 0) / \Delta t \tag{3.1}$$

where ε is the mass fraction of the shell that is used up in forming stars and will be considered a constant free parameter. $M_{sh}(m,t)$ is the mass of the shell formed in a SN explosion at time t with the progenitor mass being m, and is given by :

$$M_{sh}(m,t) = E_j(m,Z) + M_{sw} \tag{3.2}$$

where M_{sw} is the mass of the interstellar gas swept up by the expansion. This quantity is considered constant with a value of $5*10^4$ $M_\odot$ (Ryan et al. 1996; Shigeyama & Tsujimoto 1998; Tsujimoto et al. 1999), since the explosion energy of a core-collapse supernova depends only weakly on the progenitor mass (WW95; Thielemann et al. 1996). $E_j(m, Z)$ is the mass of all the ejected material from the SN with a progenitor mass m and metallicity Z. For the first SN event the metallicity Z is zero for a Pop-III star, and m is m_I. For later generations, the metallicity of a star is calculated from the metallicity of the shell that formed it $Z_{sh}(m,t)$. This will be calculated as a function of time, and is given by:

$$Z_{sh}(m,t)=1-(xH_{sh}(m,t)+xHe_{sh}(m,t)) \tag{3.3}$$

Here xH_{sh} and xHe_{sh} are the fractions of H and He in the shell, respectively, and are given by:

$$xH_{sh}(m,t)=(yH(m,t)+xH_{gas}(t)\cdot M_{sw})/M_{sh}(m,t) \tag{3.4}$$

$$xHe_{sh}(m,t)=(yHe(m,t)+xHe_{gas}(t)\cdot M_{sw})/M_{sh}(m,t) \tag{3.5}$$

xH_{gas} and xHe_{gas} are the fractions of H and He in the interstellar gas at the time of formation of the shell t. This fraction is given for any element xi_{gas} by:

$$xi_{gas}(t) = M_i(t) / M_g(t) \tag{3.6}$$

where *yH* and *yHe* are the amount of ejected *H* and *He* from the explosion, given in solar masses. We will refer to these quantities as the 'yields', which are metallicity dependent and therefore are functions of time. For the first explosion, $y_i(m_l,\tau_l)$ is the yield of elements i from the star with mass m_l and metallicity zero. For subsequent star formation, the SFR at a given time $\Psi(t)$ is summed over all shells that form at time t, and depends on the SFR at the time the progenitor star formed $\Psi(t-\tau_m)$, where τ_m is the lifetime of the progenitor.

$$\Psi(t > 0) = \int_{\max(m_t,10)}^{m_u} dm \quad \varepsilon M_{sh}(m,t)(\varphi(m)/m)\Psi(t-\tau_m) \tag{3.7}$$

where $\varphi(m)$ is the initial mass function. The upper and lower mass limits for stars are m_u and m_l respectively.. The lower mass limit for stars that produce SN events of type-II will be taken as 10 $M_\odot$. m_t is the mass of a star with lifetime equal to t, measured from the time of formation of the first shell.

Since the ejected mass from a SN changes with metallicity of the progenitor, the quantity $E_j(m,Z_{sh})$ in equation 3.2, must now be replaced by an averaged value over all stars of mass m and different values of Z_{sh} ,exploding at a given time t :

$$M_{ej}(m,t) = \int_{\max(m_{(t-\tau m)},10)}^{m_u} dm' \quad (\varphi(m')/m')\, Ej(m, Z_{sh}(m',t-\tau_m)) \tag{3.8}$$

Z_{sh} is expressed here as a function of the mass of the progenitor m' to the shell from which star m' formed. The expression $t - \tau_m$ refers to the time of formation of star m and the death of star m'. The same applies for the yields of individual elements y_i

$$yi(m,t) = \int_{\max(m_{(t-\tau m)},10)}^{m_u} dm' \quad (\varphi(m')/m')\, i_{ej}(m, Z_{sh}(m',t-\tau_m)) \tag{3.9}$$

where $i_{ej}(m, Z_{sh}(m',t-\tau_m))$ is the mass, in solar masses, of the element i ejected from the star with mass m and metallicity $Z_{sh}(m',t-\tau_m)$. The change in gas mass with time is then given by:

$$d\,Mg/dt = -\Psi(t) + \int_{\max(m_t, m_l)}^{m_u} dm\,(\varphi(m)/m)\,M_{ej}(m,t)\,\Psi(t-\tau_m) \qquad \textbf{(3.10)}$$

The first term in this equation is the SFR, equal to the amount of gas going into forming stars at time t and is substituted for from equation (3.7). The second term represents the enrichment process by all stars, the life of which will end at t, including the whole possible range from m_t to m_u.

The change in the mass of element i in the gas, is given by:

$$\begin{aligned} d\,Mi/dt = & -\int_{\max(m_t,10)}^{m_u} dm.(\varphi(m)/m)\,\varepsilon\, M_{sh}(m,t)\; xi_{sh}(m,t)\; \Psi(t-\tau_m) \\ & + \int_{\max(m_t, m_l)}^{m_u} dm\,(\varphi(m)/m)\,yi(m,t)\Psi(t-\tau_m) \end{aligned} \qquad \textbf{(3.11)}$$

The first term in this equation gives the rate at which element i is put into stars at time t, where the second term represents the rate at which it is being added to the ISM by stars. By substituting equations 3.7-3.9 into equations 3.10 and 3.11, this set of integro-differential equations is solved numerically. An auto-regressive computation of the star formation rate and the metallicity of each shell that forms was employed, and previous values were substituted in equations (3.7) - (3.11) at each time step. At every time step, the metallicities of all shells formed are calculated and stored for use at later times. Each shell is recorded and the age-metallicity relation is constructed. The evolution of the metal contents in both the gas and stars are followed as a function of time.

Chapter 4
Properties of the Clouds

4.1 Introduction

In this model, we start with clouds of primordial gas and allow one massive star to form at its core. Later star formation is induced by SN explosions, so the gas from which stars form is a mixture of the ejecta of a SN with an amount of gas from the ISM. For comparison, the IMF is varied from a simple Salpeter function to a top-heavy IMF.

4.2 Initial Conditions

4.2.1 The Gas

The masses of globular clusters observed in the Galaxy range between 10^4 and 10^6 $M_\odot$, while the minimum mass of dwarf galaxies in the Local Group are $\sim 2 * 10^7$ $M_\odot$ (Mateo 2000). Therefore, we chose initial masses for our clouds in the range (10^5-10^8) $M_\odot$. In this mass range, the clouds are extremely sensitive to stellar feedback, whether in terms of chemical enrichment or energetics. We start with gas in a single phase and uniform density, and choose the volume of each cloud such that we maintain a reasonable initial density in the clouds of ~ 0.25 particles / cm^3, corresponding to about 0.01 $M_\odot$ /pc^3. This is necessary in order to calculate the initial potential energy of the cloud, and its lifetime prior to destruction by SN energy input.

The clouds are composed initially of 77% (by mass) Hydrogen, 23% Helium, and a metal fraction Z equal to zero. The first massive star forms at the core and initiates subsequent events of SN-induced star formation. This method of star formation produces local inhomogeneities in the clouds as soon as the first SN event takes place. Each SN event will produce a group of stars reflecting the pattern of that particular core-collapse SN, since the stellar yields of a SN are different for different progenitor masses.

It has been shown that mixing timescales in the halo were sufficiently long that chemical inhomogeneities in the gas would not be erased on the timescale over which stars would form (Audouze & Silk 1995). Therefore, we do not allow mixing between shells. Still, we assume instantaneous mixing of the shell material left behind after the explosion with the gas in the ISM.

Our clouds are self-enriched over a timescale of ~ 1 Gyr. The timescale for the formation of the early halo is estimated to be of the order of a few Gyrs (Bekki & Chiba 2000), in disagreement with the 10^8 yrs suggested by ELS, although most of the processes that contributed to the formation of the earliest generations of stars will take place in the first 0.5 Gyr after the initiation of the first enrichment events.

4.2.1 The Nature of the IMF

The enrichment of the halo depends on the type and number of SN events that took place, in addition to the type of mixing processes following the explosion. Therefore, the central role that the IMF plays at these early times cannot be ignored. For a SN-induced star formation model, the SFR depends on the rate of death of massive stars at a given time. In other words, the SFR today depends on the SFR at previous times. Therefore, the IMF of the first stars (perhaps more properly referred to as the First Mass Function, FMF) will affect greatly the subsequent evolution of these clouds. Although the shape of the IMF that dominated in primordial conditions is still not certain, there is substantial observational evidence pointing to a top-heavy IMF. This includes the paucity of metal-poor stars in the solar neighborhood (the G-dwarf problem), in addition to observations pointing to the rapid early enrichment of the ISM by heavy elements produced in the explosions of high-mass stars, followed by slower enrichment at later times. The high abundances of heavy elements found in the hot gas trapped in the potential wells of rich clusters of galaxies is also larger than what would be predicted by a standard present-day IMF. Finally, the elemental abundances observed in halo stars suggest that they were made out of gas enriched only by type-II SN (Nissen et al. 1994).

The power law IMF suggested by Salpeter (1955) represents the stellar distribution in the solar neighborhood very well down to 1 $M_{\odot}$. At lower masses the form of the function is not clear due to the difficulty of obtaining a mass-luminosity relation for such faint stars. However, it is believed that it declines rapidly and flattens below 0.1

Mo in order to explain the paucity of observed brown dwarfs compared to the predictions (Basri & Marcy 1997). Empirical studies of the IMF have been conducted recently in different environments including clusters and associations in the Galaxy and the Magellanic Clouds (von Hippel et al 1996; Hunter et al 1997; Hillenbrand 1997; Massey & Hunter 1998). Although all of these studies support a Salpeter IMF with a slope in the neighborhood of ~ -1.35 for stars more massive than a solar mass, some different slopes were suggested (Scalo 1998; Massey & Hunter 1998).

A top-heavy IMF for the first stars was also suggested by (Larson 1998; Bromm et al. 2001). Two functional forms were proposed by Larson (1998), which approach the power law with a Salpeter slope at high masses and fall off at the low-mass end.

$$dN/d(\log(m)) \;\alpha\; (1+m/m_l)^{-1.35} \qquad \textbf{(4.1)}$$

and

$$dN/d(\log(m)) \;\alpha\; m^{-1.35} \cdot e^{(-m_l/m)} \qquad \textbf{(4.2)}$$

The first has a peak at $m_p = m_l / 1.35$, and falls off exponentially with increasing negative power at lower masses, while the second falls off asymptotically to a slope zero at the low end. The characteristic mass scale, m_l, has a value of 0.35 $M_\odot$ for the present-day solar neighborhood. This mass function was used by Hernandez & Ferrara (2000), who suggest that the IMF for Pop-III stars was strongly weighted towards high masses at redshifts $6 < z < 9$. They infer a value for m_l of 13.2 at redshift $z \sim 9$, and metallicity Fe/H] ~ –3.5, based on number counts of metal-poor stars from the HK survey of Beers and colleagues.

Both functions were tested in this model and compared to the simple power law. The mass scale was chosen to be a linear time dependent quantity of the form $m_l = 13.2 - 0.9t$. The range of the IMF is taken from 0.09 – 40 $M_{\odot}$, and results for the different functions are compared.

Figure 4.1 shows the different mass functions. The first is the simple Salpeter function with index *–1.35*. The second is a more moderate high-mass biased Salpeter-like function that shows a slower decline towards high masses than the simple function, but still steeper than the top-heavy functions of Larson. The two functions by Larson behave differently at low masses. While the first produces a fair amount of low-mass stars and declines slowly at the massive end, the second function produces very few low-mass stars and peaks at an intermediate value before it declines exponentially. The percentages of low- and high-mass stars produced by these functions will be shown in the next section.

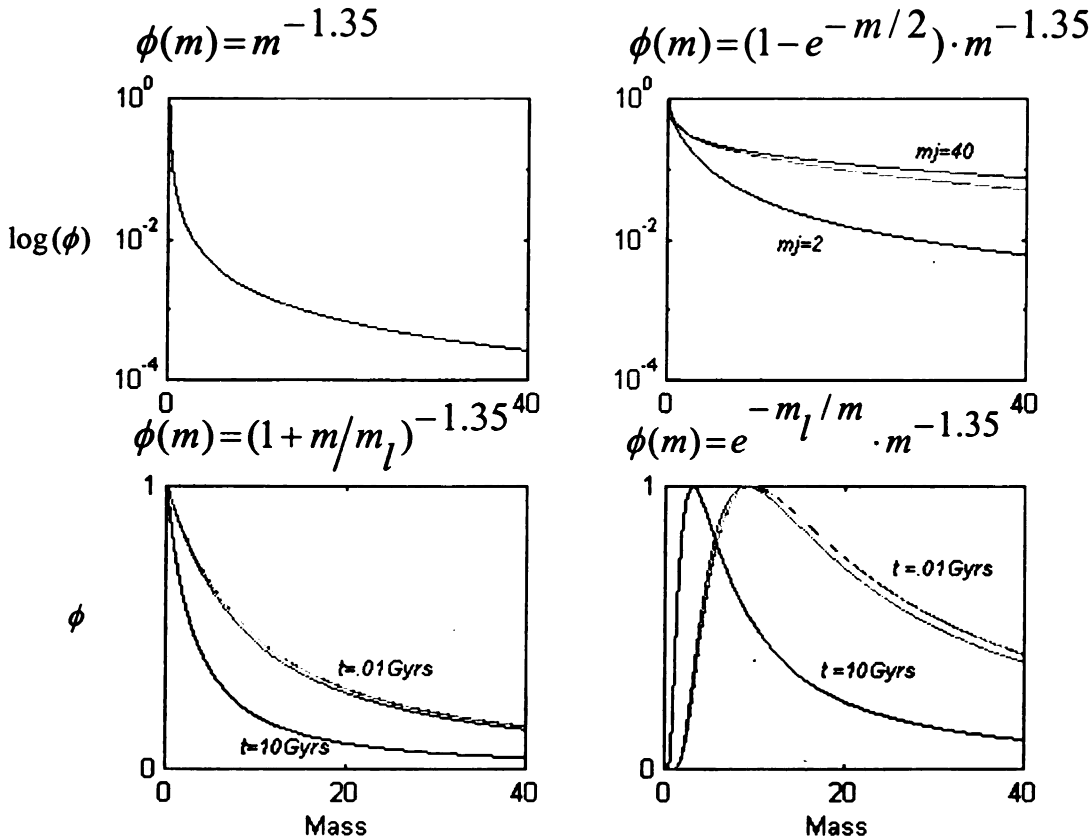

Fig. 4.1 The mass functions, $\varphi_1 = m^{-1.35}$, $\varphi_2 = (1-e^{-m/2})$ $m^{-1.35}$, $\varphi_3 = (1 + m/m_l)^{-1.35}$, $\varphi_4 = m^{-1.35}\, e^{-m_l/m}$

4.3 Results and Discussion

4.3.1 Stability of the clouds

We follow a simplified treatment when considering the stability of these clouds against destruction. Ignoring any tidal effects, heating and cooling, and any inhomogeneities in the gas, we calculate the number of SN events required for the gas to disperse,

$$n = (GM^2/R\,)\,/\,E_{SN}$$

where G is the gravitational constant, M is the total mass of the cloud, R its radius, and E_{SN} is the energy input per SN event. This energy is taken to be 10^{51} erg. Under the adopted initial conditions, clouds less massive than $3*10^6$ $M_\odot$ do not survive the first SN explosion. For more massive clouds, the survival time depends on the SFR chosen and on the form of the IMF. IMFs that are biased towards massive stars produce more SN events in a shorter time allowing star formation to stop and/or the cloud to disperse at an earlier time. The initial density has a great effect on the stability of a cloud, and we must keep in mind that star-forming regions become cooler and denser as time passes. As they form stars, the clouds are heated by the thermal input from massive stars. Therefore, such a simple treatment can only give a rough estimate of the fate of these clouds.

Table 4.1 shows the survival times of our model clouds against destruction as a function of initial mass, for three different mass functions.

Table 4.1 Survival Times of the Clouds

M_{cloud} (M)	3×10^6	5×10^6	1×10^7	1×10^8
$\phi(m)=m^{-1.35}$	--	> 10 Gyrs	> 10 Gyrs	> 10 Gyrs
$\phi(m)=(1-e^{-m/2})\cdot m^{-1.35}$	--	9 Myr	80 Myr	200 Myr
$\phi(m)=m^{-1.35}\cdot e^{-m_l/4}$	--	8 Myr	12 Myr	90 Myr

It is clear from the table that, assuming it survives the first explosion, the fate of a cloud varies greatly depending on the type of the IMF chosen. The Salpeter function, producing very few massive stars, allows enrichment to continue in all clouds more massive than $5*10^6$ $M_\odot$ for times longer than 10 Gyrs. At the same time, clouds as massive as 10^8 $M_\odot$ do not survive more than ~ 0.1 Gyr with a top-heavy IMF. This leads to the suggestion that even if the first stars were formed according to a top-heavy IMF, the subsequent star formation must have become more similar to a present day IMF. This also explains the slower enrichment observed in galaxies after the episode of rapid enrichment caused by the first stars.

The vulnerability of clouds less massive than $3*10^6$ $M_\odot$ to destruction after the first SN event does not favor the idea that they were responsible for the formation of the first generations of Pop-II stars. This also suggests that if the clouds of material in which the globular clusters first formed were of similar mass to the present mass of globular clusters, they could not have been self-enriched. A more likely picture, according to our model, is that the globular clusters must have formed initially in more stable systems such as dwarf galaxies. The homogeneous chemical composition of stars within most globular clusters suggests that they formed out of gas that was already pre-enriched and well mixed in structures that were more stable against destruction. The globular cluster population of the halo might then be explained as the result of accretion events during tidal interactions with other galaxies. This was suggested previously by Larson 1999 and Armandroff 1993.

In clouds that do survive SN explosions, star formation stops after a time *T*, when there is not enough gas to form the shells. Hence, the SN-induced star formation method used here is capable of regulating star formation in these clouds. If these clouds are allowed to accrete gas from any other source, another sequence of star formation is possible. This is consistent with the observations that suggest that the Sgr dwarf galaxy has had an episodic star formation history (Mighell et al. 1999).

4.3.2 Star Formation

Figure 4.2 shows the SFR in our models as a function of time. It is shown for all four mass functions. All clouds were taken with the same initial mass of 10^7 $M_\odot$. The first explosion takes place at time zero, and is represented in the figure as the first peak.

This is followed by a short fluctuation corresponding to the delay caused by the lifetime of the most massive star of about 6 Myrs. The subsequent evolution depends on the type of mass function. A Salpeter function with index -1.35 allows slower enrichment, as a result of producing less massive stars. The SFR declines in this case until it reaches considerably low values within the first tenths of a Gyr. With more massive stars produced, as in the case of the other functions, the SFR grows rapidly in a self-propagating manner. This is an upper limit since, although star formation is believed to self-propagate, it can be regulated on local levels by the heating radiation of newly formed stars, and the explosions of massive stars (Koeppen, Theis, & Hensler 1995). The rapid increase in star formation can be seen clearly from the two lines corresponding to the top heavy functions which terminate at the time of destruction of the clouds.

The percentage of mass locked up in low-mass stars is also varied greatly when different mass functions are used. Figure 4.4 shows the percentage of mass locked up in stars less massive than 2 $M_\odot$ compared to the percentage of mass in stars more massive than 30 $M_\odot$ for the different mass functions. The Salpeter function puts ~ 3 orders of magnitude more mass into low-mass stars than into massive stars, and maintains this ratio as star formation proceeds with a declining rate. The second function, represented in the top right figure, shows a smaller ratio of low-mass to high-mass stars, while the total number of stars continues to rise as star formation continues. When star formation is truncated, the percentage of mass in low-mass stars ceases to rise while the percentage in high-mass stars declines suddenly since they continue to contribute to SN events. A similar behavior is shown in the third figure, except that this function produces a ratio in mass of low-mass to high-mass stars of ~ 1. The final function represented in the fourth figure puts an exceptionally low ratio of mass into low-mass stars allowing for the rapid enrichment by type-II SN to take place and for star formation to truncate at earlier times compared to the other clouds. Again, the important role the first mass function plays in the evolution of the pre-Galactic clouds cannot be neglected.

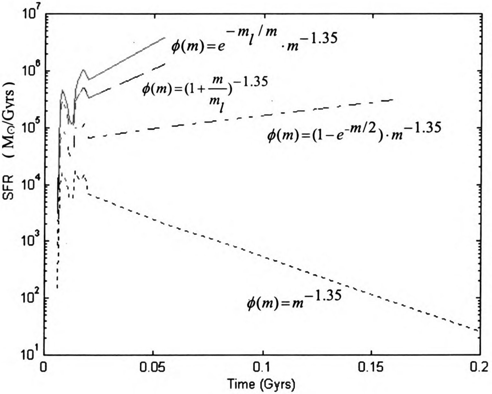

Fig. 4.2 Star formation rate in the model for different mass functions

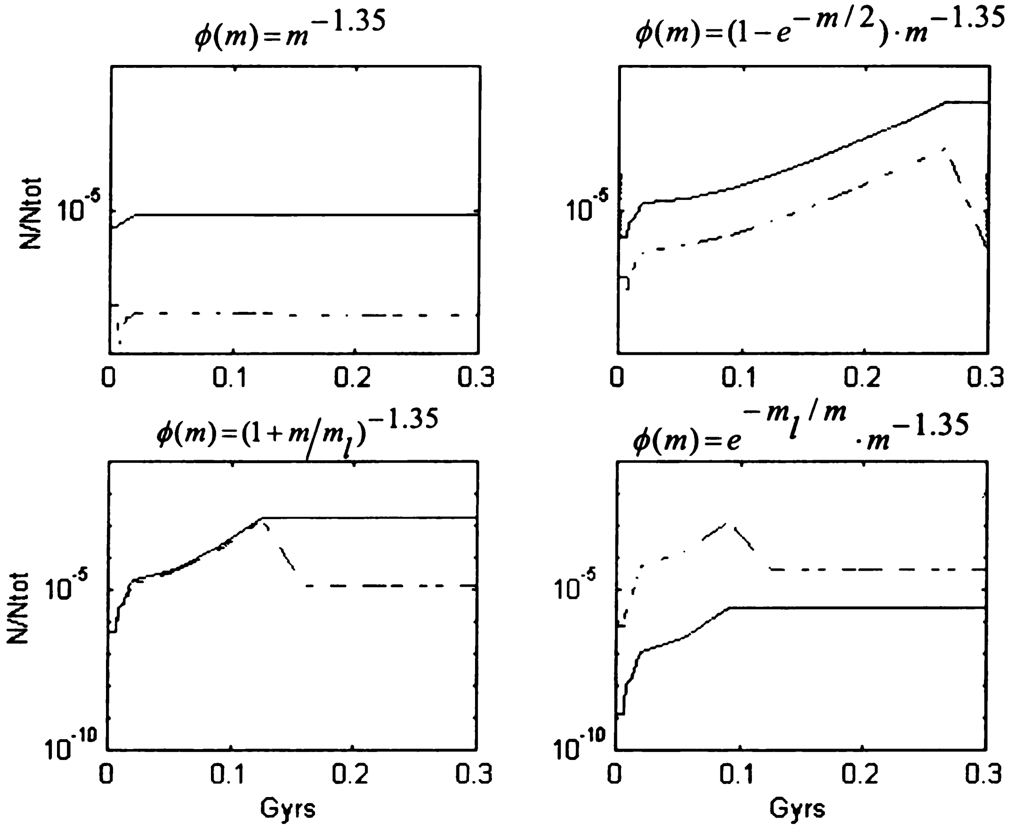

Fig. 4.3 The percentage of mass in low-mass stars (solid line), and in high-mass stars(dashed line).

Chapter 5
Stellar Abundances and Metallicities

5.1 Introduction

The elemental abundances of halo stars potentially provide detailed information about the environments in which they formed, and the nature of the enrichment processes that took place during the evolution of the halo. Study of the elemental abundance patterns in the atmospheres of these stars, and their variations with the overall metal abundance, is thus crucial for a better understanding of the types of systems that contributed to this population and their evolution.

The elemental abundances observed in extremely metal-poor stars are believed to have resulted from the enrichment of primordial gas with the ejecta of a small number of (possibly including individual) Type-II SN events (Audouze & Silk 1995). Hence, before the destruction of pre-galactic clouds, stars within them were born on a timescale smaller than the time needed for type-Ia SN to start contributing Fe-rich material. This time is estimated to be of the order of 1 Gyr (Smecker & Wyse 1991; Yungelson & Livio 1998). These self-enriching fragments of gas are eventually destroyed either by stellar feedback or external effects such as tidal forces, and star formation is truncated. The extremely metal-poor stars left behind contain information about the nucleosynthesis of elements in zero-metallicity stars, their initial mass function, and the environment in the first clouds. Thus, the identification and study of these stars is especially important if we wish to explore the earliest times of the Galaxy's evolution.

5.2 Metallicities and Ages of Stars

The metallicities of stars are calculated in this model from the metallicities of the shells formed by SN events. These are the result of mixing of the ejecta expelled during the explosion with a constant amount of gas from the ISM of the cloud. The first star that explodes is a metal-free Pop-III star, the ejecta of which mix with primordial gas. The metal composition of second-generation stars depends on the mass and the metallicity of the first star.

Fig. 5.1 shows the metallicities produced in shells of different progenitors as a function of time. They are shown for four different progenitor masses: 13, 20, 30 and 40 $M_\odot$. The metallicities produced at early times range from [Fe/H] ~ -2.5 to values well below [Fe/H] ~ -4 for the most massive progenitors of $\sim 40\ M_\odot$. This implies that Pop-II stars with [Fe/H] < –4 might be possible to form, though that would be in contradiction to present observational limits (Beers 1999). If the first stars were less massive than about 40 $M_\odot$ this could be avoided, since progenitors with masses ~ 30 $M_\odot$ produce shells with a limiting metallicity of [Fe/H] ~ –2.5. Then, shells with metallicities as low as [Fe/H] ~ –4 will not show up until the less massive (M< 20 $M_\odot$) SN start to contribute. This is in agreement with the predictions by (Heger, Woosley, & Waters 2000) for SN of type-II to be in the mass range from 10-35 $M_\odot$, while more massive stars, up to 100 $M_\odot$ will probably end up as black holes, and may not contribute significant amounts of material to the ISM. Another explanation might be that the pre-Galactic clouds from which the first stars formed were already pre-enriched. Since the amount of Fe ejected by progenitors with masses ~ 40 $M_\odot$ increases with metallicity, this rules out shells with extremely low metal content.

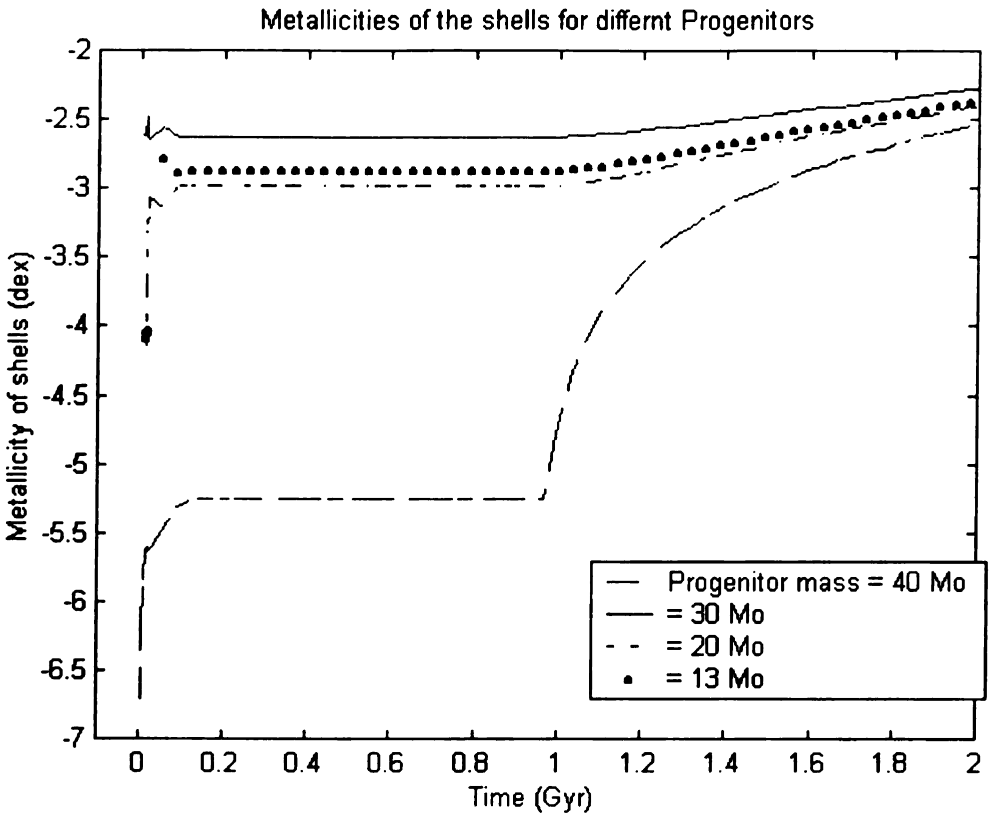

Fig. 5.1 Metallicities produced in shells of different progenitors vs. time. The progenitors shown have masses 13,20,30 and 40 M⊙

The figure also shows that type-II SN produce shells with metallicities that do not exceed [Fe/H] ~ −2.5. This is the value of metallicity at which McWilliam et al (1995b) observed a shift in the slope for relative abundances *vs.* metallicity. This suggests that this value of metallicity seperates two different stages of chemical evolution. The era of inhomogeneous composition dominated by type-II SN, followed by a stage of rapid iron enrichment by type-Ia SN. This is also consistent with the suggestion by Audouze & Silk that only a few SN events are required to raise the level of the heavy elements from zero to that which is observed in the most metal-poor stars in the halo.

Fig. 5.2 shows metallicity *vs.* age for stars in a cloud of initially primordial gas, and assuming a Salpeter mass function. This cloud was allowed to evolve up to 10 Gyrs, and the ejecta of type-Ia SN were allowed to contribute with a delay time of 1 Gyr. Each point on the figure represents a shell that formed stars. The mean value of [Fe/H] increases with time, as expected, and shows a dispersion in metallicities among stars of the same age that increases with increasing age. This is not predicted by a simple one-zone model that assumes complete mixing. This large scatter, decreasing with time, can be explained by the star formation mechanism in which stars are formed only during SN events and therefore, are the result of the mixing of SN ejecta with a limited amount of gas. This will produce stars of different elemental ratios even if they form at the same time, since the SN ejecta are dependent on both the initial mass and metallicity of the progenitor.

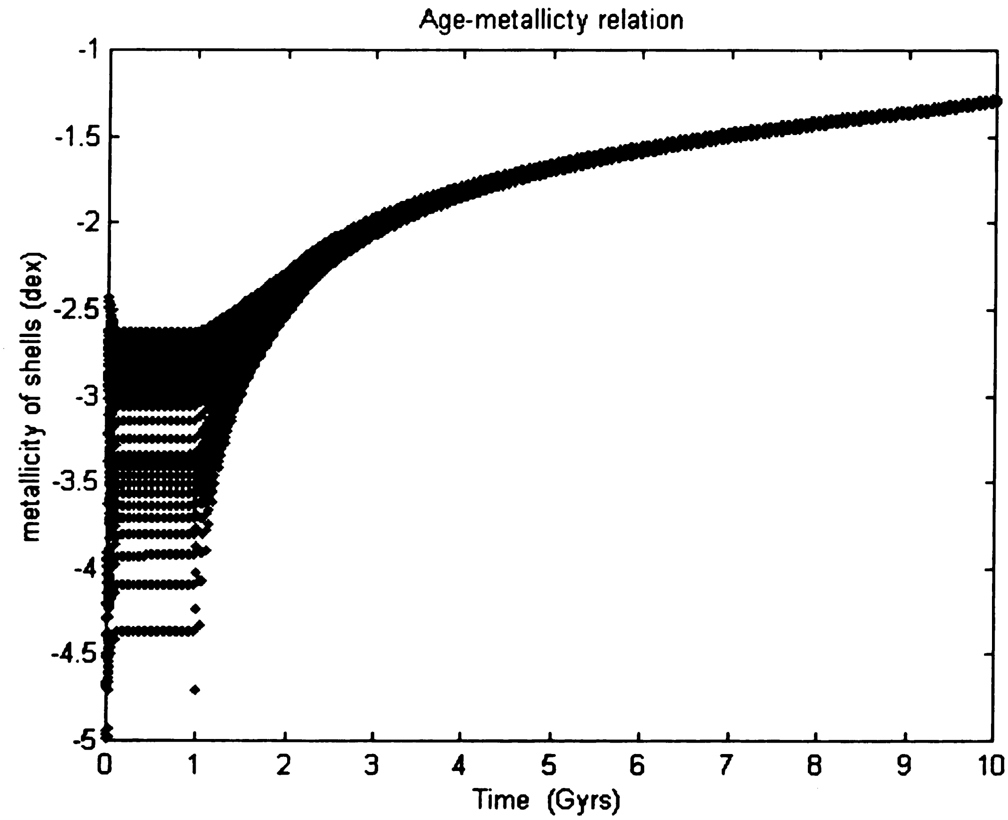

Fig 5.2 Metallicity vs. time for stars produced by the model.

The most-massive SN would contribute first and reflect their yields in the first Pop-II stars to appear, then at later times the products of the less-massive SN are expected to appear with different elemental ratios (WW95). This does not necessarily mean that the first and most massive SN will produce the lowest metallicity Pop-II stars, since it is the lowest mass SN of type-II that produce shells as low in metallicity as [Fe/H] ~ –4, while 20 to 30 $M_{\odot}$ progenitors produce higher metallicity shells. When enough time has passed for the ISM to mix on a large scale, the element ratios are expected to reflect an average of the ejecta of SN events of all masses, including those of type-Ia.

The steep rise at early times reflects the dominance of SN events, and the high efficiency of the enrichment of the metal-poor ISM. The gradual increase at later times is due to the slower enrichment process involving a well-mixed ISM. It is clear from the scatter in the figure that a simple age-metallicity relation does not result from our model, at least at early times.

5.3 The Metallicity Distribution Function (MDF)

Carney et al. (1996) compared the kinematics and chemical properties of metal-poor stars with distance from the Galactic plane for samples of stars more distant than 4 kpc, against those confined within 2 kpc from the plane. They found that stars that are closer to the plane exhibit a slightly more metal-rich mean abundance, <[Fe/H]> = −1.7, while those farther from the plane have <[Fe/H]> = −2.0. This was explained by the existence of two discrete components in the halo. The flattened, inner component was probably formed in a manner resembling the ELS model, while the more spherical, outer halo had a large contribution from nearby smaller systems similar to the Sagitarius dwarf galaxy or other proto-dwarf galaxies. This is in agreement with the SZ picture of halo formation and with the hierarchical CDM model (Kauffman, White, & Guiderdoni 1993). The halo MDF is therefore generally believed to be the result of combining the distribution functions of individual proto-dwarf galaxies accreted by the Galaxy.

The observed MDF of metal-poor stars in the Galaxy shows a relatively broad peak with a maximum at [Fe/H] ~ -1.6, and a smooth tail extending to values of [Fe/H] < -3, in contrast to the metallicity distribution of disk stars, which shows a more localized peak with a sharp cutoff (Ryan & Norris 1991a; 1991b). This suggests that the environment in which the disk formed was probably more uniform than that which formed the halo stars. The review by Norris (1999) suggests there is a hint of a "bump" in the halo MDF at lower metallicities. A feature not expected from the simple model, this bump might be suggestive of non-uniform enrichment at early times. In any case, in our models, the MDF is expected to vary from cloud to cloud depending on the initial conditions and the duration of chemical enrichment. We calculate the MDFs of stars for four different clouds and follow their evolution with time. A different IMF was chosen for each cloud and the time evolution of the MDF was followed up to the time of the cloud's destruction. In the case of the Salpeter mass function, the evolution was followed up to 5 Gyrs and was found to saturate at 1 Gyr. Figures 5.3 to 5.6 show the results for the four clouds, where the type of mass function chosen for each cloud is shown on the figure (all MDFs were normalized to unity).

The figures show that the chemical enrichment in the first cloud, with a simple power-law mass function, is much slower than in the other three clouds with mass functions biased toward massive stars. Therefore the timescales chosen for this figure are different since the enrichment is slower. At the beginning, all of the clouds show a dispersion, with the majority of stars at metallicities below [Fe/H] = –5. This describes the first stars that form from the shells of the most massive progenitors with $M>35\ M_{\odot}$. This could be concluded also from figure 5.1, which shows that these stars are the only to form such low metallicity shells. As time goes on, less-massive stars will contribute shells in the metallicity range –3 < [Fe/H] < –2.5. These will produce a rapid increase in the numbers of stars in this metallicity range that will greatly outnumber the first stars formed from higher-mass explosions. As soon as stars of mass 20 $M_{\odot}$ start to contribute,shells with metallicities down to [Fe/H] ~ –4.5 form and a dispersion is seen once again.

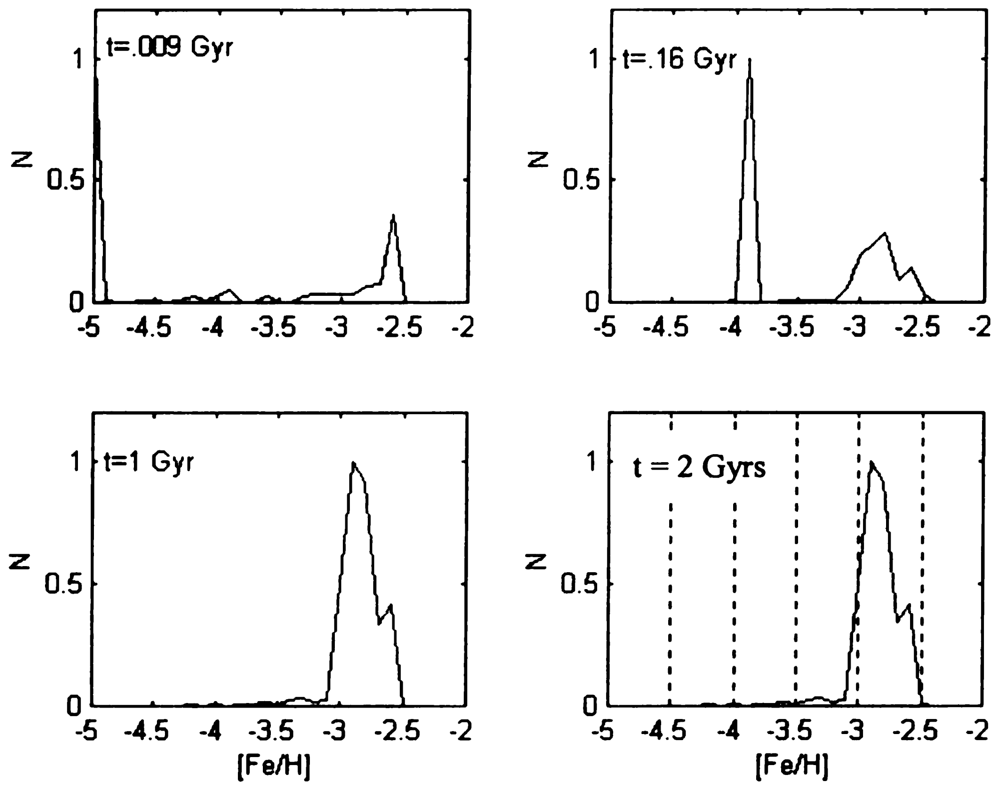

Fig.5.3 Metallicity Distribution functions of stars produced in our models, assuming a Salpeter mass function: $\varphi_l = m^{-1.35}$

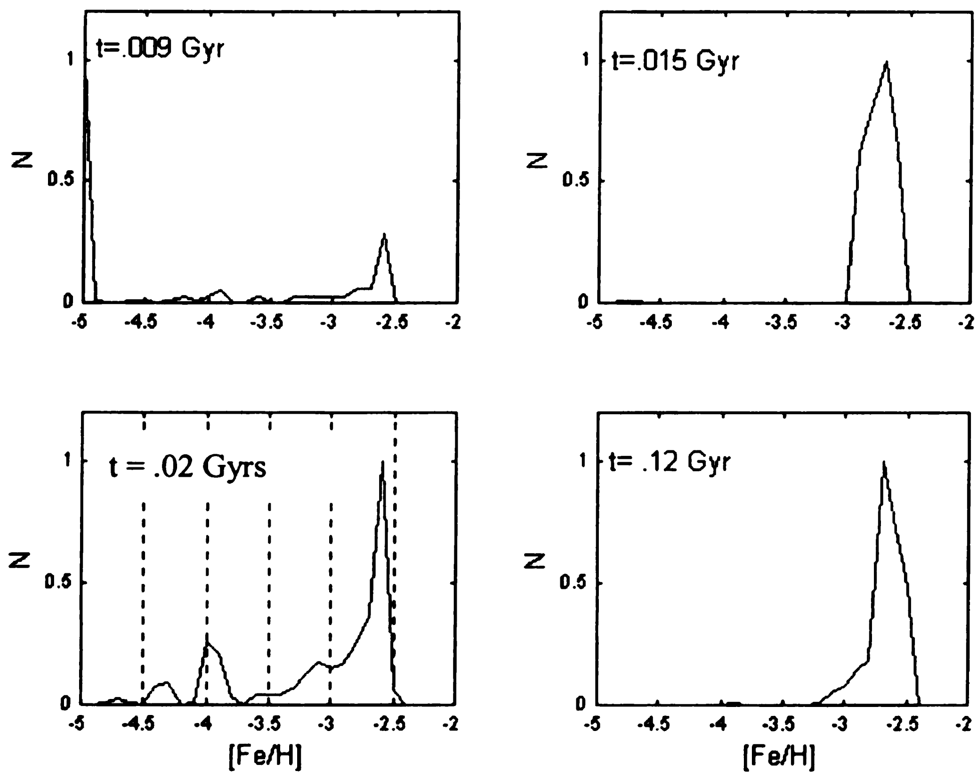

Fig. 5.4 Metallicity Distribution Functions among stars produced by our models, assuming a mass function: $\varphi_2 = m^{-1.35}(1 - e^{m/m_j})$, $m_j = 40$.

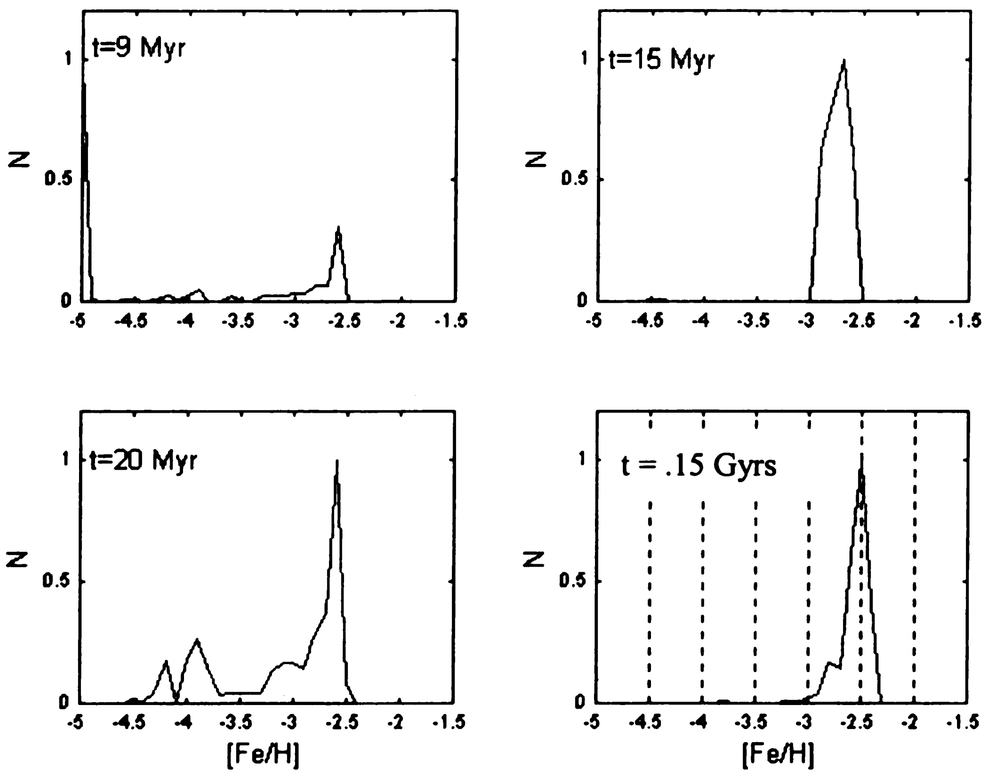

Fig. 5.5 Metallicity Distribution Functions among stars produced by our models, assuming a mass function: $\varphi_3 = (1 + m/m_l)^{-1.35}$.

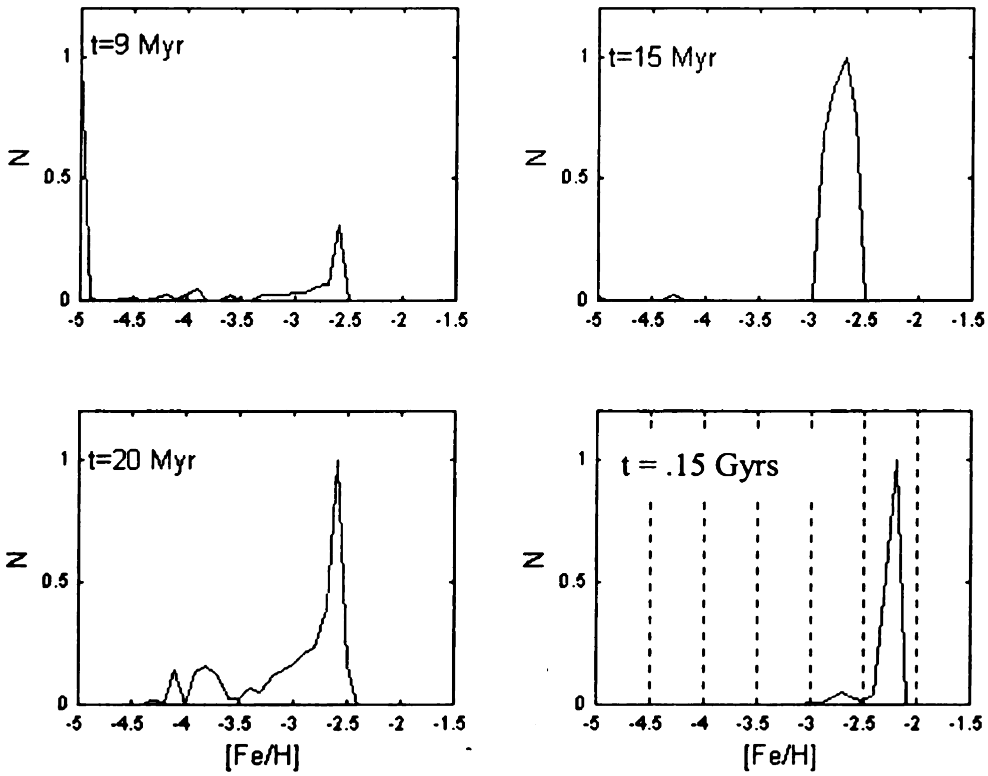

Fig. 5.6 Metallicity Distribution Functions among stars produced by our models, assuming a mass function:

$\varphi_4 = m^{-1.35} e^{-m_l/m}$

This dispersion eventually fades out as the inhomogenieties start to disappear and the stars become more metal rich. The final stage shows a peak at a different value of metallicity for each cloud. This indicates the different enrichment produced by the different mass functions.

The first cloud, with a simple mass function, achieves a peak at [Fe/H] ~ –2.7, a value consistent with the calculations of Ryan et al (1996) and Nakasato & Shigeyama, (2000) for the expected metallicity of Pop-II stars formed in the shell of a typical SN expelled into primordial gas. The other clouds produce higher metallicity peaks, corresponding to the larger number of massive stars they produce. These peaks have the values [Fe/H] = –2.6, -2.5, and –2.2, respectively. The last corresponds to the fourth mass function shown in figure 3.1, which produces the largest number of massive stars.

In figure 5.7 we show the sum of the final stages of all four clouds. This produces a broader distribution extending from about [Fe/H] = –3.2 to about [Fe/H] = –2.2 and peaked at a value of [Fe/H] = –2.6. The MDF observed in the halo shows a still broader distribution, probably due to the high number of different systems that contributed to it, and a higher value for the maximum indicating the contributions from systems that may have produced stars from pre-enriched gas.

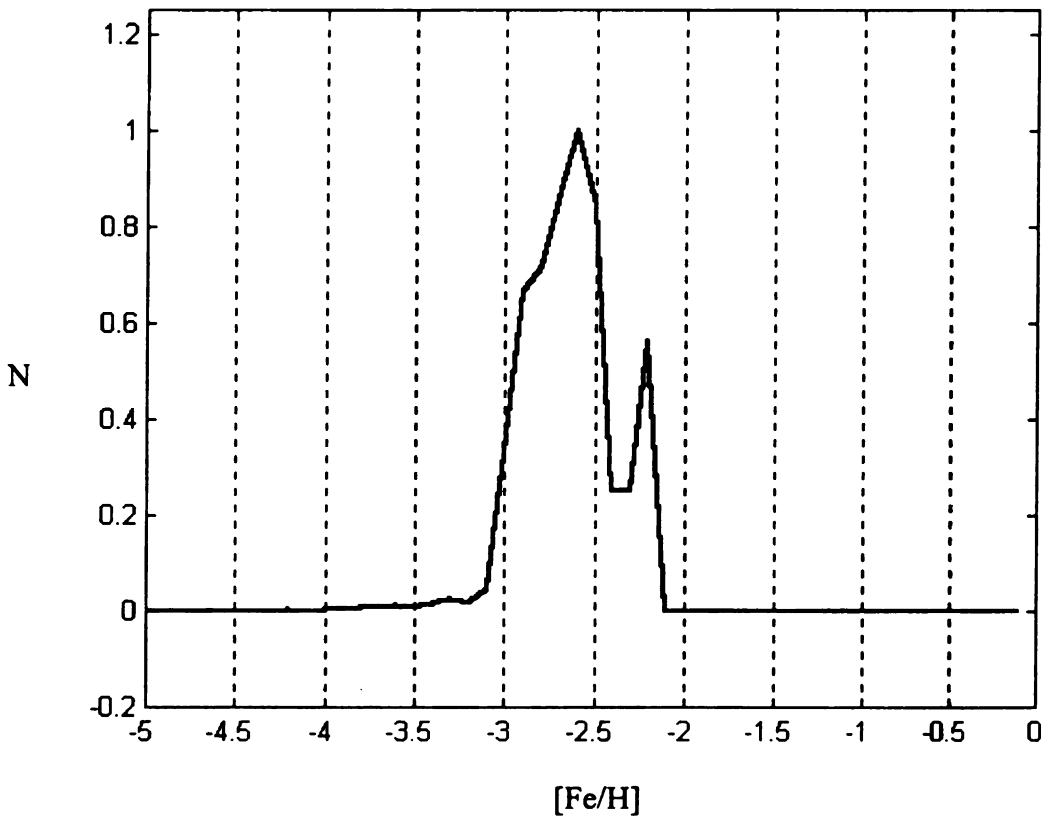

Fig. 5.7. The sum of the MDFs for the four clouds shown in figures 5.3 to 5.6

5.4 Relative Elemental Abundances

5.4.1 The observed trends in halo stars

Very metal-poor halo stars show a great diversity in their element abundances and a considerable scatter in the observed abundances of heavy elements relative to Fe, up to a range of 100 (Ryan & Norris 1991; Gratton & Sneden 1994; McWilliam et al. 1995b; Ryan et al. 1996; McWilliam 1998; Sneden et al. 1998; Norris, Ryan & Beers 2001). At higher metallicities the scatter gradually decreases until this ratio terminates at a value that corresponds to an average over the IMF of the element to iron ratios of the stellar yields. McWilliam et. al. (1995b) detected a shift in the slope of the abundances of the elements Al, Mn, Co, Cr, Sr, and Ba relative to Fe below [Fe/H] ~ -2.5. They suggested that this unusual chemical composition must have originated from the fact that supernovae yields must have changed with time, or in other words, are metallicity dependent. These results were confirmed later by Ryan et. al. (1996) , who also showed that scatter in the abundance ratios increases with decreasing [Fe/H] . These observations support the idea that the most metal-poor stars exhibit the ejecta of very small numbers of supernovae. The metallicity-dependent yields used in our present model, together with the unique method of SN-induced star formation, are capable of explaining these trends. The observed relative abundances in the halo are fully reproduced with this model for several elements. These results are shown and discussed in the following sections.

5.4.2 Overview of model predictions

For determination of elemental abundances, our code was run for 5 Gyr, using a massive cloud ($10^7\ M_\odot$), and forming stars according to a Salpeter mass function. After 1 Gyr, SN of type-Ia were allowed to contribute their ejecta. The elemental abundances are calculated and recorded for every shell that forms during the simulation.

The model produces a small number of stars at very low metallicities, [Fe/H] < -3, showing a considerable spread in [X/Fe] ratios, ranging from 0.5 dex in the case of Ni to more than 2 dex in the cases of Mg. This scatter of the abundances for model stars is given by the spread in metallicities of the SN models. Therefore, the large scatter in the abundance ratios observed in low-metallicity stars is reproduced by this model.

Local inhomogeneities start to disappear at $-3.0 <$ [Fe/H] < -2.5, corresponding to about ~ 0.1 Gyr from the onset of star formation. At this stage most of the massive SN have contributed, and their ejecta have already mixed with the gas in the ISM. This metallicity range marks the end of the early phase and the beginning of the transition to the well-mixed phase. At this stage, the gas becomes more metal-rich, hence newly formed stars will no longer exhibit abundance patterns of single SN, but rather an average over the IMF of the SN that contributed to the enrichment of the local ISM. These values resemble the predictions of a simple one-zone model. The spread in the relative abundances decreases gradually, reflecting the ongoing mixing process as more SN pollute the ISM, and the values of [X/Fe] starting to get closer to the solar value of zero.

5.4.3 [Alpha/Fe]

Figure 5.8 shows values of [alpha/Fe] vs. [Fe/H] calculated by the model, and compared to two sets of data (see figure caption). The observed values show an over-abundance relative to solar, and a scatter that is significant at all values of [Fe/H], larger at the lowest abundances. This is true for Mg, Ca, and Si. Ti, on the other hand, shows a scatter that is almost constant over the metallicity range. This dispersion can set strong limits on the nature of the first SN, and the nature of the enrichment process when compared to the predictions of chemical evolution models. The so-called plateau for [alpha/Fe] ratios at low metallicities is proving not to be really constant, as the most recent data are showing more dispersion at lower metallicities (Ryan et al 1996; McWilliam 1997; Norris et al 2001). The over-abundance in alpha elements relative to iron compared to the sun can be understood as the result of the dominance of SN of type-II at the time, since they are believed to be the major production sites for alpha elements. This also indicates that the corresponding stars formed within the first Gyr of the onset of significant star formation. After 1 Gyr, type-Ia SN events are expected to shift the trends with large amounts of Fe. Therefore, the ratios decline gradually towards solar metallicities.

The observational trends for alpha elements relative to iron are fairly well produced by the model at very low metallicities, [Fe/H] < –3, except for Ti, which shows lower values than the data and rather little dispersion. Although Ti shows abundance behavior similar to other alpha elements, it is believed to be produced in the same way as

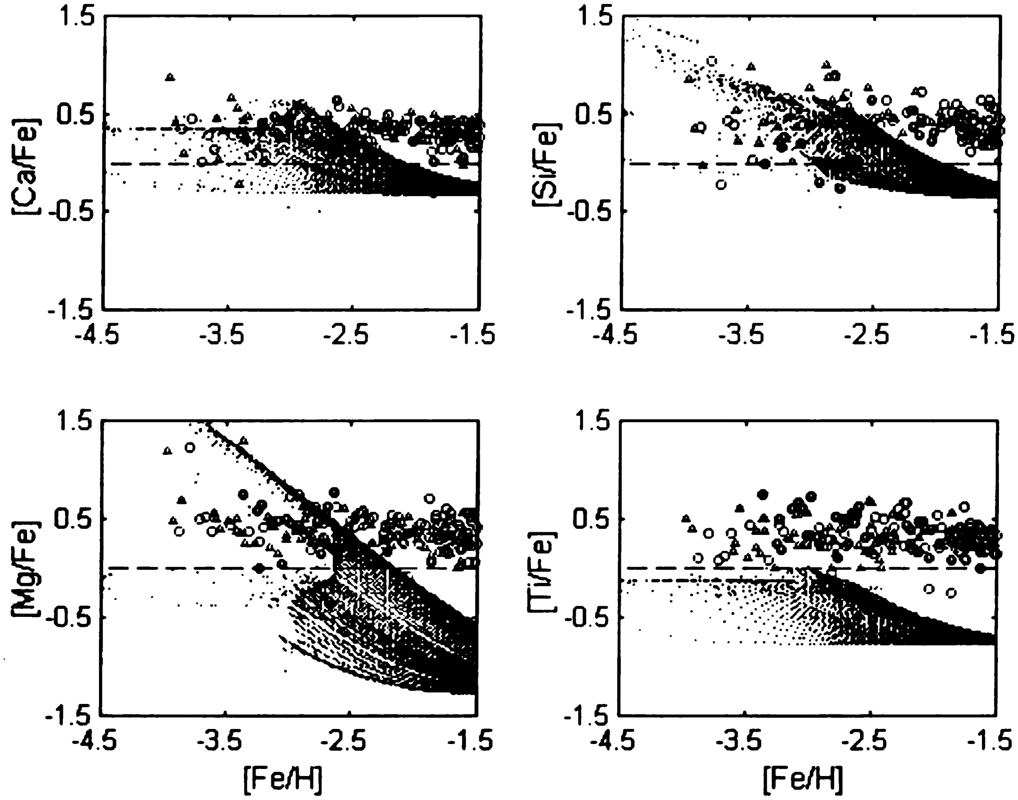

Fig. 5.8 The abundances of the alpha elements Mg, Ca, Si, and Ti. Data is from Ryan et al (1996) (triangles) and Norris et al (2001) (circles). The small (dots) represent the model stars.

iron-peak elements and therefore is sensitive to the SN explosion mechanism, which is still not fully understood. Therefore, the yields of this element are probably not as certain as the yields of the other alpha elements. Mg shows a good agreement with the data below [Fe/H] = –3, but declines with a larger slope than expected and becomes more than 0.5 dex below the observed values beyond that point. At higher metallicities, [Fe/H] > –3, the suggestion by Timmes et al (1995) of reducing the amount of Fe produced by massive stars seems to be required, especially in the cases of elements Mg and Ti. Fig. 5.9 shows the results of the model when Fe is reduced by a factor of 2. The agreement between the data and the calculation in this case is almost perfect.

The metallicity-dependent yields of Si and Ca reproduce the values of [X/Fe] and the scatter at low metallicities very well, and seem to suggest that the Fe yields suggested by WW95 are correct.

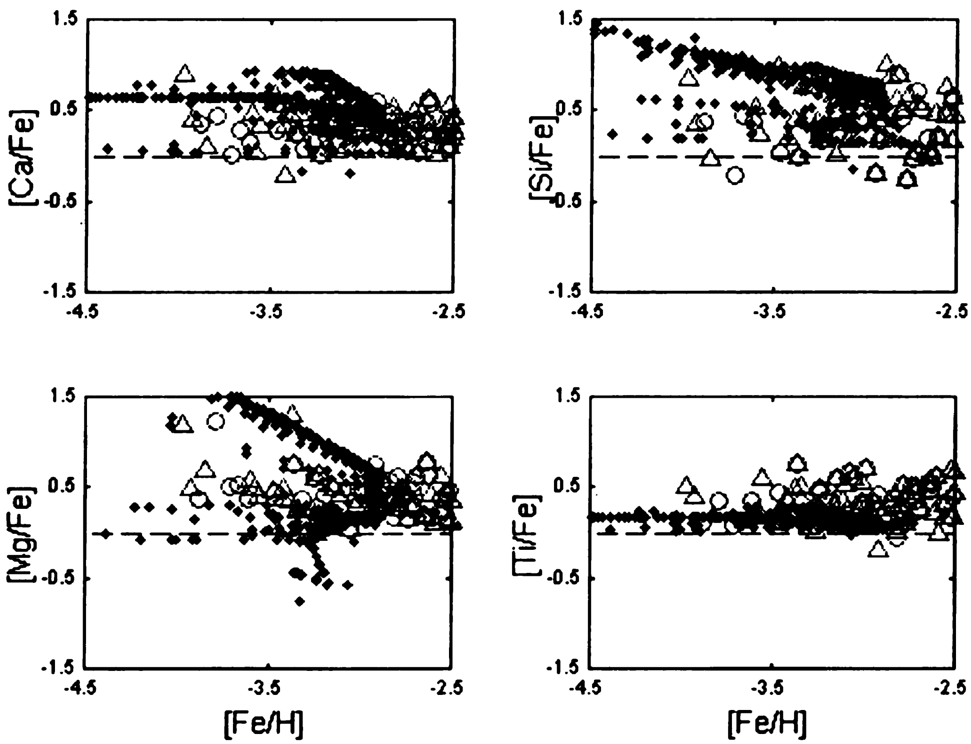

Fig. 5.9. The abundances of the alpha elements when Fe yields are reduced by a factor of 2. Data is from Ryan et al (1996) (triangles) and Norris et al (2001) (circles). The small (dots) represent the model stars.

5.4.4 [Fe-peak / Fe] :

The behavior observed for Fe-peak elements is that the ratio iron-peak/Fe is close to solar down to metallicity [Fe/H] ~ –2.5, except for Mn, which is underabundant in all halo stars. Below this value the behavior changes (McWilliam et al. 1995; Ryan et al. 1996; McWilliam 1997; Norris et al. 2001). Cr/Fe and Mn/Fe decrease to sub-solar values, Co/Fe increases to super-solar values, and Ni maintains an average slightly above solar. The scatter increases towards lower metallicities as in the case of alpha elements.

Figure 5.10 shows the calculated values of relative abundances for Cr, Co, Mn and Ni. The observed ratios of Mn and of Ni are reproduced well by the metallicity-dependent yields of WW95 in this model. Cr, on the other hand, does not seem to produce satisfactory results. The stars produced at very low metallicity show a small over-abundance relative to solar, contrary to the observed under-abundance. The excess in Co/Fe was produced fairly well with the metallicity-dependent yields below [Fe/H] = – 2.5. This behavior of Co at the lowest metallicities has not been produced by any previous models, and no known stellar yields were able to predict it even by modifications in explosion parameters of SN-II models (Nakamura et al. 1999).

Our calculations should help set limits on nucleosynthesis predictions of massive stars, especially progenitors of low metallicity. The dependence of the yields of these elements on the position of the mass cut for material ejected from SN is one of the primary reasons for potentially large errors in their calculation. Mn and Cr are produced mainly during explosive Si burning, and therefore have a complicated dependence on the

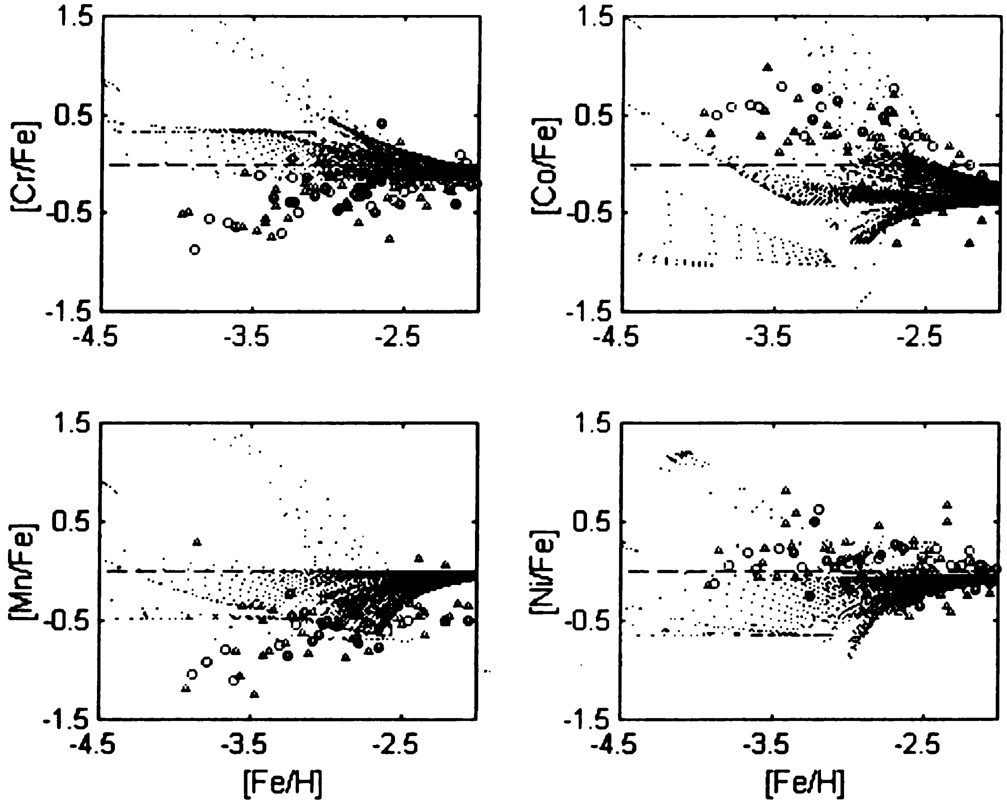

Fig. 5.10. The abundances of the Fe-group elements, Mn, Ni, Cr, and Co . Data is from Ryan et al (1996) (triangles) and Norris et al (2001) (circles). The small (dots) represent the model stars.

progenitor mass. Efforts to understand the abundance trends of iron-peak elements, which are formed close to the mass cut, have focused on the possible alpha-rich freeze-out (McWilliam et al. 1995), the location of the mass cut, and the dependence of yields on the star mass, metallicity, and neutron excess (Nakamura et al. 1999).

Our model predicts a scatter in the ratios for Fe-group elements that is larger at very low metallicities than the observed values. The true situation will have to await future observations, which will better fill out the phase space at low metallicity.

5.4.5 Contributions from different SN

The ejecta of the most massive stars are expected to dominate the earliest phases of the chemical evolution of each cloud. These stars produce values of [Fe/H] in their shells of < -2.5. According to WW95, at zero metallicity, the most massive stars (35 $M_\odot < M < 40\ M_\odot$) produce metallicities lower than observed while the lowest observed metallicities of [Fe/H] ~ -4 are produced by progenitors of masses less than 20 $M_\odot$. These different behaviors of SN with progenitor mass is responsible for the dispersion in metal abundances at low metallicities. Studying the dispersion in the relative abundances of elements in the halo will allow for constraints to be set on chemical evolution models. It can help us understand the nature of the first SN, and the inhomogeneous enrichment processes that took place, in addition to the nature of the IMF and star formation rates at the corresponding times.

Figures 5.11a to 5.11d show the contributions to the elemental abundances by different progenitor masses up to metallicities [Fe/H] = – 2.5. The mass ranges are shown on the figures. The same is shown for Fe-group elements in figures 5.12a to 5.12d. The main observation that can be seen in all eight figures is that the stars responsible for producing the extremely low metallicities unobserved in the Galaxy are either more massive than 35 $M_\odot$ or less massive than 20. This can be explained simply by suggesting that Pop-III stars with such low metallicities do exist and will be found in the near future by the many groups devoted to finding stars with low metal abundance. If such stars have not been available in the halo from the beginning, then one can suggest that stars more massive than 35 $M_\odot$ do not contribute their ejecta, and instead, end their lives as black holes. Another way to explain this is that the first stars that formed in pre-Galactic clouds formed out of pre-enriched gas, and that there are no Pop-III stars in our Galaxy. For higher metallicities [Fe/H] > –4, contributions from progenitors more massive than 25 $M_\odot$ seem to fit very well into the observations up to 40 $M_\odot$ in the case of alpha-elements, and fairly well for Fe-group elements, except for Co. The calculated values from the high-mass progenitors do not fit the observed values for Co even at higher metallicities, while the rest of the mass range down to 10 $M_\odot$ reproduces the observations very well. This result for the low-mass end is in contrast to what is found for the other elements Mg, Ti, Cr, and Mn. In these cases, the low-mass progenitors produce values of the relative abundances out of the range of the data. This may be suggestive of the fact that the first stars were massive and that the SN that contributed before [Fe/H] ~ −2.5 were all massive SN. The alpha-element enhancement observed for stars with [Fe/H] <−2.5 is indicative of a high-mass IMF in the first Gyr of the Galaxy's formation. After this time, as type-Ia SN contribute their Fe ejecta, at [Fe/H]~ −2.5, the alpha-element ratios go down to solar values.

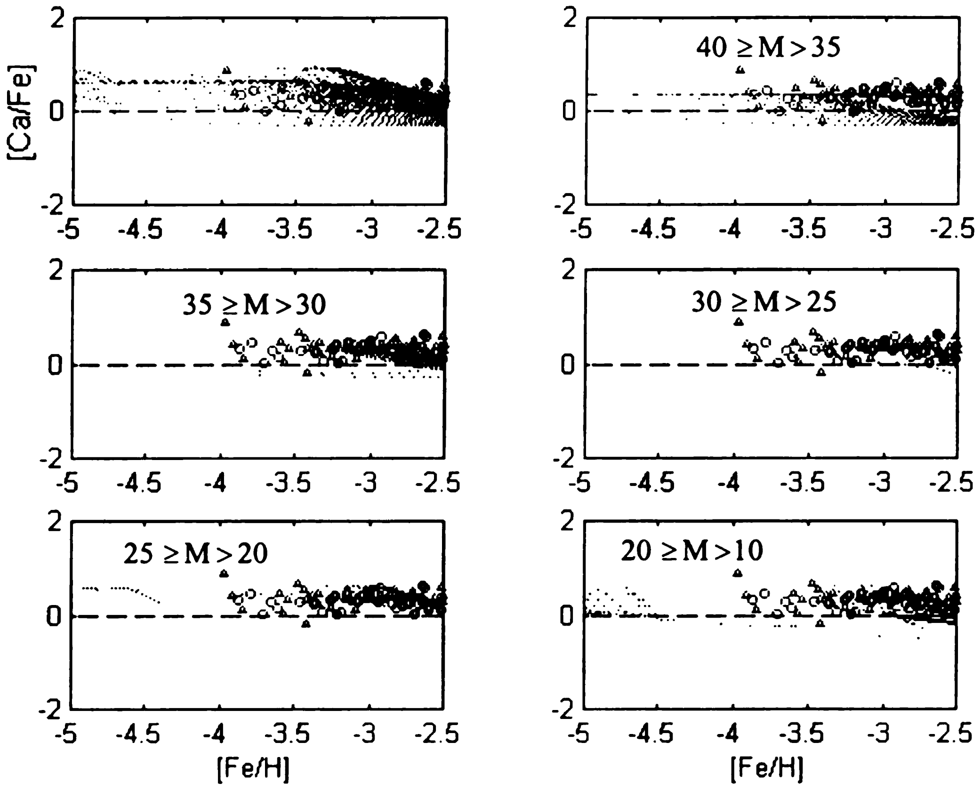

Fig. 5.11a. The contribution from different progenitor masses to the value of [Ca/Fe]. The mass ranges are given in solar masses. The top left figure shows the whole range. Data is from Ryan et al (1996) (triangles) and Norris et al (2001) (circles). The small (dots) represent the model stars.

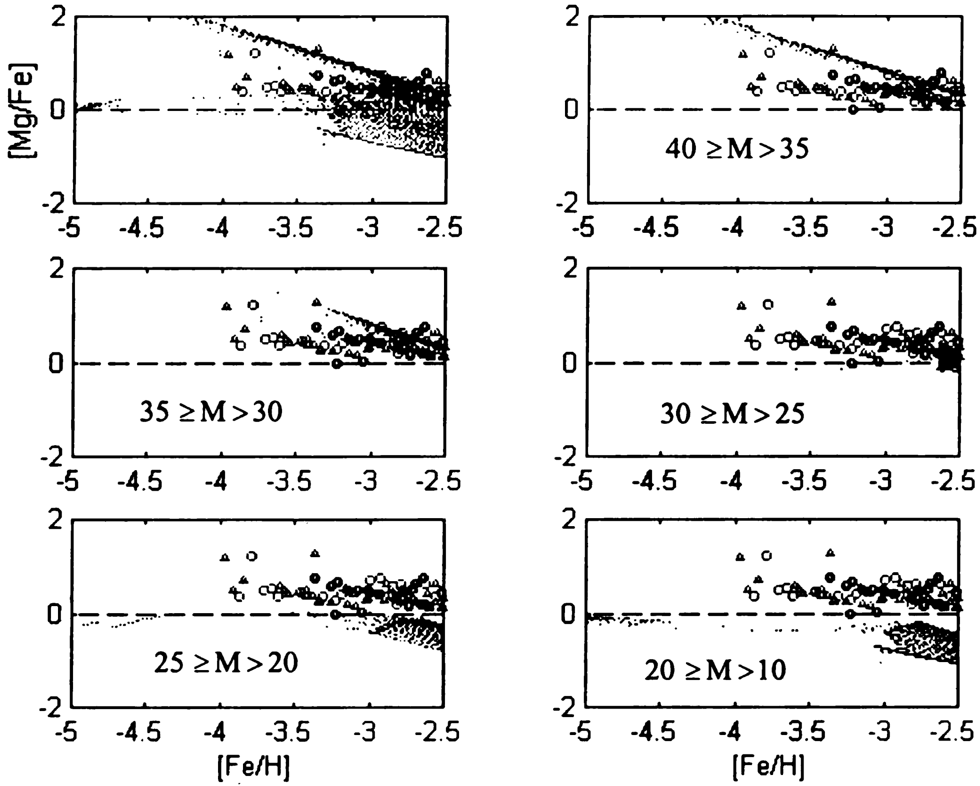

Fig. 5.11b. The contribution from different progenitor masses to the value of [Mg/Fe]. The mass ranges are given in solar masses. The top left figure shows the whole range. Data is from Ryan et al (1996) (triangles) and Norris et al (2001) (circles). The small (dots) represent the model stars.

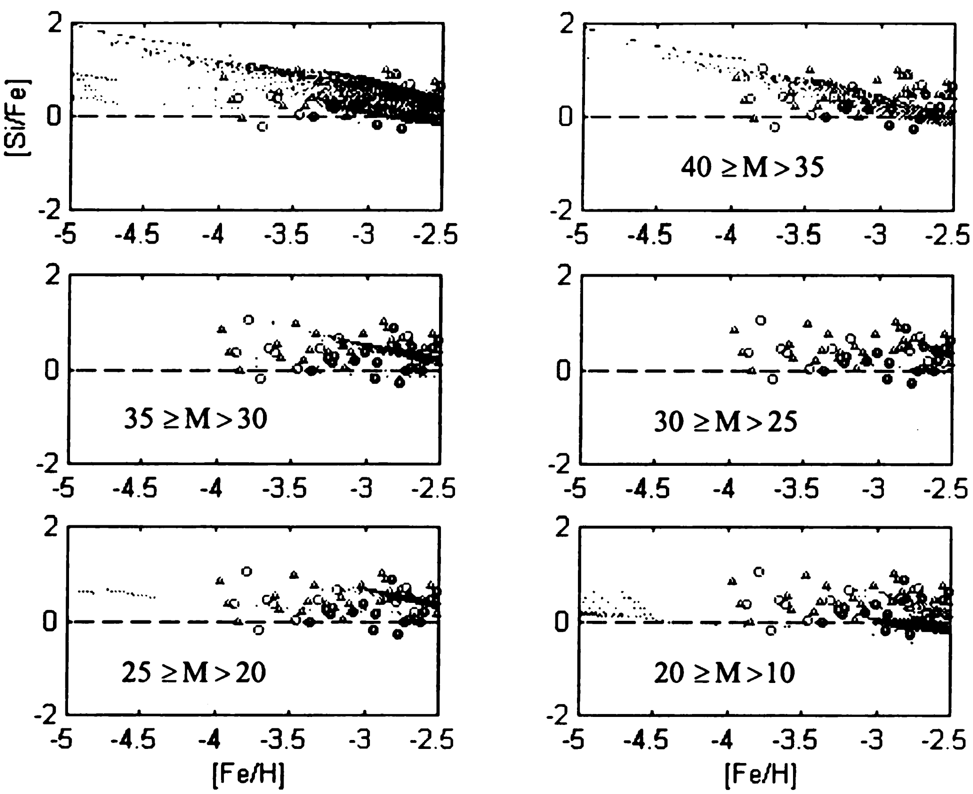

Fig. 5.11c. The contribution from different progenitor masses to the value of [Si/Fe]. The mass ranges are given in solar masses. The top left figure shows the whole range. Data is from Ryan et al (1996) (triangles) and Norris et al (2001) (circles). The small (dots) represent the model stars.

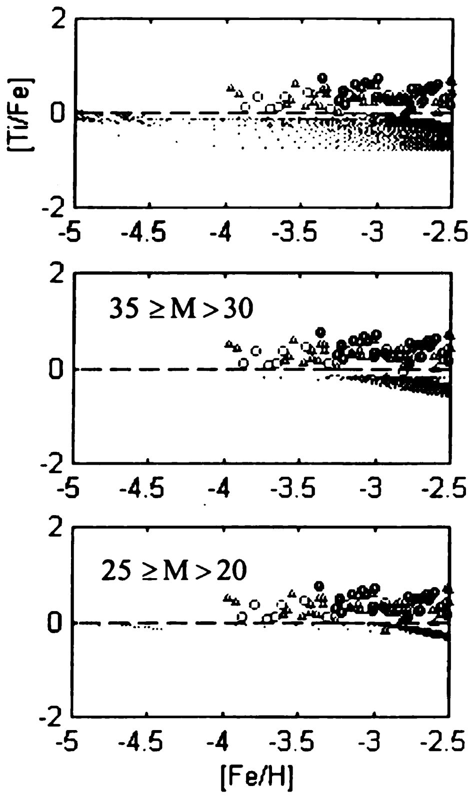

Fig. 5.11d. The contribution from different progenitor masses to the value of [Ti/Fe]. The mass ranges are given in solar masses. The top left figure shows the whole range. Data is from Ryan et al (1996) (triangles) and Norris et al (2001) (circles). The small (dots) represent the model stars.

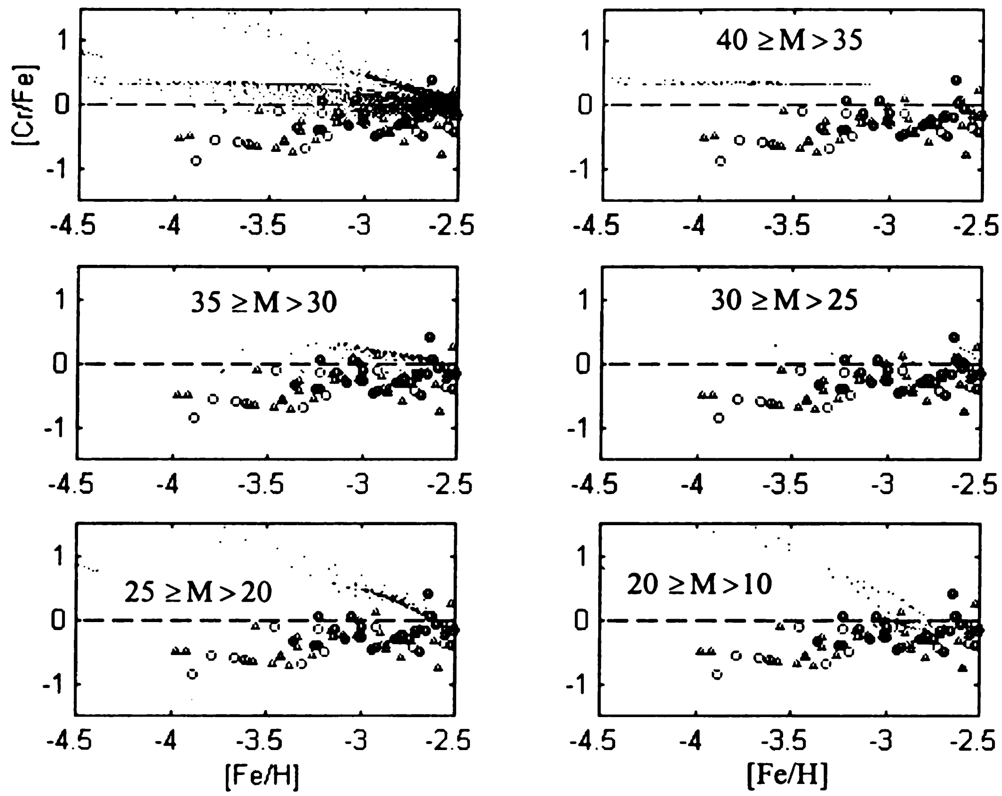

Fig. 5.12.a. The contribution from different progenitor masses to the value of [Cr/Fe]. The mass ranges are given in solar masses. The top left figure shows the whole range. Data is from Ryan et al (1996) (triangles) and Norris et al (2001) (circles). The small (dots) represent the model stars.

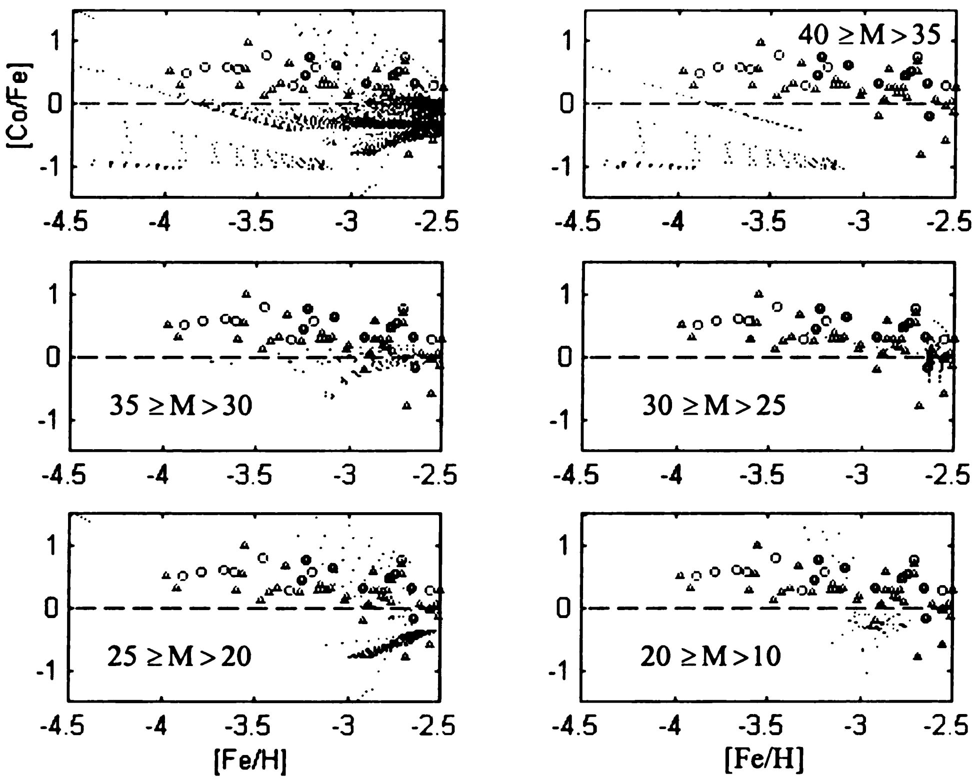

Fig. 5.12b. The contribution from different progenitor masses to the value of [Co/Fe]. The mass ranges are given in solar masses. The top left figure shows the whole range. Data is from Ryan et al (1996) (triangles) and Norris et al (2001) (circles). The small (dots) represent the model stars.

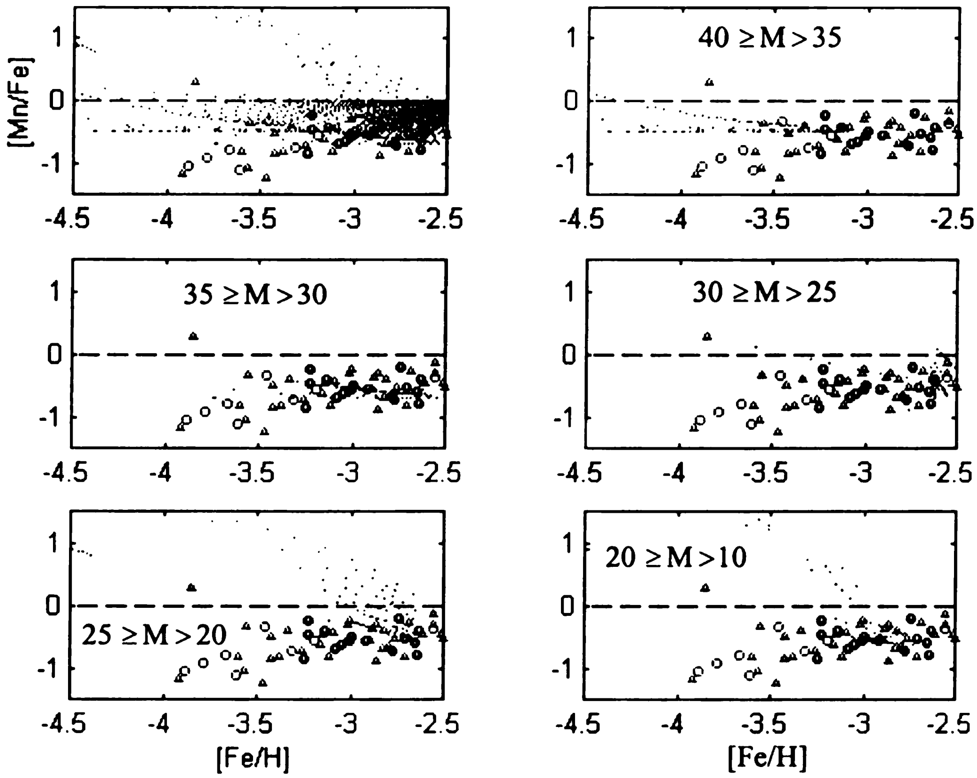

Fig. 5.12c. The contribution from different progenitor masses to the value of [Mn/Fe]. The mass ranges are given in solar masses. The top left figure shows the whole range. Data is from Ryan et al (1996) (triangles) and Norris et al (2001) (circles). The small (dots) represent the model stars.

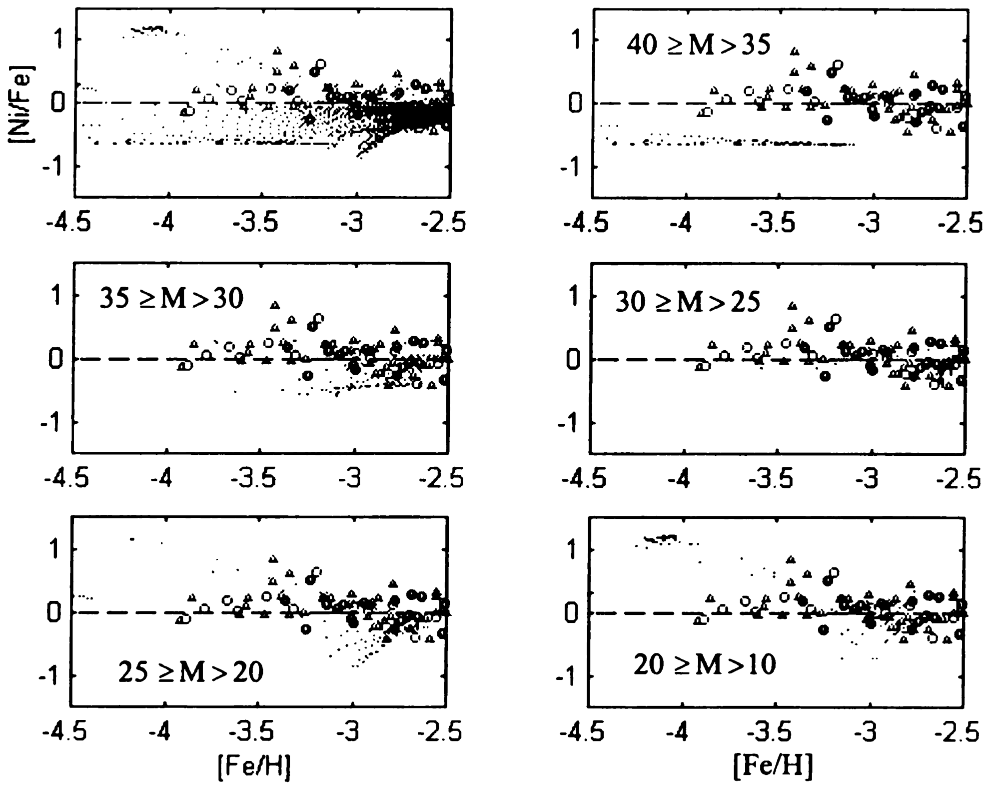

Fig. 5.12d. The contribution from different progenitor masses to the value of [Ni/Fe]. The mass ranges are given in solar masses. The top left figure shows the whole range. Data is from Ryan et al (1996) (triangles) and Norris et al (2001) (circles). The small (dots) represent the model stars.

Chapter 6
Final Remarks

6.1 Conclusions

This thesis presents the results of a chemical-evolution simulation in which we have evolved pre-Galactic clouds similar to those suggested to exist in the early Galaxy by the cold dark matter scenario of hierarchical galaxy formation. The clouds were studied for several sets of initial conditions and total mass. All clouds contained initially primordial gas and were assumed to form a single metal-free Pop-III star at their cores. Subsequent star formation was taken to occur under the assumption of a SN-induced star formation mechanism in which stars form only in SN shells.

We studied the stability of these clouds against destruction from the energy input of SN explosions, taking into account the main-sequence lifetimes of individual stars. We ignored all tidal interactions with other systems and heating and cooling effects in the gas. The total mass and initial mass functions were varied and results were compared. Four different IMFs were employed: a Salpeter mass function with an index of -1.35, a

Salpeter function moderately biased towards high masses, and two IMFs that were strongly biased toward the formation of high-mass stars.

We find that clouds in the mass range of globular clusters are very vulnerable to destruction and could not have formed the first stars. We conclude that these clusters were probably not self-enriched, but rather must have formed from an ISM which was likely to have been uniformly mixed in higher-mass systems, such as dwarf galaxies. Systems with masses and sizes of presently observed dwarf galaxies were found to survive destruction for more than 10 Gyrs, using the present-day mass function. This indicates that if systems like these did form the first stars, then a top-heavy IMF could not have operated (except during the formation of the first stars) and that later star formation must have been slower or episodic.

These results are consistent with expectations from the cold dark matter hierarchical clustering model of galaxy formation. In this scenario, the smaller clouds will contribute their material to the halo at the time of their destruction, while the gas may also contribute to stars that form in the later collapse of the disk. More stable systems will then continue to form stars and contribute to the halo population during tidal interactions. Globular clusters may have formed from pre-enriched gas with a population of older, less-massive stars.

The metallicities and relative elemental abundances in stars were calculated, using metallicity-dependent yields for type-II SN, and SN of type-Ia were allowed to contribute with a delay time of 1 Gyr. The MDF was calculated for stars in the different clouds and compared for all four assumed IMFs. The evolution was followed for each cloud up to the time of its destruction, in the cases of high-mass biased IMFs. For the Salpeter IMF, the evolution was followed up to 5 Gyrs. All distributions showed a dispersion in the metallicities of the stars formed in the first stages, followed by the formation of a well-defined peak at a metallicity that varied for the different mass functions. This final metallicity ranged between [Fe/H] = –2.7 in the case of the simple function to [Fe/H] = –2.2 in the case of the top-heavy mass functions. Assuming that the stars formed in these clouds will become members in the field halo population due to later interactions, we sum the final stages of all four clouds. The result is a broad distribution peaked at [Fe/H] = –2.6. When compared to the observed MDF of halo field stars, which shows a broader distribution peaked at [Fe/H] = –1.6, we conclude that the halo must have had contributions from many systems, some of which were not initially primordial in composition.

We were able to reproduce the observed trends in relative elemental abundances observed in very metal-poor stars fairly well with the SN-induced star formation mechanism, together with the metallicity-dependent yields.

6.2 The Future

With no doubt, this is an era of astronomy. So much that has been hidden from us is now becoming understood, and the future holds within it many promises for understanding the beginning of structure in the universe, leading to the formation of galaxies in general, and the formation and evolution of the Milky Way in particular. So much remains to be done.

The cold dark matter scenario holds much promise, but needs to be tested further. The first clouds of primordial material predicted by this theory to have been the result of density fluctuations in the early universe need to be studied in more detail, including the effects of gas dynamics, heating and cooling of the gas, and interactions with the other systems. The initial conditions in these clouds and the mechanism by which the first stars are formed still need to be investigated in more detail.

Our results show that the role of the IMF at these early times cannot be ignored. A better understanding of the types of mass functions that dominated at different times as a result of the changing conditions is crucial for the understanding of the chemical and dynamical evolution of the Galaxy.

There is still a great deal to learn about the nature of Pop-III stars. How massive were they? Did they have a different IMF than later generations? What kind of nucleosynthetic yields did they produce? And finally, do low-mass stars that may have occasionally formed at that time still exist? Whether true Pop-III stars are found or not, the following generation of Pop-II stars hold within them a fossil record that reveals a great deal about their progenitor stars and the environments in which they formed. Therefore, the identification and analysis of large numbers of extremely metal-poor stars is a key to many questions, and gives great hope for the future. The very near future holds so much promise, with the anticipated completion of many ongoing and proposed observational programs. The next generation of astrometric satellites, NASA's SIM (Space Interferometric Mission), and ESA's GAIA (Global Astrometric Interferometer for Astrophysics), will provide direct geometric distances and space motion information for halo stars with accuracies a thousand times greater than those obtained by the HIPPARCOS satellite. In the meantime, much can be learned from ongoing ground-based proper motion programs such as SPM, NPM, and USNO. In addition, we can soon expect results from full sky (or nearly so) photometry programs such as 2MASS and SDSS, as well as radial velocity and abundance information from wide-field spectroscopic surveys being conducted with 2DF and 6DF. All of this is expected to create a huge leap forward in our understanding of the halo population in the Galaxy, and open the door for a new generation of testable models to emerge.

The amount of information that can be deduced from halo stars is enormous. From their chemical composition, one can learn about the enrichment processes (Ryan et al 1996; Tsujomoto et al. 1999; Nakasato & Shigeyama 2000), the nature of the first IMF (Larson 1998), and set constraints for nucleosynthesis calculations. Such calculations in massive stars are being performed intensively at present (Heger et al. 2000a; Heger et al. 2000b; Nakamura et al. 2000; Rauscher et al. 2000; Rosswog et al 2000) due to great improvements in the reliability of the input data, including opacity tables (Iglesias & Rogers 1996), nuclear reaction rates (Rauscher & Thielemann 2000), and physical processes such as winds and the associated mass loss (Langanke & Martinez-Pinedo 2000). Still, nucleosynthesis calculations need to be tested further, specially for the yields of iron-group elements which require better understanding of the SN explosion mechanism including the position of the mass cut, and the explosion energy.

The oldest stars in the Galaxy can also set limits on the age of the Galaxy (and hence the universe), with better estimates of their ages. The use of the ratios of radioactive elements in these stars, compared with those predicted from r-process models, is a very useful tool that has been used with great success lately (Cayrel et al 2001; Hill et al 2001; Toenjes et al. 2001; Sneden et al 2001).

Since it is believed that halo stars have kinematic properties similar to those of the systems in which they were formed, studies of the kinematics of halo stars can help us understand how the halo was assembled. Clumping of at least a small number of halo stars in angular momentum phase space has already been observed, indicating that such stars were accreted by the Galaxy from a previous system. Helmi et al (1999) suggested that about 10% of metal-poor stars in the halo may have come from a single coherent structure that was disrupted during or soon after the Galaxy's formation. Chiba & Beers (2000) confirm these findings and identify an additional elongated feature in angular momentum space. They summarize the global kinematics of the halo stars and report that they do not show a net retrograde rotation at large heights above the Galactic plane, as claimed previously, but rather exhibit a near zero systematic rotation, with a continuous decrease in rotational velocity with increasing height above the plane. They also observe no correlation between [Fe/H] and eccentricity e and no change of the average rotational velocity with abundance for stars with [Fe/H] < -1.7. These results are basically in agreement with the SZ scenario, in which the halo is assembled from different fragments accreted from merging nearby systems

There is also great interest today in nearby dwarf galaxies, which are believed to have contributed to the halo population by merging and tidal destruction. The halo stars identified as members in clumps in angular-momentum space, and therefore believed to have been accreted from such nearby systems, are being pursued by observers hoping that they may be able to give some insight as to how dwarf galaxies evolved, and influenced the evolution of the Milky Way. The low alpha-element abundances observed in some halo stars are suggestive of slow star-formation rates in such systems, allowing little enrichment by SNII before SNIa events take place and contribute their iron-rich material. Therefore, the substructure observed in the halo is a very important finding that needs to be pursued further, and promises to help astronomers tell a story of the formation of the Galaxy and its relation with other nearby systems.

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