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Stellar Relics from the Early Galaxy

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Abstract. We reviewed the recent progress in the field of stellar/galactic archeology, which is a study of the relics from the early galaxy. The oldest and most pristine objects that can be observed in the galaxy are the low mass metal poor stars of the Milky Way. They were formed during the early phases, when the ISM might have been polluted only by the Pop-III supernovae. With the recent large spectroscopic surveys (e.g. HK survey by Beers and collaborators, the Hamburg-ESO survey by Christlieb and collaborators and Sloan Digital Sky Survey) it has been possible to get clues on the nature of the first stars that has contributed to the heavy elements. Most of these metal-poor low mass stars also retain their signature of the early dynamical evolution of the galaxy, which can be studied through their orbits around the galaxy and spatial distribution. Here, we discuss the connection between the chemical and the kinematical properties of metal-poor stars in order to probe the early galaxy formation. We also discuss about the globular clusters, the satellite galaxies around the Milky Way and its possible contribution to the formation of the galaxy halo.

Key words. Galactic halo—chemical evolution—metal poor stars—chemical abundances—inner halo—outer halo—globular clusters—ultra-faint dwarf galaxies.

1. Overview

Halo of the galaxy is one of the oldest component of the Milky Way. It hosts the oldest globular clusters, which might have been formed only about 1–2 Gyr after the Big Bang. The halo stars have a mean metallicity of $[Fe/H] = -1.6$ and an extended low metallicity tail, down to $[Fe/H] \sim -5.5$ (Chrislieb *et al.* 2002; Frebel *et al.* 2005). In fact, these stars are the lowest metallicity objects that can be observable with the current observing facilities (8–10 m telescopes). Since, halo hosts the oldest globular clusters and the most pristine stars which are metal poor, it is an ideal system to study the early stages of the galaxy formation. Many of these metal-poor stars, still retain the chemical composition of the ISM, from which they were formed. Chemical tagging (Freeman & Bland-Hawthorn 2002) various abundance ratios of metal-poor stars is used to study the chemical history of the galaxy. Apart from this, we can also probe the dynamical history of the galaxy through the spatial distribution and the orbits of halo stars around the galaxy, as they still keep the imprints of dynamical history of the galaxy. One such clear observational evidence of such relics is the discovery of the Sagittarius dwarf spheroidal galaxy (Sgr-dSph) by Ibata *et al.* (1994).

The elemental abundance ratios along with kinematics can be used to understand the galaxy formation models. The two most popular models of galaxy formation are the monolithic collapse (ELS) and the hierarchical merging (Searle & Zinn 1978) through accretion of smaller satellites galaxies. The monolithic collapse of matter was proposed by Eggen, Lyden-Bell and Sandage (ELS), in 1967, which forms the halo and the continued collapse will form the disk of the galaxy. They proposed that the collapsing time scale to be shorter than the galactic rotation time scale ($\sim 2 \times 10^8$ yr), but longer than the evolutionary time scale for the massive stars. This allows for metallicity increase of the stars formed later. In the observed correlation of orbital eccentricity, the vertical velocity of the stars and the metallicity were the supporting evidences of the ELS model. Searle & Zinn (SZ 1978), proposed a hierarchical merging and accretion model for the formation of the galaxy, based on the observed metallicity gradient and the Horizontal Branch (HB), morphology of the globular clusters. They did not find any metallcity gradient in the outer halo clusters and found significant difference in the HB morphology of the inner and outer halo clusters. This indicates that there is considerable age difference between the inner and outer halo (Zinn 1993). Recently, Carollo *et al.* (2007) and Beers *et al.* (2012) have also found such dichotomy in the field stars of the halo. In recent years, the SZ model received a firm cosmological footing. Though ΛCDM is successful at large scales, at galactic scale the observations indicate the workings of both the models.

Another way to probe the ancient halo is through the chemical tagging of elements. The abundance ratio of different elements are sensitive to the masses of the supernovae and AGB stars which may have contributed to the chemical evolution of the galaxy. Here, we try to derive possible connection between the chemical and kinematical evolution of the smooth halo (the field halo stars) and substructures like the globular clusters, streams and satellite galaxies of Milky Way in the making of the halo.

2. The halo metal poor stars

Halo stars are metal poor with a mean metallicity of [Fe/H] ~ -1.6. They have an average [α/Fe] ratio ~ 0.4. This indicates that halo was formed much before the SN Ia supernovae contribution to the galaxy. Carollo *et al.* (2007, 2010, 2012, 2013), based on the SDSS (Aihara *et al.* 2011) data, found two distinct halo components which are overlapping entities. They have distinct kinematics and chemical properties. The outer halo stars are more metal-poor than the inner halo stars.

2.1 *Inner and outer halo*

Over a large range of metallicities ($-1.0 <$ [Fe/H] < 4.0), Carollo *et al.* (2010) found that the inner halo dominates the outer halo at galacto-centric distances < 10–15 kpc, with a peak metallicity distribution at [Fe/H] $= -1.6$. The inner halo stars

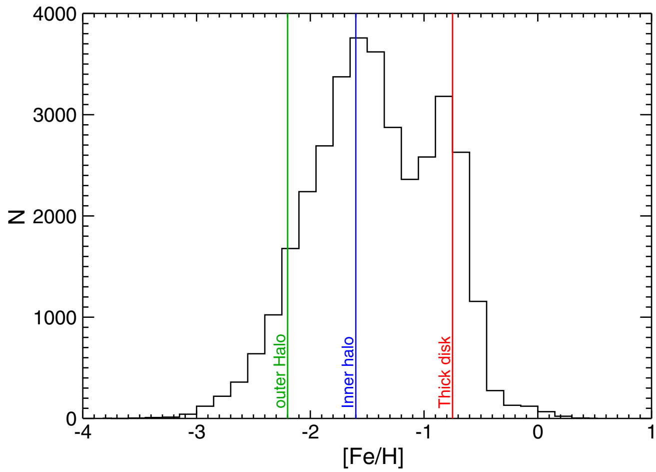

Figure 1. The observed metallicity distribution is shown. The data is from SDSS-DR8 calibration sample. We can clearly see the thick disk and the dominant inner halo peak. There is also a clear peak of the outer halo peak at [Fe/H] $= -2.2$, if we plot stars beyond 15 kpc galacto centric radius.

have slightly prograde rotation. The outer halo starts to dominate at distances > 15–20 kpc, with a metallicity peak at [Fe/H] $= -2.2$ (see Fig. 1 based on SDSS data). The outer halo stars have retrograde rotation and have a more uniform distribution of eccentricity and spatial distribution which is more spherical. Kinman *et al.* (2012), based on the Blue Horizontal Branch stars (BHB) and RR Lyrae, also found the transition from the inner and outer halos. An *et al.* (2013) from SDSS Stripe-82 data found a similar metallicity distribution function, with a peak around [Fe/H] $= -1.6$ and [Fe/H] $= -2.2$ corresponding to the inner and outer halo stars. Based on the SEGUE data of the vertical stripes, de Jong *et al.* (2010), also found the metallicity shift as a function of galactocentric distance and confirmed the results of Carollo *et al.* (2007). They fit a color-magnitude diagram in order to trace different stellar population and derived a Metallicity Distribution Function (MDF). They found that the mean metallicity of the halo is [Fe/H] $= -1.6$ for galactocentric distances $R <$ 15 kpc and the value becomes [Fe/H] $= -2.2$ at larger distances.

Carollo *et al.* (2007) proposed a dissipative radial merging of few massive sub-galactic fragments, for the formation of the inner halo. The merging event happened at an early stage of the galaxy before the SN-Ia started to contribute. The inner halo stars formed mainly *in situ* during the merging event. Dissipationless chaotic merging of small sub-systems within a pre-existing dark matter halo, was proposed as an origin of outer halo stars. These are mainly accretion in origin.

2.1.1 *Chemical abundances of the inner/outer halo.* Apart from different metallicity distribution of the inner and outer halo stars, they also show distinct differences in the chemical abundances of many other elements. Their abundances can not be simply explained by the time evolution of the halo (younger metal-rich inner halo and an older metal-poor outer halo). It looks like the inner and outer halos represent distinctly different stellar population with a different origin.

Nissen & Schuster (2010), found that the inner halo stars have higher [α/Fe] ratios, similar to the thick disk stars which are of the same metallicities. However, the α poor halo stars show kinematics similar to the outer halo stars (see Fig. 2). Using simulated stellar halos, Zolotov *et al.* (2010) showed that for metallicites [Fe/H] $>$ -1.5, the inner halo stars are more alpha-rich than the outer (accreted) halo stars at similar metallicities. At lower [Fe/H] < -2.0, the two populations exhibit similar [α/Fe] ratios. They explained that the bimodal distribution of [α/Fe] of the two halo populations is primarily due to a mass-metallicity relationship. The inner halo stars which are formed *in situ* in the Milky Way halo would have had a high star formation rate, whereas accreted stars were formed in less massive galaxies with less efficient star formation. The different formation environments result in a decrease of [O/Fe] at a lower [Fe/H] for accreted stars than for *in situ* stars. These trends do not hold if the primary galaxy had experienced a recent major merger. The bright dwarf spheroidals (dSph) around the Milky Way have stars which are much more α-poor compared to the halo stars of the same metallicities (Tolstoy *et al.* 2009). Hence, the α-poor halo stars might have come from accretion of stars from satellite galaxies similar to the bright dSph galaxies we see around the Milky Way.

Roederer (2009) found that there was an increased scatter in the abundances of the outer halo stars, compared to the inner halo stars. This is consistent with that proposed by Zolotov *et al.* (2010) that lower scatter (for the inner halo stars) due to the *in situ* formation of mixed gas and higher scatter (for the outer halo stars) due to accretion of stars from different satellite galaxies, might have had a range of masses

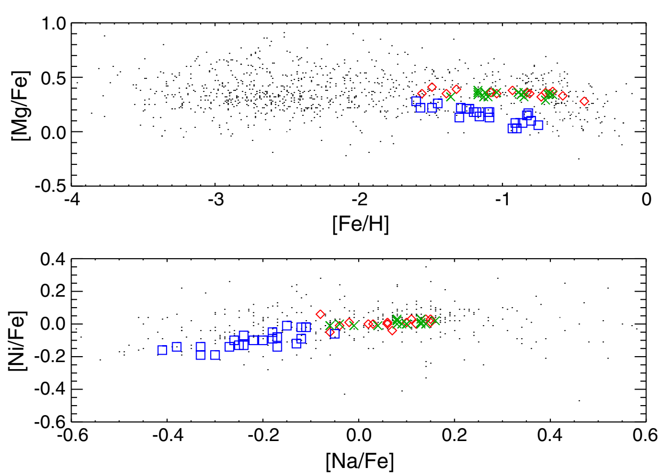

Figure 2. The plot is adopted from Nissen & Schuster (2010). The alpha poor stars which belong to the outer halo kinematics are plotted in blue. The inner halo stars in red and the thick disk stars are shown in green. The black points are the data compiled from the SAGA database (Suda *et al.* 2008). In the top panel, thick disk and the inner halo stars show high [Mg/Fe] ratios, compared to the outer halo stars. The bottom panel shows that the Na and Ni abundances for the inner and outer halo stars are very different. The inner halo stars have similar ratios as that of the thick disk stars.

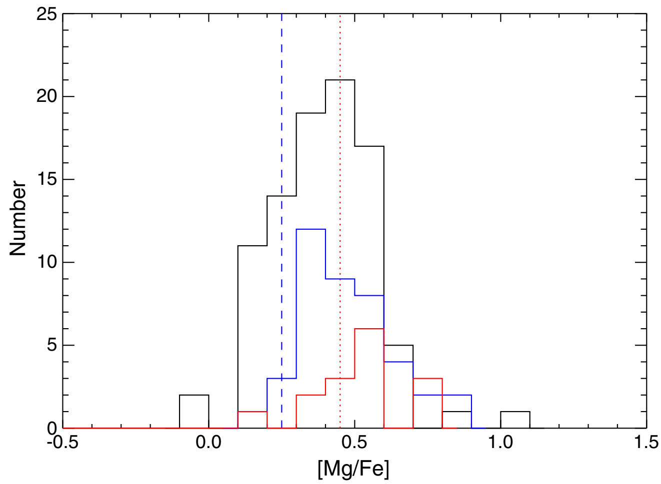

Figure 3. The plot shows the distribution of [Mg/Fe] for halo stars in the range $-1.0 <$ [Fe/H] < -2.0. The histogram shown in black are from the SAGA database (Suda *et al.* 2008). The vertical dotted and dashed lines represent approximated peaks in [Mg/Fe] for the inner and outer halo stars. The blue (outer halo) and red (inner halo) histograms correspond to stars with galactocentric distance $d > 7$ kpc and $d < 7$ kpc respectively, using online data from Ishigaki *et al.* (2010).

and star formation history. Ishigaki *et al.* (2010), showed that the outer halo stars (accreted stars) show lower [α/Fe] compared to the inner halo stars (see Fig. 3). Nissen & Schuster (2010) showed that Na and Ni abundances in the inner and outer halo stars are quite different (see Fig. 2). The data from Roederer (2009) also showed that for the metal-poor stars below [Fe/H] < -2.0, the abundance ratios of the inner and outer halos are very similar. This might mean that halo stars below [Fe/H] < -2.0 have similar origins. The metal-poor halo is primarily originating from the accretion of merging events compared to the dominant *in situ* formation of the halo at metal-rich end (above [Fe/H] > -1.5). This would indicate that the properties of the satellite galaxies accreted during these epochs are quite different compared to the accreted satellites during the metal-rich phase of the galaxy.

2.2 *Carbon enhancement in the inner and outer halo stars*

Recently, Carollo *et al.* (2012), compared carbon abundances of the inner and outer halo stars to much lower metallicities. The authors show that the outer halo stars are more enhanced in carbon abundance compared to the inner halo stars, for a given metallicity. The frequency of carbon enhanced stars in the outer halo is double compared to the inner halo. They also found that all the stars below [Fe/H] < -4.0, belong to the outer halo and 90% of them are carbon-rich.

Carbon abundance derived from SDSS spectra for the calibration sample (same as used in Carollo *et al.* 2012) is shown in Fig. 4. We can see that the frequency of Carbon Enhanced Metal-Poor stars (CEMP) increases at low metallicites. The frequency increases from 5% at [Fe/H] $= -1.6$ (the MW halo metallicity) to 20% at [Fe/H] $= -2.5$. Carollo *et al.* (2012) showed that halo stars with the kinematics

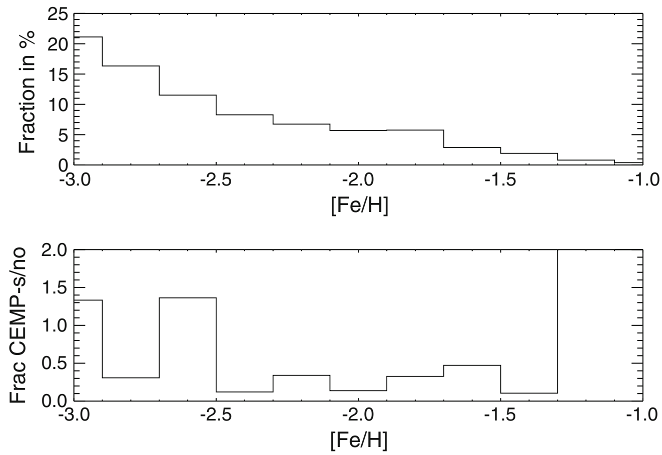

Figure 4. The top panel shows the fraction carbon enhanced stars ([C/Fe] $>$ 1.0), at different metallicities, using the carbon abundances derived from SDSS spectra. One can clearly see the increase in the fraction of carbon enhanced stars at low metallicities, reaching up to 20% below [Fe/H] < -2.5. In the bottom panel, we show the relative frequency and CEMP-s (stars which have C and s-process enhancement mainly through AGB binary mass transfer) and CEMP-no stars (stars which show only carbon enhancement without and s-process, likely through massive star contribution). An increase in the frequency of AGB contribution is seen at [Fe/H] ~ -2.5. The peak at [Fe/H] $= -3.0$, is due to lack of barium detection due to weak lines at low metallicities.

of the inner halo has lower CEMP frequency compared to the MW outer halo stars. They also showed that the CEMP frequency also depends on the galactic scale height, apart from the metallicity. For a given metallicity, the CEMP frequency increases at larger scale heights.

High resolution follow-up studies of CEMP stars show that about 80% of them are rich s-process elements (Sivarani *et al.* 2004; Aoki *et al.* 2008, 2013; Masseron *et al.* 2010). Hence, these stars might have had low mass (1–3$M_\odot$) AGB binary mass transfer. These AGB stars produce copious amount of carbon and s-process elements. Possible reasons for increased CEMP frequency could be due to change in IMF at low metallicities (Lucatello *et al.* 2005; Komiya *et al.* 2007). Studies of local star formation (Larson 2005; Jappsen *et al.* 2005), suggest that characteristic mass of stars, depends on the minimum cooling temperature at which the gas becomes optically thick to cooling radiation and gets thermally coupled to dust. At low red-shifts the minimum temperature is set by the metal cooling and dust ($Z_{\rm min} = 10$ K), however at higher red-shifts CMB temperature itself, can act as a minimum ceiling for the gas cooling. Thus stars formed in the Milky Way earlier to $Z > 5.0$ will be affected (Tumlinson 2007) However, Pols *et al.* (2012) showed that any change in the IMF would mean an increase in the number of nitrogen-enhanced metal-poor (the so-called NEMP stars) stars. NEMP stars are nitrogen-rich metal-poor stars, which have AGB binary which is of intermediate mass (4–8$M_\odot$). These AGB stars go through hot bottom burning and have enhanced nitrogen abundances and depletion of carbon. However, observations indicate only a very few NEMP stars (e.g. Sivarani *et al.* 2006; Masseron *et al.* 2006; Johnson *et al.* 2007).

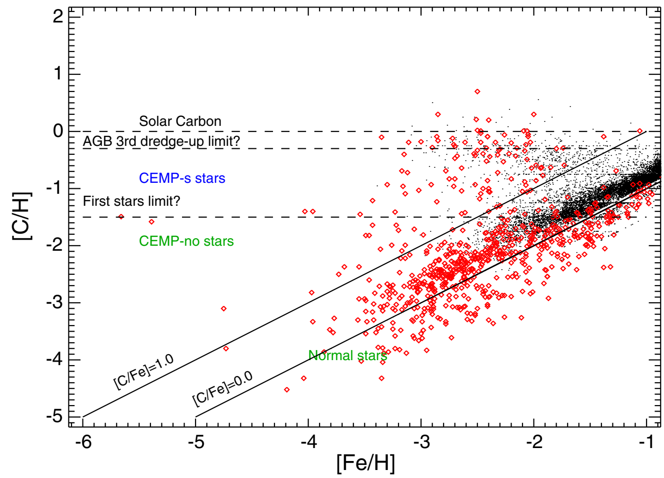

Figure 5. The figure is adopted from the recent work by Spite *et al.* (2013). The black dots are the carbon abundances derived from SDSS spectra. The red points are the carbon abundances derived from high resolution spectra, compiled by SAGA database.

Figure 5 shows the carbon abundances from the SDSS sample (in black) and from the high resolution spectroscopy (in red).) The black line indicates the solar ratios for carbon ([C/Fe]=0, showing that carbon abundance decreases with decreasing metallicity. If there was no change in the IMF, then most stars will have values closer to [C/Fe]=0.0. Clearly, we see many more stars above [C/Fe]=0. This indicates increased contribution of carbon, relative to iron at low metallicities.

The horizontal lines indicate two possible plateau in the carbon abundances. The AGB plateau is due to AGB mass transfer and the plateau indicates the third dredge-up limit. Spite *et al.* (2013) showed in their recent work that there is likely another plateau corresponding to carbon enhancement due to massive first stars, which is seen in stars which do not show s-process enhancement (CEMP-no stars). If this is true, the CEMP-no stars can be the most pristine objects.

In order to understand the origin of the CEMP stars, we derived barium abundance for a subset of stars, with spectra above $S/N > 20$ (in Carollo *et al.* 2012). In Fig. 6, the stars that lie closer to the AGB plateau have high barium abundances, which clearly points to AGB mass transfer for the high C and s-process abundances.

In Fig. 4, one can see the fraction of CEMP stars and CEMP-s/CEMP-no stars. CEMP stars increase at low metallicities. The CEMP-s stars (AGB mass transfer binaries), have a maximum contribution [Fe/H] ~ -2.5. If one can further estimate the fraction of CEMP-s/CEMP-no stars in the inner and outer halos, that will give better insights to the origin of carbon in the early halo stars. Observation of ultra-faint satellite galaxies around the Milky Way shows that they have high fraction of CEMP stars (e.g. Lai *et al.* 2011; Norris *et al.* 2010).

2.2.1 *Possible origin of the carbon at very low metallicities.* Discovery of a carbon-rich metal-poor damped Lyα system at red-shift $z \sim 2.5$, indicate that massive stars must have contributed to carbon enhancement. AGB stars do not contribute to ISM

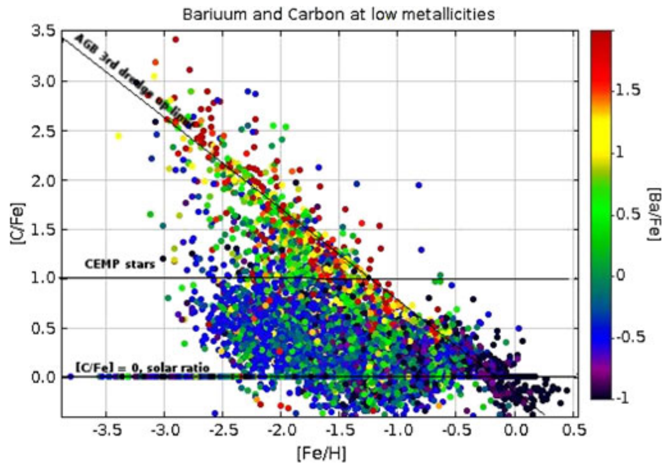

Figure 6. The plot shows the carbon enhancement along with enhancement in [Ba/Fe], in different color codes. Stars which have high carbon abundances closer to the AGB 3rd dredge-up limit, have high [Ba/Fe], clearly pointing to the fact these stars have got their carbon and s-process abundances through AGB binary mass transfer.

before $z > 1.8$ (Kobayashi *et al.* 2011). Meynet and collaborators propose fast rotating massive star (spinors) winds as a possible mechanism for carbon production. Many observed abundances in metal-poor stars indicate rotation mixing of massive stars. The observed low $^{12}C/^{13}C$ ratio and s-process at low metallicity may be possible evidences of spinors at work. However, the data is not sufficient to make a choice between the faint supernovae model over the spinors, for the early production of carbon.

3. Globular clusters

Globular clusters are very old system of the galaxy. They might have formed when the Universe was just 1–2 Gyrs old. There are two different population of globular clusters in our galaxy. They are different in their age, location and metallicity. Bimodal distribution in the metallcities of the globular clusters is known for a long time. The metallicity peaks around [Fe/H] ~ -1.6 and -0.6. The age spread among the metal-poor (blue and old) clusters is smaller in the range of 1–2 Gyr. However, the metal-rich (red and younger) clusters have a significant age spread of about 6 Gyr (Dotter *et al.* 2010). The more metal-rich clusters are systematically younger and are located within a few degrees of the galactic plane. Gnedin and collaborators, based on a hierarchical cosmological simulations of galaxy formation were able to reproduce some of the observed properties of globular clusters. They propose that the metal-poor older clusters are formed within a low mass dwarf galaxy, which merged into the bigger host galaxy. Only the massive clusters could survive the merging event and the low mass clusters would have dissolved into the halo field of the bigger galaxy. The metal-rich clusters are formed through few, but massive and dissipative merging events. With this model they were able to reproduce the bimodality in the metallicity distribution.

3.1 *Globular cluster's contribution to the halo stars*

Carollo *et al.* (2013) have studied the contribution of dissolved globular clusters to the formation of a halo. Since globular cluster stars have very different chemical abundance, especially the lighter elements, compared to the halo stars, they can be used to identify the globular cluster stars. They studied the kinematics and orbital properties of a sample of red giants in the halo of the Milky Way that are thought to have formed in globular clusters, based on their anomalously strong UV/blue CN bands. The CN-strong field stars and the globular clusters both exhibit kinematics and orbital properties similar to the inner-halo population, indicating that stripped or destroyed globular clusters could be a significant source of inner-halo field stars, suggesting that both the CN-strong stars and the majority of globular clusters are primarily associated with this population.

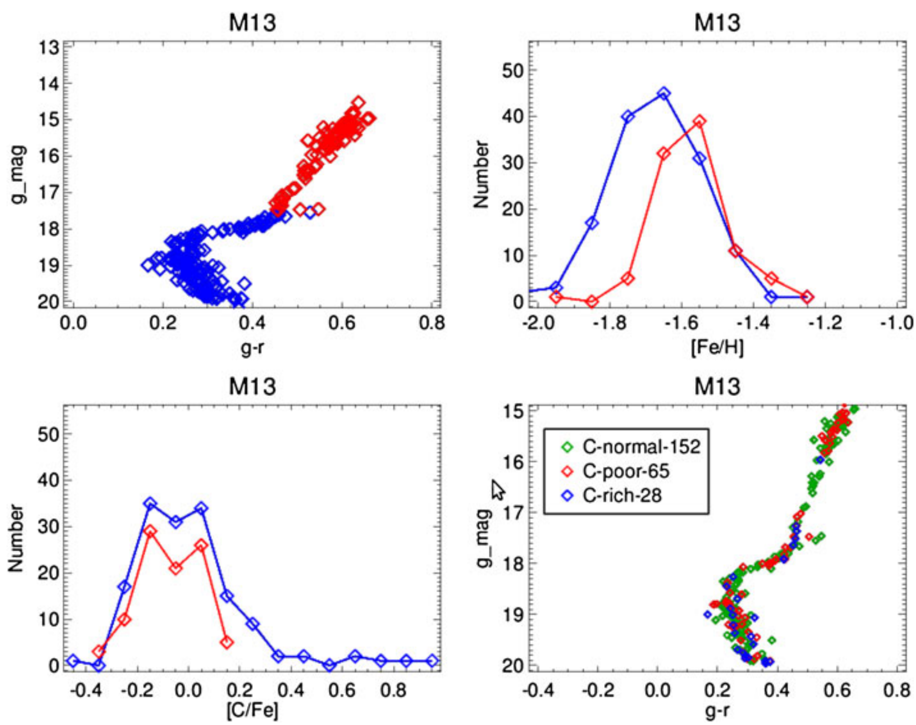

Figure 7. The plot shows [C/Fe] for M13, along the color magnitude diagram (CMD). The stars which are in the main sequence and sub-giant branches are shown in blue. They do not go through 1st dredge-up which might alter their initial C and N abundances through CN processing. The red points are stars which belong to the Red Giant Branch (RGB), they might have gone through 1st dredge-up. The results in the bottom right panel show that there is a large spread in the [C/Fe], values throughout the CMD, indicating it could be primordial. There are some systematics in the metallicities of RGB and main sequence stars, which needs further detailed analysis. However the spread in the [C/Fe] abundances will not change, as the systematic errors in [Fe/H] and [C/H] cancel each other.

3.2 *Chemical abundances and the stellar population of globular clusters*

Globular clusters were thought to be homogeneous systems with a single stellar population. However, recent results based on precise photometry from HST suggest the presence of more than one stellar population among globular cluster stars. These stars have a different abundance pattern compared to halo stars of similar metallicities. Within a cluster the stars have same metallicity (e.g Fe), however they have a wide range of light element abundance (see Gratton *et al.* 2012 for a detailed review). It is still difficult understanding how to form multiple population within existing high stellar density. To understand globular cluster formation, in the context of hierarchical galaxy formation models, it is necessary to understand the origin of their abundance pattern. However, the interpretation of the globular clusters seem much more complex than field stars. Fiorenza *et al.* (2013) used the SDSS spectra from Data Release-8 to estimate the carbon abundances for 5 globular clusters. They find large spreads in carbon abundances throughout the CMDs of the clusters, indicating multiple populations with different carbon abundances (see Fig. 7).

4. Ultra-faint dwarfs (UDFs)

Wide-field modern surveys like SDSS has been successful in detecting faint substructures in the galaxy. These surveys have extended the low luminosity end of the satellite galaxies closer to that of the globular clusters ($M_v \sim -4$). These new class of Ultra Faint Dwarf (UDFs) galaxies appear to be an extension of the classical dwarf spheroidals to low luminosities. They are the low luminous, most dark-matter dominated, and least chemically-evolved galaxies known. Brown *et al.* (2012) based on HST photometry of these galaxies showed that they are at least as old as M92 globular cluster. They do not host intermediate age population. The age spread among their stellar population is less than 1 Gyr. This could be due to truncation of star formation due to a global event like reionization. With high resolution follow-up of the individual stars of these satellite galaxies, it is now possible to compare the chemical abundances of the stars in these satellites with that of the halo stars (e.g. Kirby *et al.* 2011a, b). The kinematic studies of these systems (e.g., Simon & Geha 2007) show evidence that they are more dark matter-dominated with M/L 100–1000. The average stellar metallicities ([Fe/H] $\leq$ 2) is lower than in most globular clusters. The spread in the metallicities is much more than the globular clusters. The average metallicities are also lower than in other more luminous dwarf galaxies (see also Kirby *et al.* 2011a), and the lowest metallicity stars appear to be more metal-poor than most metal-poor stars found in the brighter classical dSphs.

The abundances of the individual stars show that their alpha abundances [α/Fe] are high. This indicates that they might have had a high star formation rate. One of the major challenges for chemical evolution models of dwarf galaxies has always been to reconcile their low observed metallicity with the fairly high SFR of most metal-poor systems. There has been several models proposed. A metal-rich gas outflows triggered by supernova explosions in systems with shallow potential wells will be an efficient way to remove the metal-enriched gas from the system.

Thus the nature of some of the UFds still remains a mystery. Norris *et al.* (2010) also found evidence for carbon-rich metal-poor stars in Segue-I. Lai *et al.* (2011)

found that the CEMP fraction of Boo-I is about 12%. This suggests that the metal-poor stars in UFds may be more similar to those found in the MW halo, where a large fraction of stars at low metallicity are carbon-rich. Almost 90% of stars below [Fe/H] < -4.0 are carbon-rich and belong to the outer halo (accretion origin). Massive faint supernovae and a spinor scenario proposed for early carbon production can also play an important role in removing the metal-rich gas out of the galaxy.

5. Summary

We discussed the properties of the smooth halo component of the Milky Way field stars, which contain inner and outer halos. We also discussed the globular clusters and satellite galaxies of MW, and its contribution to the halo.

The inner halo might have either formed *in situ* or due to accretion stars and gas from few massive mergers. This is based on the observed low scatter in the chemical abundances of the inner halo stars.

The major merging events should have happened much before the SN-Ia supernovae contribution, since the halo stars have high [α/Fe] ratios.

The outer halo stars stars are formed due to dissipation-less minor dry mergers, due to the observed spherical distribution and the retrograde orbits of them around the galaxy.

The low alpha abundances of the outer halo stars at higher metallicity is due to accretion of low mass satellites similar to the bright dSph galaxies around the Milky Way. They have low star formation rate and hence low [α/Fe] ratios.

At low metallicities though the α abundances of the inner and outer halos overlap, and there may be differences in the carbon abundances of the inner and outer halo stars.

At low metallicities the high carbon and high alpha abundances of the halo stars indicate that satellite galaxies similar to the UFDs might have been the major contributors to the accreted halo. The UFDs have high CEMP frequency and high [α/Fe].

The very low metallicity tail of the galaxy primarily originate from accreted satellite galaxies.

The two population of globular clusters we see in the galaxy might have come from the mergers of galaxies similar to UFDs for the metal-poor blue clusters and the bright dSph for the red- and metal-rich clusters.

Still the origin and the nature of these UFDs is not clear. Globular cluster evolution is much more complex and forming them through the hierarchical galaxy formation is still a challenge.

Larger planned surveys, like GAIA, HERMES and ngCFHT (next generation CFHT) will soon revolutionize our understanding of galaxy formation and probe the early stages of its infancy.

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