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Distribution of the disrupted satellite galaxies as a function of metallicity

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Abstract. Recent observations show that some dwarf satellite galaxies fall into the gravitational well of the Galaxy while being disrupted by the tidal force. As a consequence, the Galactic halo suffers contamination from this process, the stellar populations of the tidal disrupted satellites make an additional contribution and alter the intrinsic metallicity distribution of the halo stars. The distribution of this kind of disrupted satellite galaxy as a function of metallicity is investigated in this paper. The model is limited to one class of dwarf spherical satellite galaxy, that is assumed to have similar abundance patterns to the Galactic field halo stars. We discuss their distributions through the links between minor merger processes in the history of the Galaxy and the observed distribution of metal-poor field halo stars. The upper limit of 35% of the metal-poor halo field stars was established by merging of this kind of satellite galaxy with characteristic mass $M_{\rm sat}$, and adopting the mass-metallicity relation among dwarf spheroidal galaxy, the distribution of the disrupted satellite galaxy as a function of metallicity is derived to reproduce the observed metallicity distribution of the extremely metal-poor halo field stars in the Galaxy. The problem of missing metal-free halo stars in the Galaxy is explained in this model as well.

Key words. galaxies: halos, evolution, abundance, interactions

1. Introduction

Dwarf spheroidal (dSph) satellite galaixes are faint galaxies whose luminosity L is 10^5–$10^7\,L_\odot$. They are characterized by their low surface brightness (Gallagher & Wyse 1994). The studies of such objects are important since lower-mass dwarf galaxies are considered to have formed earlier in a hierarchical structure formation scenario based on the cold dark matter (CDM) model (Blumenthal et al. 1984). The abundance patterns among the dwarf galaxy stars suggest that dwarf galaxies are the surviving building blocks from which large galaxies are formed (Larson 1988; Zinn 1993). Such dSph galaxies are believed to be the key for the understanding of the physical properties of the building blocks themselves (Kunth & Östlin 2000). Particularly, the galactic halos are regarded as assembling from such chemically distinct, low-mass fragments, empirically and analytically (Searle & Zinn 1978; Zinn 1993; Ibata et al. 1994; Klypin et al. 1999; Moore et al. 1999; Côtè et al. 2000; Yanny et al. 2000). Some hydrodynamical simulations of galaxy formation also pointed to the assembly of large galaxies from low-mass, gas-rich, protogalactic fragments (Haehnelt et al. 1998, 2000). The Galactic halo is partly made of debris of objects such a dSphs. This fact is supported by the following two observations. Firstly, more and more observations show that the accretion of a dwarf galaxy is ongoing in the Galaxy and is likely to have occurred often in the past, for instance, the discovery of the Sagittarius dwarf satellite galaxy is a dramatic confirmation of this kind of merging processes (Ibata et al. 1994; Grillmair et al. 1995; Johnston et al. 1996, hereafter JHB); ω Cen also may be the nucleus of a dwarf galaxy that has been tidally stripped by the Galaxy (Majewski et al. 2000). It is noted that the globular cluster G1 in M 31 has been suggested to be the nucleus of a disrupted dwarf (Meylan et al. 2001), and indications of tidal streams have been found around M 31 (Ibata et al. 2001). Secondly, the observations show that the abundance patterns in dSph stars, like Draft, Sextan, and Ursa Minor differ from the Galactic halo (Shetrone et al. 2001, hereafter SCS), as well as the abundances inferred from the infrared CaII triplet strength in Tolstoy et al. (2001), implying that the Galactic halo has not been assembled entirely through the disruption of very low luminosity dSph galaxies. Richer et al. (1998) argued that the metal-poor stars in dSph do not display the enhanced [alpha/Fe] ratio seen in the Galactic halo, and the abundances of the dSph sampled by Shetron et al. (2001) are different from the abundances of RGB stars in ω Cen (Smith et al. 2000). Therefore,

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the observed differences in the abundance patterns may put some interesting limitations on the suggestion that the Galaxy was assembled from building blocks (Searle & Zinn 1978; Lason 1988; Zinn 1993; Cötè et al. 2000), or proto-galactic fragments, similar to the dSphs sampled by Tolstoy et al. (2001) and Shetrone et al. (2001).

Accretion and disruption involving dwarf satellite galaxies might have played a certain subtle role in the formation and structure of the Galaxy (JHB), for these processes will affect the star formation activity in galaxies, and therefore are important for chemical evolution. A number of studies have contributed to these fields (Quinn et al. 1993; Oh et al. 1995; Johnston et al. 1995; Sellwood et al. 1998). To understand the properties of the dwarf satellite galaxies from the observed data, our own galaxy is very important because it has access to 6D information that is not available for other galaxies. Particularly, very metal-poor low mass halo field stars (VMPs) in the Galaxy are of considerable interest since these stars have lifetimes that are much greater than the age of the Galaxy. Hence, "fossil" information about the chemical composition patterns of the halo is kept in these stars. Therefore, the elementary abundance observed in VMPs directly reflects the chemical abundance and the chemical inhomogeneity of the interstellar medium (ISM) during halo formation, and the history of accreting and disrupting satellite galaxies.

The metallicity of VMPs are considered to be similar to globular-cluster stars (Ryan & Norris 1991). These stars must have formed either outside the Milky Way or before the Galactic ISM became significantly polluted with metals. The former situation has been studied by many authors, for example, some authors (Bekki 1998; Bullock et al. 2000, hereafter BKW; Gilmore 2001; Gilmore & Wyse 1998) proposed that a large fraction of the stellar halo of the Galaxy is made of the stellar component through the disruption of many building block of galaxies (Searle & Zinn 1978). Unavane et al. (1996) argued that about 10% of VMPs could have been accreted from the destruction of dwarf spheroidal satellite galaxies by comparing the color distribution of the turn-off stars in the halo within the Carina dwarf.

Motivated by the above investigations, we consider the connection between the distribution of VMPs and the accreted satellite galaxies by modeling the observed distribution of VMPs, as a function of [Fe/H], instead of modeling the color distribution of the turn-off stars in the Galaxy. This model is limited to the distributions of the disrupted dSphs, which has an abundance pattern similar to the Galactic halo stars. We describe and quantify the model in Sect. 2. The results and discussion are given in Sect. 3.

2. Model description

2.1. The basic assumptions

As mentioned in the last section, the Galactic halo can be divided into two components, namely, an intrinsic component that is formed at the same time as Galaxy formation, and an external one made by minor merger processes. To facilitate our model, the following assumptions are adopted:

1. The stellar contents of an accreted satellite galaxy are 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. When merging into the Galactic halo, stars in the satellite with the age and metallicity of the SSP are instantly mixed into the halo;
2. The accreted satellite galaxies satisfy a general mass-metallicity relation of dSph galaxies in the Local Group. The metallicity of different satellite galaxies ranges from [Fe/H] $= -4$ to about -2.0;
3. The accreted satellite has the same stellar content as the observed dSph at the present time.

2.2. The mass-metallicity [Fe/H] relation of disrupted satellite galaxies

Despite significant effort, theoretical predictions of the physical properties of the satellites, especially the metallicities, are far from satisfactory (Klypin et al. 1999; Kauffman et al. 1993). The chemical enrichment history of dSph galaxies remains uncertain(Hirashita et al. 1998). However, The relation between the initial gas mass $M_{\rm G}$ and [Fe/H] has been investigated by Yoshii & Arimoto (1987, hereafter YA87), which is

$$[{\rm Fe/H}] = 0.745 \log(M_{\rm G}) - 7.55 \qquad (1)$$

where $M_{\rm G}$ is the initial mass of the system, and the luminosity-weighted [Fe/H] is adopted. Since YA87 did not include the Dark Matter (DM), the relation Eq. (1) may not able to be compared directly with the relation $M_{\rm sat}$–[Fe/H] (Tamura et al. 2001, hereafter THT). However, YA87 suggested that the galactic wind model can be extended to the mass range ($<10^9\,M_\odot$) of dE and dSph galaxies. The fitting of the prediction by YA87 is discussed by THT; it is shown that YA87 roughly reproduced the overall trend in the observed mass-metallicity relation. We adopt $M_{\rm G}$ as the satellite mass $M_{\rm sat}$ in this paper. We stress here that the estimates of our model should be regarded as a preliminary step due to the specific problem we want to examine and the hypothesis made in order to facilitate our thoughts. The exact chemical enrichment history is still not clearly know, and the sample of dSphs is not yet rich enough, so the precise chemical enrichment properties are not unambiguously determined. Furthermore, there are many factors, such as the regulated star formation in low-mass dSph galaxies with $M_{\rm vir} \leq 10^8\,M_\odot$ suggested by Nishi & Tashiro (2000), the mechanisms associated with gas removal (MacLow & Ferrara 1999), and the initial density of a galaxy as well as its total mass and dark matter/baryonic mass ratio (Ferrara & Tolstoy 2000; Carraro et al. 2001), that are not considered in our work, that also influence the matellicity level. All these points will introduce uncertainties in the predictions of the current model, and they will be dealt with in a further work. YA87 extended solutions are used to describe the mass-metallicity relation of the low-mass dSph galaxies, and the solution applies successfully to the high-mass dSph galaxies, giving general predictions of the metallicity distribution of halo stars.

2.3. The mass M_{acc} of the accreted components of the halo

The approximate analytical model of BKW is used to describe the accretion history in the Galaxy. Based on a ΛCDM cosmology with $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$, and $\sigma_8 = 1.0$, where h is the Hubble constant in units of 100 $\rm km\,s^{-1}\,Mpc^{-1}$, σ_8 is the rms fluctuation on the scale of 8 h^{-1} Mpc, $\Omega_{\rm m}$ and Ω_Λ are the densities of matter and the vacuum respectively, in units of the critical density. The BKW model provides masses, approximate disruption times and orbital evolution for each disrupted satellite. The masses of the disrupted satellite galaxies can be estimated according to BKW: low mass satellites with virial temperature below $\sim 10^4$ K and a circular velocity $v_{\rm circ}$ about 30 $\rm km\,s^{-1}$ can only accrete gas before the universe is re-ionized at $z = z_{\rm re}$ ($z_{\rm re}$ is re-ionized redshift). We assume that the reionization stellar mass at $z_{\rm re}$ is f, which is adjusted in a manner that the observable halos have mass-to-light ratios (M/L_V) in the range of observed dwarf satellites (BKW). Since the observed M/L_V is different in different galaxies, the f differs from galaxy to galaxy. A very low value of $f(\leq 0.1)$ would imply excessive mass-to-light ratios, unless the fraction of the halo's virial mass ξ_* that lies within its final optical radius is much smaller than assumed by BKW. The mass $M_{*\rm tid}$ in stars of each disrupted sub-halo and the total stellar mass $M_{*\rm tot}$ of the disrupted components with $z_{\rm f} > z_{\rm re}$ have been discussed by BKW, and are

$$M_{*\rm tid} = f\left(\frac{\Omega_{\rm b}}{\Omega_0}\right)\xi_* M_{\rm sat}, \tag{2}$$

$$M_{*\rm tot} = M_{*\rm tid} N_{\rm sat} \sim 5\times 10^8\ h^{-1}\,M_\odot, \tag{3}$$

where $N_{\rm sat}$ is the accreted number of different satellite galaxies (specified with SSP of given age and metallicity). The values of the parameters $\Omega_{\rm b}$, Ω_0, ξ_*, and f are the same as BKW.

If the stellar halo of the Galaxy was built by merging of $N_{\rm sat}$ similar smaller systems of characteristic mass $M_{\rm sat}$, and assuming that a disrupted satellite galaxy has the same stellar content $N_{\rm halo} \sim 6\times 10^4$ as the surviving satellite halos (BKW), the total mass of the external component $M_{\rm acc}$ accreted from each sub-halo can be calculated as

$$M_{\rm acc} = K M_{*\rm tid} N_{\rm sat}, \tag{4}$$

where K is an efficiency factor of accretion, which is the fraction of stars liberated from the satellites and mixed into the Galactic halo. $(1-K)$ is the fraction of stars remaining in the satellites. The value of K could range anywhere between 0 and 1. $K = 0$ stands for no disruption and accretion, while $K = 1$ means complete disruption. $K = 2\%$, $K = 5\%$ and $K = 10\%$ are calculated in this paper.

2.4. The number of disrupted satellite galaxies

We must introduce a model efficiency term η, defined as the ratio of the external and the total (including intrinsic) distribution of the Galactic halo stars to quantify how many VMPs of the Galactic halo come from the external components by accreting dSph systems. The characteristic mass $M_{\rm sat} \geq 10^6\,M_\odot$ of the dSph systems is valid. The observed Galactic halo stellar mass (including the masses of the field halo stars and the cluster stars) (Gilmore 2001) is

$$M_{\rm halo} = 2\times 10^9\,M_\odot. \tag{5}$$

Using Eqs. (3) and (5), the value of η can be determined, which is

$$\eta = M_{*\rm tot}/M_{\rm halo} \sim 35\%. \tag{6}$$

We adopt an approach (see Eq. (3)) that leads to a generous upper limit ($\eta \sim 35\%$) of VMPs of the Galactic halo being mergers of the satellite galaxies with the halo of the Galaxy.

To obtain a quantitative link between the number of disrupted satellite galaxies $N_{\rm sat}$ and the observed number of very metal-poor stars in different metallicity bins, we consider that 35% of the total VMPs mass M^* should be consistent with the total mass of the external halo stars $M_{\rm acc}$ accreted from each satellite galaxy.

The total mass M^* of very metal-poor halo field stars can be calculated by

$$M^* = \int_{m_{\rm l}}^{m_{\rm u}} C m^{-\alpha+1}\,{\rm d}m, \tag{7}$$

where $m_{\rm l} = 0.8\ M_\odot$, $m_{\rm u} = 0.9\ M_\odot$. C is the coefficient related to the total mass of the very metal-poor halo field stars (VMPs), which is determined by the mass distribution of the VMPs. Assuming that the mass distribution of the very metal-poor halo field stars obeys the following power-law initial mass function (IMF)

$${\rm d}N = C m^{-\alpha}{\rm d}m \tag{8}$$

where ${\rm d}N$ is the number of stars with mass between m and $m + {\rm d}m$, α is the power-law index; the original Salpeter's $\alpha = 2.35$ (Salpeter 1955) is adopted here. The mass of very metal-poor halo field stars ranges from 0.8 $M_\odot$ to 0.9 $M_\odot$. Given the number ${\rm d}N$ of halo stars with mass between m and $m + {\rm d}m$, from Eq. (8), we can obtain the values of C.

Using Eqs. (1) to (8), and bearing in mind that the disrupted satellites have the same star counts as those of the surviving satellites (BKW), the number of disrupted satellite galaxies $N_{\rm sat}$ in different metallicity bins can be deduced by fitting the observed number of very metal-poor stars binned in 0.2 dex grid (Ryan & Norris 1991).

Table 1. Relative frequency of stars in the homogeneous intermediate resolution survey of Ryan & Norris (1991), binned with bin size 0.2 dex, and the model number $N_{\rm sat}$ of disrupted satellite galaxies with typical mass while $f = 0.1$ and $k = 2\%$.

[Fe/H]	[−3.8, −3.6]	[−3.6, −3.4]	[−3.4, −3.2]	[−3.2, −3.0]
Ryan & Norris	1	1	2	2
$N_{\rm sat}$	49	26	28	15
$M_{\rm sat}$	1.5×10^5	2.7×10^5	5.1×10^5	9.4×10^5
[Fe/H]	[−3.0, −2.8]	[−2.8, −2.6]	[−2.6, −2.4]	[−2.4, −2.2]
Ryan & Norris	9	12	21	25
$N_{\rm sat}$	36	27	25	16
$M_{\rm sat}$	1.7×10^6	3.2×10^6	6.0×10^6	1.1×10^7

Table 2. Relative frequency of stars in the homogeneous intermediate resolution survey of Ryan & Norris (1991), binned with bin size 0.2 dex, and the model number $N_{\rm sat}$ of disrupted satellite galaxies with typical mass while $f = 0.8$ and $k = 2\%$.

[Fe/H]	[−3.8, −3.6]	[−3.6, −3.4]	[−3.4, −3.2]	[−3.2, −3.0]
Ryan & Norris	1	1	2	2
$N_{\rm sat}$	6	3	4	2
$M_{\rm sat}$	1.5×10^5	2.7×10^5	5.1×10^5	9.4×10^5
[Fe/H]	[−3.0, −2.8]	[−2.8, −2.6]	[−2.6, −2.4]	[−2.4, −2.2]
Ryan & Norris	9	12	21	25
$N_{\rm sat}$	5	4	3	2
$M_{\rm sat}$	1.7×10^6	3.2×10^6	6.0×10^6	1.1×10^7

The number of disrupted satellite galaxies $N_{\rm sat}$ that matches the observed number of very metal-poor stars binned in a 0.2 dex grid is illustrated in Tables 1 and 2; the accretion efficiency is $K = 2\%$. The number of satellite galaxies as a function of [Fe/H] in the bin $-4 < [\mathrm{Fe/H}] < -2.0$ is shown in Figs. 1 and 2. Figure 1 corresponds to $f = 0.1$, while accretion efficiency varies ($K = 2\%$, $K = 5\%$ and $K = 10\%$). Figure 2 is the same as Fig. 1 but $f = 0.8$. The dotted line corresponds to the observed distribution of VMPs as a function of [Fe/H] in the survey sample of Ryan & Norris (1991). The observed VMPs in the plots is normalized to the number (334) of stars in the range $-4 < [\mathrm{Fe/H}] < -2.0$.

The plots also show the mass distribution of different satellite galaxies that is needed to fit the observed distribution of VMPs.

3. Conclusion and discussion

3.1. conclusions

It is suggested that there are two families of dSphs based on their abundance patterns. The first of these is being accreted by the Galaxy and is likely to have occurred often in the past, and is assumed to have similar abundance patterns to the Galactic halo. The second class is from the sample given by Shetrone et al. (2001) and Tolstoy et al. (2001). A possible approach to estimate the distribution of the former satellite galaxies is developed by reproducing the distribution of the observed VMPs of the Galaxy. This work can be summarized as follows:

Instead of using the color distribution of the turn-off stars in the Galactic halo in the model of Unavane et al. (1996), we work our model considering the distribution of VMPs in the Galactic halo. The upper limit of 35% very metal-poor stars in the Galactic halo made by merging of $N_{\rm sat}$ similar satellite galaxies with typical mass $M_{\rm sat}$

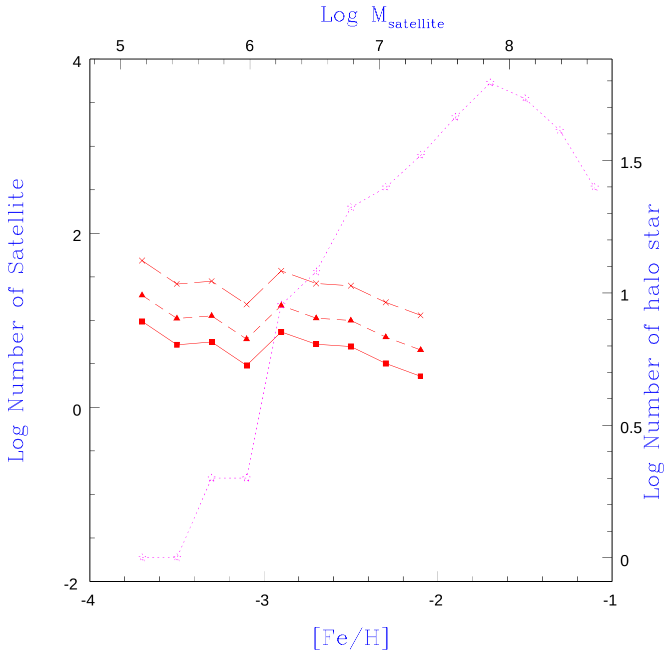

Fig. 1. The distribution of satellite galaxies as a function of [Fe/H] in the bin $-4.0 < [\mathrm{Fe/H}] < -2.0$, with $f = 0.1$ The solid line, the short dashed line and the long dash line correspond to $k = 10\%$, $k = 5\%$, and $k = 2\%$, respectively. The dotted line corresponds to the observed distribution of very metal-poor halo field star as function of [Fe/H], which is normalized to the number of stars (334) in the range $-4.0 < [\mathrm{Fe/H}] < -2.0$ in the survey sample of Ryan & Norris (1991).

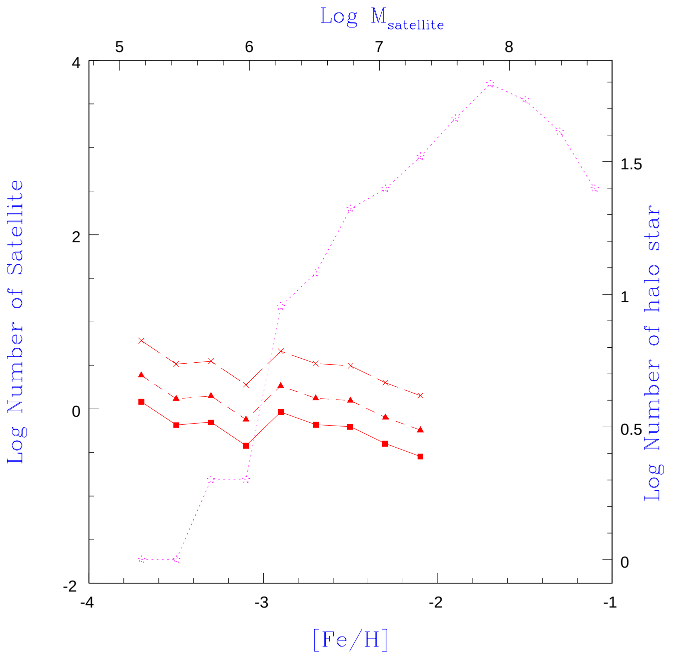

Fig. 2. The distribution of satellite galaxies as a function of [Fe/H] in the bin $-4.0 <$ [Fe/H] < -2.0, with $f = 0.8$. The solid line, the short dashed line and the long dash line correspond to $k = 10\%$, $k = 5\%$, and $k = 2\%$, respectively. The dotted line corresponds to the observed distribution of very metal-poor halo field star as function of [Fe/H], which is normalized to the number of stars (334) in the range $-4.0 <$ [Fe/H] < -2.0 in the survey sample of Ryan & Norris (1991).

is derived, and is marginally larger than that of Unavane et al. (1996).

The number of different satellite galaxies expected to fit the observed data of VMPs of the Galaxy in different metallicity bins is presented in the tables. Given the values of f, the number of satellite galaxies decreases with the increase in accretion efficiency K. The higher the mass of satellite galaxies, the higher the metallicity. The number of satellite galaxies increases with decreasing ratios of f in a given metallicity bin (see Figs.1 and 2).

The growing number of halo stars coming from merging satellite the galaxies can be characterized by the model efficiency. The larger the efficiency η is, the fewer satellite accretion events are needed to fit the observed data in a certain metallicity bin, therefore the mixing is more efficient.

The average metallicity [Fe/H] of the external stars that depends on the mass of typical satellite galaxy gives the average metallicity [Fe/H] of VMPs of the Galaxy. A larger mass of satellite galaxies leads to a higher mean halo star metallicity and vice versa (see plots.).

Up to a decade ago, searching for the first generation stars (“population III stars”) of the chemical composition left by Big Bang Nucleosynthesis (BBN) in the Galaxy result in a negative answer (Beers Preston & Shectman 1992, hereafter BPS). A range of explanations have been proposed to account for the negative result of population III star searches (Cayrel 1986; Yoshii et al. 1995; Shigeyama & Tsujimoto 1998; Tsujimoto & Shigeyama 1998; Tsujimoto et al. 1999; Lu et al. 2001). The present model predicts a genuine shortage of population III stars naturally. The key point of the model is that the merging of dSphs into the Galactic halo is already happening when the intrinsic Galactic halo stars are formed from a primordial cloud. The external component accreted from dSphs experienced their own chemical enrichment history before they mixed into the Galactic halo, and this certainly alters the chemical properties of the intrinsic halo. It is clear that the chemical composition of stars formed out of such a polluted Galactic halo is unlikely to be metal-free.

3.2. Discussions

Based on the present evidence, we show how mixing of disrupted satellites can be quantified using a distribution of VMPs in the Galactic halo. We obtain a distribution of satellite galaxies as a function of metallicity [Fe/H]. We require complementary observational data to address these issues. The parameter f is critical to our model. It varies from galaxy to galaxy, requiring further observational constraints.

The star formation history (SFH) of each satellite is simplified as a SSP for simplicity in this work. However, the SFH of each satellite galaxy shows a remarkable complication. We reluctantly describe the formation and evolution of satellites with an SSP model in this paper. It is more accurate to use evolutionary stellar population synthesis to describe the stellar components of satellite galaxies.

We adopt a universal IMF of the Salpeter form in this model. The use of a different IMF essentially alters the relative number of low-mass stars compared with the number of more massive ones. If the IMF were flatter at early times, relatively fewer low-mass stars would have been formed. Thus, more accreted satellite galaxies are need to fit the observed data of VMPs. Finally, because no objects with $M_{\rm G} < 10^5\,M_\odot$ are known yet, this model is limited to the samples of VMPs with the lowest metallicity, about [Fe/H] ~ -3 (see Table 1).

One of the next two “cornerstones” of the ESA, the Global Astrometric Interferometer for Astrophysics (GAIA), will make great advances towards answering questions (Freeman 1993; Gilmore 1999; Hernandez et al 2000; Perryman et al. 2001), such as when were the stars formed in the Galaxy, and when and how was the halo assembled. The complete satellite system will also be evaluated as part of a detailed technology study (Perryman et al. 2001). Therefore, with GAIA (Gilmore et al. 1998), we should be able to distinguish almost all streams in the solar neighborhood originating from the disrupted satellites.

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