Metallicity distribution of halo stars and minor merger processes of the Galaxy

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ABSTRACT

In this paper, a possible relation between the high dispersion in metallicity of metal-poor halo stars and the minor merger processes in the history of the Galaxy is presented. Observations show that satellite galaxies have been falling into the gravitational well of the Galaxy and then disrupted by the tidal force through minor merger processes. As a result, the foreign populations of stars in the satellites make considerable contributions to the Galactic halo, therefore alter the intrinsic distribution of metallicities of the halo stars. A model for the distribution of metallicities of halo stars with $[Fe/H] < -2$ is made, which is constrained by observations. We show that most of the metal-poor halo field stars come from the satellite galaxies merged into the Galaxy. Assuming the bulk of stars in a satellite galaxy were formed in a cloud which had been enriched by previous type II supernova events, our model reproduces the observed trends in the metallicity distribution of the extremely metal-poor halo field stars in the Galaxy. Taken all the parameters for our model, through merging satellite galaxies into the Galactic halo, a density of $1.9 \times 10^{-3} \text{kpc}^{-3}$ of extremely metal-poor halo stars in $-5 < [Fe/H] < -4$ is predicted, which explains why no such stars have been observed so far.

Key words: galaxy: haloes, evolution, abundances, interactions-stars: Population III
1 INTRODUCTION

The origin of the Galactic stellar halo is a long-standing problem. Theories of the formation of the Galaxy can generally be viewed as variations on the monolithic collapse model of Eggen, Lynden-Bell, & Sandage (1962, hereafter ELS) and the chaotic accretion model of Searle (1977) and Searle & Zinn (1978, hereafter SZ), or combinations of the two models. The SZ picture seems more popular in recent years (Wyse 1999 a,b; Gould et al. 1992; Irwin & Hatzidimitriou 1995; Kuhn, Smith & Hawley 1996). SZ proposed a scenario in which the Galaxy was assembled through the gradual merger of many sub-Galactic-sized clouds. Galactic merger events generally can be divided into two classes: (Kauffmann & Charlot 1998) (a) minor mergers (i.e. accretion events), which occur when one galaxy has less than a third of the mass of the other one, and (b) major mergers, which happen when the galaxies are within a factor of 3 in mass. For the goal of the present work, only minor mergers are considered.

Minor mergers involving satellite galaxies might have played a certain subtle role (Johnston, Hernquist & Bolte 1996, hereafter JHB), although not being critical for the formation and structure of the Galaxy. Observational evidence associated with minor mergers, such as some quasar activities (Bahcall, Kirhakos, & Schneider 1995), Grand design spiral structure, close companions (i.e. M51), are shown. Considerable observational evidence supporting accretion processes has accumulated, e.g. Through looking at the distribution of halo stars in age and metallicity, Unavane et al. (1996) concluded that about 10% of these stars could have been accreted from the destruction of galaxies with stellar populations like those of the dwarf spheroidal satellites of the Galaxy. Numerical simulations also have confirmed the physical intuition that lumps observed in the halo phase-space distribution could be associated with accretion events (McGlynn 1990; Moore & Davis 1994; Oh et al. 1995; Piatek & Pryor 1995; Velazquez & White 1995; Johnston, Spergel & Hernquist 1995; JHB; Kroupa 1997). The observations of dwarf companions in the Galaxy, the discovery of the Sagittarius dwarf galaxy (Ibata et al. 1994; Grillmair et al. 1995; JHB) have been observed. Furthermore, the possible observable signatures left by that minor mergers is supported by observations of satellites of the Galaxy that display evidence for ongoing tidal interactions. In general, it can be concluded through numerical simulation and observational data show that satellite accretion is ongoing in the Galaxy and is likely to have occurred often in the past.
To explore various formation scenarios of the Galactic halo, commonly employed tracers include the kinematics of halo field stars as a function of $[Fe/H]$; the age distribution of Galactic globular clusters; trends in cluster age with $[Fe/H]$ and Galactocentric radius or height above the disk, and the persistence of a cloud, i.e. the thin disk (Larson 1990; Majewski 1993). Low mass extremely metal-poor halo field stars have lifetimes that are much greater than the age of the Galaxy so that they will not evolve away from the main sequence, and due to very long dynamical time scale of their orbital motion, the halo stars do not dissipate their orbital energy. Hence, “fossil” information about the chemical composition patterns of the halo is kept in these stars. In this paper, we consider the feasibility of probing “fossil” signatures of the formation of the Galaxy through the frequency distribution of extremely metal-poor halo field stars, as a function of $[Fe/H]$.

To address the properties of the extremely metal-poor halo stars that appear in the range $[Fe/H] = -4$ to $-2.4$, many theoretical models have been invoked in the framework of ELS prescription (Cayrel 1986; Yoshii et al. 1995; Shigeyama & Tsujimoto 1998; Tsujimoto & Shigeyama 1998; Tsujimoto et al. 1999; Lu et al. 2001). A challenging view against above models has been suggested, in which, a Galactic halo is formed through the disruption of many SZ fragments (Bekki 1998; Bullock et al. 2000, hereafter BKW; Gilmore 2000; Gilmore & Wyse 1998). The later view argues that a diffuse stellar component produced by a large number of tidally disrupted satellite galaxies, is perhaps sufficient to account for most of the Galactic stellar halo. Smaller galaxies collapse earlier when the density of the universe was higher could be expected from the hierarchical (Kravtsov et al. 1998; Kormendy & Freeman 1998). Thus it is likely that the satellite galaxies should have formed prior to the epoch of main body of the Galaxy was assembled and would be the building blocks of larger galaxies (Gilmore 2000). Observationally, it is difficult to distinguish the foreign contribution by the disrupted population from the normal stellar halo component.

Motivated by above investigations, we present a model to reproduce the observed metallicity distribution in the low metallicity range ($[Fe/H] < -2.5$) of the Galactic halo stars by taking into account the minor mergers of satellites. The description and quantification of the model are given in Sect.2. The results of our model and the conclusion are given in Sect.3.
2 MODEL DESCRIPTION

Up to a decade ago, searches for the first generation stars with strictly the chemical composition left by Big Bang Neucleosynthesis (BBN) had led to the result that the observation limit towards the lowest metallicities (Beers Preston & Shectman, 1992, hereafter BPS) is now about \([Fe/H] = -4\). More than 100 stars with metallicities between \([Fe/H] = -4\) to \([Fe/H] = -3\) were found, while no stars at all with \([Fe/H] = -5\) were discovered. These very metal-poor halo stars show a great diversity in their elemental abundances and therefore a scatter in their element-to-iron ratios \([El/Fe]\) of order 1 dex. This scatter gradually decreases with increasing metallicity and eventually becomes the same as that of the mean metallicity.

2.1 The basic assumptions

To facilitate our model, the following working assumptions are adopted:

(i) Our initial conditions assume that a Galactic halo interstellar medium (ISM) consisting of a homogeneously distributed single gas phase with primordial abundance and a total mass of about \(10^8 M_\odot\).

(ii) Most of the metal-poor Galactic stellar halo stars with a high dispersion in metallicity come from accretion of satellites which are tidally disrupted during the merger processes within Galactic halo. If such tidal components were to maintain spatial and kinematic coherence in the lifetime of the Galaxy, then a halo formed through the disruption of many different satellite galaxies (SZ fragments) would exhibit a diversity in its phase-space, unlike a unique origin coming from a smooth, monolithic collapse (ELS models) which ought to be featureless (JHB). Our present model will use this distinguishing feature of the tidal components to account for the high dispersion in metallicity of the Galactic extremely metal-poor halo stars.

(iii) The stellar contents of a accreted satellite galaxy is approximated with a single stellar population (SSP), which is defined as a group of stars born at the same time in a chemically homogeneous cloud with a given metallicity. The satellite galaxies mergered into the Galaxy at different time have distinct properties and are assumed to be represented by SSP models of various metallicities and ages. When mergered into the Galactic halo, stars in the satellite with the age and metallicity of the SSP are simply added to the halo and will make its contribution to the distribution of metallicity of the halo. In fact, the star
formation history of each satellites shows a remarkable complication, it is very difficult to describe the formation and evolution of satellites by using SSP model. We will discuss this in future work.

(iv) The metallicities of SSPs goes from \([Fe/H] = -4\) to approximately \(-2.5\), as noted by McWilliam et al. (1995). We limit the metallicity range of SSPs based on the long-lived halo star lifetime. It is further assumed that the age of SSP in the satellite galaxy is as long as that of the Galactic halo star. An approximation to the metallicity dependent mass-lifetime relation of the Geneva Stellar Evolution and Nucleosynthesis Group (Schaller et al. 1992; Charbonnel et al. 1993) is used to determine the lifetime of SSP,

\[
\log T = (3.79 + 0.24Z) - (3.10 + 0.35Z) \log M \\
+ (0.74 + 0.11Z) \log^2 M, \tag{1}
\]

where \(T\) is the lifetime in \(10^6\) yr, \(Z\) the metallicity in solar metallicity \(Z_\odot\), and \(M\) the mass in solar mass \(M_\odot\). Usually, theoretical metallicity distribution of stars are constructed as a function of metallicity \(Z = \log(n_Z/n_H)_\star - \log(n_Z/n_H)_\odot\), where \(\log(n_Z/n_H)_\star\) is the stars iron abundance and \(\log(n_Z/n_H)_\odot\) is the solar iron abundance. Whereas observations of stellar abundances are usually expressed in terms of \([Fe/H]\), since the abundance of iron is the most easily measurable. For halo stars, \([Fe/H] \neq Z\), because not all elements are deficient by the same factor. The chemical evolution models adopted in our paper is parameterized by the “effective yield”, which is a measure of the efficiency of the enriching processes. The yield determined from observed \([Fe/H]\) values is not the effective yield of metals, but rather that of iron. Following the argument of Lambert (1989) and Kurucz (1979), we also assumed that the effective yield of metals will be 0.35 dex higher, so the relation between metallicity \([Fe/H]\) and \(Z\) is,

\[
[Fe/H] = Z - 0.35. \tag{2}
\]

Given the final metallicity \([Fe/H]\) of a SSP, with low mass limit of \(0.8 \leq M \leq 1\), we can solve Eqs.(1) to (2) to obtain the lifetime of SSP.

### 2.2 Quantifying the model

The model can be quantified based on the assumptions discussed above. Two conceptions are introduced: (a) the accretion mass \(M_{\text{acc}}\) of halo field stars which is defined as the total mass of the accreted halo field stars by \(N_{\text{sat}}\) isolated satellites tidally disrupted at time \(\tau\),
where \( N_{\text{sat}} \) is defined as the accreted number of satellites that occurred during the elapsed time \( \tau \), and \( \tau \) is given by
\[
\tau = \frac{2}{3H_0} \left[1 - \left(\frac{1}{1 + z}\right)^{3/2}\right],
\]
where \( z \) is the redshift, \( H_0 \) is the Hubble constant. (b) the total iron yield \( M_{Fe} \) of the accreted satellite integrated along the isochrone with a given initial mass function (IMF).

We use the approximate analytic model of BKW which provides the accretion histories of an ensemble of 100 Galactic-type galaxies (\( v_{\text{circ}} = 200 \text{km s}^{-1} \), \( v_{\text{circ}} \) is circular velocities of galaxy). The model assumes a \( \Lambda \)CDM cosmology with \( \Omega_m = 0.3, \Omega_\Lambda = 0.7, h = 0.7 \), and \( \sigma_8 = 1.0 \), and provides masses, approximate disruption times, and orbital evolution for each disrupted satellite, where \( h \) is the hubble constant in units of \( 100 \text{km s}^{-1} \text{Mpc}^{-1} \), \( \sigma_8 \) is the rms fluctuation on the scale of \( 8h^{-1}\text{Mpc} \). The total stellar masses of the disrupted satellites is estimated by applying the same hypothesis used by BKW: low mass satellites with virial temperatures below \( \sim 10^4 K \) (while the circular velocity is \( v_{\text{circ}} \sim 30 \text{km s}^{-1} \)) can only accrete gas before the universe was reionized at \( z = z_{\text{re}} \) (\( z_{\text{re}} \) is reionization redshift). If the parameters of \( z_{\text{re}} = 8 \) and \( f = 0.3 \), where \( f \) the reionization stellar mass at \( z_{\text{re}} \), which is constrained so that the observable halos have mass-to-light ratios in the range of observed dwarf satellites (a range \( f \sim 0.1 - 0.8 \) is plausible), the total stellar mass of the disrupted component at time \( \tau \) is roughly \( M_{*\text{tid}} = 5 \times 10^8 h^{-1} \text{M}_\odot \).

Zhao et al. (1999, hereafter ZJHS) analyzed a tidal components (stars or gas clouds) that are turned from a satellite galaxy into the Galactic halo. They suggested that the number of field halo stars which share the same proper motion with a tidal disrupted stellar components is
\[
N_f = N_{HB} \frac{\sigma_{\text{tid}}}{\sigma_{\text{halo}}} \leq 70,
\]
where \( \sigma_{\text{halo}} \sim 3000 \mu \text{asyr}^{-1} \) and \( \sigma_{\text{tid}} \sim 100 \mu \text{asyr}^{-1} \) are the dispersion velocities of halo stars and tidal disrupted stellar components, respectively. \( N_{HB} = (6 \pm 2) \times 10^4 \) is horizontal (HB) stars (Kinman 1994). If a disrupted satellite galaxy had the same stellar content \( N_{\text{halo}} \sim 6 \times 10^4 \) as the surviving halos (BKW), with \( M_{*\text{tid}} \) and Eq.(3), we could obtain the total disrupted halo field star’s mass at time \( \tau \)
\[
M_f = \frac{N_f}{N_{\text{halo}}} M_{*\text{tid}},
\]
\[
= 4.08 \times 10^5 \left(\frac{N_{\text{halo}}}{6 \times 10^4}\right)^{-1} \left(\frac{h}{0.7}\right)^{-1} \left(\frac{70}{N_f}\right) \text{M}_\odot,
\]
The relation among $M_f$, $M_{acc}$ and $N_{sat}$ is given as

$$M_{acc} = M_f N_{sat}.$$  \hfill (5)

Since the accreted mass $M_{acc}$ is directly proportional to the number of accreted satellites, it can become larger than the total Galactic halo mass $M_{tot}$. Furthermore, the accretion efficiency per unit time can be defined as the ratio $f_{acc} = M_{acc}/M_{tot}$, which depends only on $N_{sat}$ for fixed $M_f$ and $M_{tot}$. When $f_{acc} = 1$, the total mass of the stars with chemical enrichment is the same as the primordial halo mass of the Galaxy. Since the stars coming from the accreted satellites have been mixed into the Galactic halo, the ratio $M_f/M_{tot}$ determines the mixing efficiency in our model, therefore gives the number of the minor mergers of satellites in the unit volume that is needed to reach a certain value of $f_{acc}$. Given $f_{acc}$, $M_{tot}$ and the mean integrated iron yield $\langle M_{Fe} \rangle$ for a typical disrupted satellite, the mean metallicity of the halo stars could be determined.

Despite significant effort, theoretical prediction of the abundance and properties of the satellites are far from being complete (Klypin et al. 1999; Kauffman et al. 1993). The self-enrichment mechanism of galactic halo globular clusters (Parmentier et al. 1999) is adopted here to model the abundances of disrupted satellite galaxies. The basic idea is that the cold and dense clouds embedded in the hot protogalactic medium are assumed to be the progenitors of satellite galaxies. A first generation of metal-free massive stars form in the center regions of proto-galaxies. The corresponding massive stars evolve very quickly, end their lives as Type II supernova (hereafter SNII) and eject $\alpha$, $r$-process and possibly a small amount of light $s$-process elements into the ISM. A second generation of stars is born in these compressed and enriched layers of ISM. These SSPs can recollapse and form a satellite galaxy. The mass $M_{Fe}$ ejected in the ISM by a SNII whose progenitor mass $m$ is approximately given by Woosley & Weaver (1995), which ranges from $12M_\odot$ to $60M_\odot$. If the mass distribution of the first generation of stars obeys the universal Salpeter form (Salpeter 1955)

$$dN = Cm^{-2.35} dm,$$

$$\int_{M_{11}}^{M_u} Cm^{-2.35} dm = 1,$$

where $dN$ is the number of stars with masses between $m$ and $m + dm$, $M_u = 60M_\odot$ is the upper mass limit, $M_{11} = 0.1M_\odot$ is the lower mass limit for the IMF. Then integrated iron
yield $M_{Fe}$ in the accreted satellite galaxy is

$$< M_{Fe} > = \int_{m_{I2}}^{m_{u}} C m^{-2.35} M_{Fe} dm,$$

where $M_{I2}$ is the lowest star mass for a SNII event. The mean metallicity of the halo field stars can be given by,

$$\left[\frac{Fe}{H}\right] = \log \frac{N_{sat} < M_{Fe} >}{M_{tot}} - \log \frac{(n_{Fe})_{\odot}}{(n_{H})_{\odot}},$$

$$= \log \frac{f_{acc} < M_{Fe} >}{M_{f}} - \log \frac{(n_{Fe})_{\odot}}{(n_{H})_{\odot}},$$

where $\log (n_{Fe}/n_{H})_{\odot}$ is the solar iron abundance. Because the minor merger process simply adds the stars of the disrupted galaxy into the Galactic halo, the evolution of the abundance ratios as a function of $[Fe/H]$ is almost independent of the star formation timescale in our model.

Table 1 shows the accretion factor in unit volume needed to reach the mean metallicities of the extremely metal-poor Galactic halo stars: $[Fe/H] = -5.0, -4.5, -4.0, -3.5, -3.0, -2.5, -2.0$. Also shown in the table are the corresponding accreted satellite frequency $N_{sat}$.

Assuming that the disrupted satellites have the same star counts as those of the surviving satellites (BKW), we can deduce the number of metal-poor halo field stars $N$, that is expected in different metallicity bins,

$$N = N_{field} M_{acc}/M_{tid},$$

$$= N_{field} N_{sat} M_{f}/M_{tid}$$

The number of metal-poor stars predicted by our model binned in 1.0 dex grid are listed in Table 2. For comparison, the observed data from a homogeneous intermediate resolution sample of Ryan & Norris (1991) also lists in Table 2. Assuming that total halo stars distributed in a volume of $\frac{4\pi}{3} R_{G}^{3}$ ($R_{G} = 20 kpc$), from Table 1 and Table 2, we find that 178 mergers are need to produce a density of $1.9 \times 10^{-3} kpc^{-3}$ for the metal-poor stars in the bin $-5 < [Fe/H] < -4$.

3 CONCLUSION AND DISCUSSION

We have developed a model for the early chemical enrichment of the Galactic halo stars. The aim of the model is to understand the frequency distribution and the scatter in the $[El/Fe]$ ratios of the observed extremely metal-poor halo stars.

As can be seen in the Table 2, we have deduced the expected number of extremely
Metallicity distribution of halo stars

metal-poor stars (with $[Fe/H] < -4$) which should have been observed. We expect about 14 model stars with $-5 < [Fe/H] < -4$ while the observation sample contains none. If the ratio of stars in these two metallicity bins for this admittedly inhomogeneous sample is representative for the Galactic halo stars, this would suggest a genuine shortage of the most metal-poor stars. It is possible that Population III stars have caused a pre-enrichment in the satellites and the true population III stars already have disappeared before the onset of satellites accreted by the Galaxy. Furthermore the possibility to see the true Galactic population III is much reduced by accretion of those pre-enriched foreign stars.

The growing number of the halo stars coming from merged satellites can be characterized by the accretion efficiency $f_{\text{acc}}$, defined as the ratio of the mass $M_{\text{acc}} = N_{\text{sat}} M_f$ produced by the number $N_{\text{sat}}$ tidally accreted satellites and the Galactic halo mass $M_{\text{tot}}$ with primordial abundance gas. The enrichment history of the halo stars is mainly determined by the mixing efficiency which in turn is fixed by the ratio of the mass $M_f$ of the accreted stars of the satellite disrupted event and $M_{\text{tot}}$. The more mass $M_f$ is, the less satellite accretion event is needed to reach a certain value of $f_{\text{acc}}$, therefore the mixing is more efficient. $M_{\text{field}}$ also determines the average metallicity $[Fe/H]$ of the halo stars for a given accretion efficiency. A larger $M_{\text{field}}$ leads to a lower mean halo stars metallicity and vice versa.

Our model shows that the Galactic halo stars are the outcome of a large number of tidally disrupted satellite galaxies, which is in agreement with the prediction of BKW. Our analysis supports that the Galactic halo is formed through the disruption of many SZ fragments.

The observed differences in element ratio patterns of extremely metal-poor halo field stars is a naturally results of our model, because these stars come from galaxies with different SSP. However, the alpha elements, iron peak elements and heavy elements, as a function of $[Fe/H]$ in satellite galaxies are produced by SNeII alone. The abundance ratios of tidal disrupted components are predicted to exhibit a large star to star scatter, depending in detail on the abundance patterns of SN ejecta with different progenitor masses (Tsujimoto & Shigeyama 1998; Shigeyama and Tsujimoto 1998).

Based on present evidence, we propose a possible model for the formation of our Galactic halo in this paper. Do large galaxies form from accumulation of many smaller systems which have already initiated star formation? Does star formation begin in a gravitational potential well in which much of gas is already accumulated? and how to distinguish a disrupted population from a stellar halo formed by other means observationally? Answers to such questions require complementary observational approaches. Fortunately, One of the next two 'corner-
stones’ of ESA’s science programmes, Global Astrometric Interferometer for Astrophysics (GAIA), will advance all these questions (Freeman 1993; Gilmore 1999; ZJHS; Hernandez et al 2000; Perryam et al. 2001). GAIA’s main scientific goal is to clarify the origin and history of our Galaxy, from a quantitative census of the stellar populations. It will advance questions such as when the stars in our Galaxy formed, when and how it was assembled. The complete satellite system was evaluated as part of a detailed technology study (Perryam et al. 2001).

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Metallicity distribution of halo stars

Table 1. Accretion efficiency $f_{\text{acc}}$ and tidal disrupted number $N_{\text{sat}}$ of satellite galaxy.

| [Fe/H] | $f_{\text{acc}}$ | $N_{\text{sat}}$ |
|--------|------------------|------------------|
| −5.0  | 0.074h$^{-1}$    | 1.2610$^4$      |
| −4.5  | 0.233h$^{-1}$    | 3.9910$^4$      |
| −4.0  | 0.737h$^{-1}$    | 1.2610$^2$      |
| −3.5  | 2.332h$^{-1}$    | 3.9910$^2$      |
| −3.0  | 7.374h$^{-1}$    | 1.2610$^3$      |
| −2.5  | 23.32h$^{-1}$    | 3.9910$^3$      |
| −2.0  | 73.74h$^{-1}$    | 1.2610$^4$      |

Table 2. Top: Relative frequency of stars in the homogeneous intermediate resolution survey of Ryan & Norris (1991), and our model, binned with binsize 1.0 dex. Bottom: Absolute numbers. the last row gives the number of stars per 1.0 bin which we expect to be present, if our model gives a fair representation of the halo metallicity distribution. The number of model stars is normalized to the number of stars in the range $−4 < [\text{Fe}/\text{H}] < −2.0$ in the survey sample of Ryan & Norris (1991). No stars was detected with confirmed $[\text{Fe}/\text{H}] < −4.0$, in contrast to the predicted by the model.

| [Fe/H] | $[−3.0,−2.0]$ | $[−4.0,−3.0]$ | $[−5.0,−4.0]$ |
|--------|--------------|--------------|--------------|
| Model  | 0.943        | 0.057        | 0.0          |
|        | 0.971        | 0.097        | 0.0096       |
| Ryan & Norris | 100      | 6.0      | 0.0      |
| Expected | 1420 | 142 | 14 |
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Metallicity distribution of halo stars

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