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Accreted versus *In Situ* Milky Way Globular Clusters

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ABSTRACT

A large, perhaps dominant fraction, of the Milky Way's halo is thought to be built-up by the accretion of smaller galaxies and their globular cluster (GC) systems. Here we examine the Milky Way's GC system to estimate the fraction of accreted versus *in situ* formed GCs. We first assemble a high quality database of ages and metallicities for 93 Milky Way GCs from literature deep colour-magnitude data. The age-metallicity relation for the Milky Way's GCs reveals two distinct tracks – one with near constant old age of ∼12.8 Gyr and the other branches to younger ages. We find that the latter young track is dominated by globular clusters associated with the Sagittarius and Canis Major dwarf galaxies. Despite being overly simplistic, its age-metallicity relation can be well represented by a simple closed box model with continuous star formation. The inferred chemical enrichment history is similar to that of the Large Magellanic Cloud, but is more enriched, at a given age, compared to the Small Magellanic Cloud.

After excluding Sagittarius and Canis Major GCs, several young track GCs remain. Their horizontal branch morphologies are often red and hence classified as Young Halo objects, however they do not tend to reveal extended horizontal branches (a possible signature of an accreted remnant nucleus). Retrograde orbit GCs (a key signature of accretion) are commonly found in the young track. We also examine GCs that lie close to the Fornax-Leo-Sculptor great circle defined by several satellite galaxies. We find that several GCs are consistent with the young track and we speculate that they may have been accreted along with their host dwarf galaxy, whose nucleus may survive as a GC. Finally, we suggest that 27-47 GCs (about 1/4 of the entire system), from 6-8 dwarf galaxies, were accreted to build the Milky Way GC system we seen today.

1 INTRODUCTION

In a ΛCDM Universe, Milky Way-like galaxy halos are built up by the accretion of smaller galaxies (Bullock & Johnson 2005; Abadi et al. 2006; Font et al. 2006). These small galaxies contain dark matter, stars, gas and in some cases globular clusters (GCs). Although the dwarf galaxy may be completely disrupted, the high density of some GCs allows them to survive the accretion process (Penarrubia, Walker & Gilmore 2009). They will then add to any pre-existing globular cluster population (Searle & Zinn 1978; Abadi et al. 2006). However, galaxy halos will also include a contribution from stars and clusters formed *in situ* within the host galaxy. Simulations suggest that the transition from an *in situ* to accretion-dominated stellar halo occurs at a galactocentric radius of ∼ 20 kpc for a Milky Way-like galaxy (Abadi et al. 2006; Zolotov et al. 2009).

In the recent simulation of four Milky Way-like halos, Zolotov et al (2009) found the accreted fraction of the halo stellar mass to be 30-85%, with the large variation due to differences in the merger history of the four halos. These accreted stars tended to be acquired early on, and are mostly in place 9 Gyr ago. The *in situ* stars, on the other hand,

generally formed at very early epochs and are more than 11.5 Gyr old.

Observationally, there is now good evidence for the accretion and disruption of dwarf galaxies in the form of several stellar streams having been detected (Helmi et al. 1999; Newberg et al. 2002; Duffau et al. 2006; Grillmair 2009), the most famous of which is associated with the Sagittarius dwarf spheriodal galaxy (Ibata, Gilmore & Irwin 1994). Recently, Carollo et al. (2007) have presented evidence from the SDSS for a dual nature of our Galaxy's inner and outer halo; with the outer halo indicating more retrograde motions and lower metallicities indicative of the accretion of low-mass galaxies. Streams, from disrupted dwarfs, have also been detected in the halo of the Andromeda galaxy (McConnachie et al. 2009).

Perhaps the 'gold standard' in searching for evidence of disrupted dwarf galaxies and their GCs, is via integrals of motion. These energy and angular momentum parameters are largely invariant to phase mixing and hence survive intact for many orbits (Helmi & de Zeeuw 2000). However, their use is limited as the full orbital information is often not available and assumptions about the Galactic potential are required. A phase-space search is a more practical method, although it is limited by the accuracy of the orbital model of

the disrupted object. Integrations backwards and forwards in time become increasingly less certain.

Alternative signatures of accreted GCs may include the Oosterhoff type (Catelan 2005), peculiar element ratios (Pritzl et al. 2005), ellipticity, size and luminosity (Mackey & van den Bergh 2005), and horizontal branch class and kinematics (Mackey & Gilmore 2004). Despite the strong evidence for accretion, observational estimates of the mass fractions involved are difficult to quantify. From their study of the Milky Way GC system, Mackey & Gilmore (2004) suggested that 41 (27%) of the Milky Way's GCs were accreted and their host dwarf galaxies were responsible for roughly half of the current halo stellar mass. Using blue halo stars, Unavane, Wyse & Gilmore (1996) suggested an accretion fraction closer to 10%.

The age-metallicity relation (AMR) of a galaxy can also be used to constrain its evolutionary history via the chemical enrichment of its constituent stars and clusters. The exact shape of the AMR is determined by the complex interplay between Iron injected into the ISM by SN Ia and Iron lost/gained via any outflows/accreted gas (e.g Lanfranchi & Matteucci 2004). These are in turn affected by the depth of the potential well and tidal interactions with another galaxy or the intragroup medium. For example, interactions can lead to a burst of star formation as gas is funneled into the galaxy centre (Mayer et al. 2001; Forbes et al. 2003; Mayer 2009). Tidal interactions between the Magellanic Clouds and the Milky Way may have been responsible for the formation of young/intermediate age star clusters in the Clouds (Bekki et al. 2004).

For 'massive' Local Group dwarfs, such as Sgr, the review of Mayer (2009) concludes they are largely shaped by tidal effects. Over a few Gyr, tidal shocks induce an instability which drives new star formation. The outer layers of the galaxy can be lost before complete disruption. Previous work on the Sgr dwarf galaxy has shown that it continued to form field stars and star clusters as it interacted, and ultimately accreted, with the Milky Way over a period of several Gyrs (Layden & Sarajedini 2000; Siegel et al. 2007). Models of the Sgr orbit also suggest a long orbital timescale (Helmi & White 2001; Fellhauer et al. 2006). In Forbes et al. (2004) we showed that the Sgr dwarf and the accreted Canis Major (CMa) dwarf galaxy revealed a very similar, well-defined AMR. It is therefore a powerful tool in which to identify accreted GCs via their measured age and metallicity.

In this work we compile a new catalogue of age and metallicity measurements for Milky Way GCs from published analysis of deep colour-magnitude diagrams. We use this catalogue to revisit the AMR of the Sgr and CMa dwarfs. After removing the GCs that can be confidently associated with these two 'accretion events' we proceed to examine the AMR of the remaining Milky Way GCs. In particular, we focus on those with retrograde motions, extended horizontal branches and those associated with the Fornax-Leo-Sculptor great circle. Finally, we estimate the accreted vs *in situ* fractions for Milky Way GCs.

2   A DATABASE OF GLOBULAR CLUSTER AGES AND METALLICITIES

New *relative* ages for 64 Milky Way GCs have recently been determined using deep ACS imaging from the *Hubble Space Telescope* (HST) by Marin-Franch et al. (2009). These data were sufficiently deep to derive ages from the main sequence turnoff and form a high quality homogeneous database. The mean *absolute* age of the metal-poor GCs is 12.80 Gyr (using the Dartmouth models of Dotter et al. 2007), which we adopt as the normalisation to derive absolute ages. Note, that in some cases the relative age is greater than the normalisation value, with the oldest absolute age in their sample being 14.46 Gyr (albeit with a large error of $\pm$ 1.8 Gyrs). The typical error quoted is closer to $\pm$ 0.5 Gyr. We use Carretta & Gratton (1997; CG) based [Fe/H] metallicities as given by Marin-Franch et al. but we do not convert these into [M/H] as they have done.

The main limitation of the ACS study above was that the GCs were restricted to be within $\sim$ 20 kpc of the Galactic centre. We have chosen to supplement these data with the relative ages of 13 GCs from de Angeli et al. (2005), again assuming a normalisation age of 12.8 Gyr. Marin-Franch et al. show that their ages are consistent, within errors, with the full sample of de Angeli et al. Absolute ages and metallicities for a further 10 GCs are taken from Salaris & Weiss (1998). The typical age error here is larger at $\pm$ 1.3 Gyr.

The above data are supplemented by high quality colour-magnitude diagram studies of individual GCs. The age and metallicity for the GCs Whiting 1 and AM 4 are taken directly from Carraro et al. (2007) and Carraro (2009) respectively. For NGC 5634, Bellazzini, Ferraro & Ibata (2002) derived a CG metallicity of [Fe/H] = –1.94 and an age similar to that of the GCs NGC 4590 and Terzan 8. Taking the average of the Marin-Franch et al. ages for these two GCs, i.e. 11.52 and 12.16 Gyr respectively gives 11.84 Gyr for NGC 5634. We also include two outer GCs from the deep HST study of AM 1 and Pal 14 from Dotter, Sarajedini & Yang (2008). We use their age estimates and convert their Zinn-West metallicities using Carretta & Gratton (1997) to get [Fe/H] = –1.47 for AM 1 and –1.36 for Pal 14. Catelan et al. (2002) derive a CG metallicity of [Fe/H] = –1.03 for NGC 6864 (M75) and an age coeval with NGC 1851, i.e. 9.98 Gyr. Thus our final sample of GCs with age and metallicity measurements totals 93 and is dominated by the recent ACS data.

In Fig. 1 we show the age-metallicity distribution of our sample of 93 GCs, coded by the different data sources. The Salaris & Weiss (1998) data are on average younger than the other data sources, however this is partly due to the fact that the GCs included from their survey tend to be 'young halo' objects at relatively large galactocentric distances. The distribution shows a relatively constant old age for the most metal-poor GCs. For the ACS data, Marin-Franch et al. (2009) measured a rms dispersion of only $\pm$0.64 Gyr for the most metal-poor GCs. At [Fe/H] $\sim$ –1.5 there is a track to younger ages (which is particularly tight if only the ACS data are considered) and, after a small gap in metallicity, a group of metal-rich GCs at old ages. The latter group are largely associated with the bulge of the Milky Way (see Minniti 1995 and Côté 1999 for further details), although some may be inner halo objects (Burkert & Smith 1997).

Our final sample includes almost 2/3 of the known GCs in the Milky Way. In Fig. 2 we compare the metallicity distribution for 148 GCs from the latest version of the Harris (1996) catalogue with our final sample. Although we have converted the Harris quoted metallicities from the Zinn & West scale to the Carretta & Gratton (1997) scale, slight differences will exist for individual GCs. Nevertheless, the histograms show that we sample well the low metallicity end of the distribution but we are under-represented by metal-rich GCs. A number of these GCs are located in the bulge, and the lack of good age determinations is probably due to the difficulty of obtaining deep colour-magnitude diagrams (due to foreground stars and extinction).

3 SAGITTARIUS AND CANIS MAJOR DWARF GALAXIES

3.1 Sagittarius (Sgr) dwarf galaxy

Since its initial discovery by Ibata, Gilmore & Irwin (1994), several GCs have been associated with the Sgr dwarf galaxy on the basis of their location in phase space compared to the predicted orbit of the dwarf (Bellazzini et al. 2003). They are Terzan 7, Terzan 8, Arp 2, Pal 12, NGC 4147 and NGC 6715 (M54), with the latter being the probable remnant nucleus (see also Bellazzini et al. 2008). To this list of 6 GCs we include the GC Whiting 1, which Carraro, Zinn & Moni Bidin (2007) have shown is consistent with the Sgr orbit in phase space.

Carraro & Bensby (2009) recently concluded that the outer disk open clusters (OCs), Berkeley 29 and Saurer 1, were also associated with the Sgr dwarf in phase space. Here we use the age and metallicity of these open clusters from their table 1. The Sgr dwarf galaxy reveals ongoing star formation in its field star population (Layden & Sarajedini 2000). Siegel et al. (2007) have derived new age and metallicity estimates for the Sgr field stars using the HST/ACS. We include their young/intermediate age field star populations.

Thus in revisiting the age-metallicity relation for the Sgr dwarf galaxy, we have updated data for 7 GCs, 2 OCs and 3 field star populations.

3.2 Canis Major (CMa) dwarf galaxy

Although its existence as a disrupted dwarf galaxy and its connection to the Monoceros overdensity is still the subject of debate (Mateu et al. 2009), there is good evidence supporting its distinct nature (Martin et al. 2004; Dinescu et al. 2005). Martin et al. (2004) found that four GCs (NGC 1851, 1902, 2298, 2808) occupied a tight location in phase space, close to their orbital model for CMa. Bellazzini et al. (2004) argued on the basis of position, distance and stellar populations that the old open clusters AM 2 and Tom 2 were also associated with the CMa dwarf. This was supported by F04. The field stellar population of CMa is currently less well constrained than for the Sgr dwarf, so we do not consider field stars further. We consider 4 GCs and 2 OCs initially associated with the CMa dwarf.

3.3 A combined Sgr and CMa AMR

In F04 we showed that the AMR for the Sgr and CMa dwarfs, as defined by their GCs, OCs and field stars, were very similar. In Fig. 3 we plot the open and globular clusters that can be confidently associated with these two disrupted dwarf galaxies using updated data as described above. We also include the data points for the young/intermediate field star populations in the Sgr dwarf from the HST/ACS study of Siegel et al. (2007). Finally, we include NGC 5634 and AM 4 as probable members of the Sgr dwarf, and NGC 4590, Pal 1 and Rup 106 as probable members of the CMa dwarf (see Section 3.4 and Table 1).

Fig. 3 shows that the updated data for the Sgr and CMa dwarfs continue to reveal a similar AMR for both galaxies which is remarkably tight over a large range in age and metallicity. This further supports claims that CMa is indeed a distinct feature (i.e. a remnant dwarf galaxy) and not simply an overabundance or warp in the Galactic disk. Both galaxies appear to have been forming stars and star clusters for $\sim$10 Gyr enriching from about 1/100 solar to solar metallicity.

We also show a simple closed box chemical enrichment model, with constant star formation from a starting age of 12.8 Gyr. A single AMR provides a good representation for the chemical enrichment history of both dwarf galaxies. We show a dispersion about the AMR of $\pm$ 0.64 Gyr which is the same as the rms dispersion of the metal-poor GCs in the ACS study of Marin-Franch et al. (2009). We note that the Sgr and CMa dwarfs have a similar luminosity of $M_V \sim -14$ (Bellazzini et al. 2006). So as well as a similar mass, they appear to have had a similar enrichment history. Below we refer to the combined Sgr and CMa AMR as the joint AMR.

The AMR of the Sgr dwarf has been modelled by Lanfranchi & Matteucci (2004), along with other Milky Way dwarf satellites. They suggested that Sgr had a particularly high star formation efficiency compared to other dwarfs and its chemical enrichment has proceeded continuously since its formation some 13 Gyr ago. Our results, combining field stars and clusters, supports this model.

3.4 Additional Sgr and CMa GCs

Given the tightness of the joint AMR we can use it as a diagnostic for helping to confirm the membership of other GC candidates that have been suggested on the basis of their location in phase space.

Carraro (2009) has suggested a possible association of the GC AM 4 with the Sgr dwarf although it lies at a somewhat higher galactic latitude than the Law et al. (2005) orbital model. As shown in Fig. 4, the age and metallicity of AM 4 are quite distinct from the general GC distribution but they are consistent with the joint AMR. Thus we support the suggestion of Carraro (2009) that AM 4 is associated with the Sgr dwarf.

Bellazzini, Ferraro & Ibata (2002) investigated the phase space location of NGC 5634 suggesting it may belong to the Sgr GC system. It is a metal-poor GC but somewhat younger than the general GC distribution and we tentatively support Bellazzini et al. claim and include NGC 5634 in the Sgr GC system.

The faint ($M_V \sim -2$) GC Koposov 1 is spatially nearby

to stars from the Sgr dwarf which led Koposov et al. (2007) to suggest an association. They quote stellar population estimates of $\sim$8 Gyrs and [Fe/H] $\sim$ –2. Such values deviate strongly from the joint AMR and so we conclude that Koposov 1 is very unlikely to be a member of the Sgr dwarf GC system.

Martin et al. (2004) identified several GCs that lie close to the favoured prograde orbit of the CMa dwarf in phase space (but see also Penarrubia et al. 2005 for alternative view). These potential CMa GCs are NGC 4590, 5286, 6205, 6341, 6426, 6779, 7078, 7089, IC 1257, Pal 1 and Rup 106. Our sample includes all except IC 1257. We show the remaining 10 GCs in Fig. 4, along with the joint AMR and main GC distribution. Of these GCs we support the association of NGC 4590, Pal 1 and Rup 106 based on their consistency with the joint AMR. We note that Pritzl et al. (2005) favours an extragalactic origin for NGC 4590 and Rup 106 on the basis of their peculiar alpha-element content. For the other 7 GCs, they may have an association with CMa but this can not be determined on the basis of their stellar populations as they overlap with both the joint AMR and the general AMR. So for now, we only include NGC 4590, Pal 1 and Rup 106 with the CMa dwarf.

Thus, we have added AM 4 and NGC 5634 to the Sgr dwarf GC system and NGC 4590, Pal 1 and Rup 106 to the CMa dwarf GC system. These GCs were included in the joint AMR shown in Fig. 3.

As summarised in Table 1, we assign 9 GCs to the Sgr dwarf and 7 to CMa dwarf. The specific frequency S_N assuming $M_V = -14$ for both galaxies would be 23 and 18 respectively. If we associate one GC with the nucleus of each dwarf (NGC 6715 for Sgr and NGC 2808 for CMa), then the S_N values would become 20 and 15. Although such values are high, they are similar to that for the Fornax dSph galaxy which has a system of 5 GCs for a luminosity of $M_V \sim -13$, giving $S_N \sim 30$. Other dwarf galaxies also reveal high S_N values (e.g. Durrell et al. 1996). We also note that high frequency values for dwarfs are less extreme when one considers the total GC mass normalised by the galaxy stellar mass (e.g. see Spitler & Forbes 2009).

Tables 2 and 3 list the age and metallicity of the remaining Milky Way GCs in our sample that we have not associated with either the Sgr or CMa dwarf galaxies. Most of the 'young track' GCs are no longer present, however there are still several GCs at intermediate metallicities with younger than average ages. These are prime candidates for accreted GCs, which we discuss further below.

4 MAGELLANIC CLOUDS

The small and large Magellanic (SMC, LMC) clouds are currently interacting with the Milky Way. This interaction may have served to dislodge some Magellanic cloud GCs, which we now associate with the Milky Way.

In Fig. 5 we compare the age-metallicity relations of the SMC and LMC with that of the joint AMR and the general distribution of Milky Way GCs. We include the average of the disk and bar region in the LMC from Carrera et al. (2008a) and the SMC from Carrera et al. (2008b). Metallicities come from Calcium triplet measurements on the Carretta & Graton (1997) scale. We also include the

Table 1. Sagittarius and Canis Major Star Clusters.

Name	Age (Gyr)	[Fe/H] (dex)	Source	Class	Member
Sagittarius					
NGC 6715	10.75	–1.25	1	YH	√ √
Terzan 7	7.3	–0.56	1	YH	√ √
Terzan 8	12.16	–1.80	1	OH	√ √
Arp 2	10.88	–1.45	1	YH	√ √
Pal 12	8.83	–0.83	1	YH	√ √
NGC 4147	11.39	–1.50	1	YH	√ √
Berk 29	4.5	–0.44	7	OC	√ √
Saurer 1	5.0	–0.38	7	OC	√ √
Whiting 1	6.5	–0.65	4	UN	√ √
AM 4	9.0	–0.97	5	UN	√
NGC 5634	11.84	–1.94	6	OH	√
Canis Major					
NGC 1851	9.98	–1.03	1	OH	√ √
NGC 1904	11.14	–1.37	2	OH	√ √
NGC 2298	12.67	–1.71	1	OH	√ √
NGC 2808	10.80	–1.11	1	OH	√ √
AM 2	5.0	–0.50	8	OC	√ √
Tom 2	2.0	–0.28	9	OC	√ √
NGC 4590	11.52	–2.00	1	YH	√
Pal 1	7.30	–0.70	1	BD	√
Rup 106	10.2	–1.49	3	YH	√

Notes: YH = young halo, OH = old halo, BD = bulge/disk, UN = unknown, OC = open cluster. √ √ = secure member on the basis of phase space, √ = probable member. 1 = Marin-Franch et al. (2009); 2 = de Angeli et al. (2005); 3 = Salaris & Weiss (1998); 4 = Carraro et al. (2007); 5 = Carraro (2009); 6 = Bellazzini et al. (2002); 7 = Carraro & Bensby (2009); 8 = Lee (1997); 9 = Frinchaboy et al. (2008).

7 SMC open and globular clusters from the ACS study by Glatt et al. (2008). We take their derived ages using Dartmouth isochrones (Dotter et al. 2007) and we convert their metallicities to the Carretta & Graton (1997) scale. We also include the 'age-gap' GC in the LMC from ACS data by Mackey, Payne & Gilmore (2006), taking their age estimate of 73% of the age for NGC 104 (47 Tuc). Both the SMC and LMC AMRs can be well represented by a simple closed-box model (Carrera et al. 2008a,b; Glatt et al. 2008).

The figure shows that the LMC has a similar AMR to that of Sgr and CMa dwarfs. The SMC AMR is systematically shifted to younger ages for a given metallicity. We conclude on this basis that it is very unlikely that Rup 106 (age = 10.2 Gyr, [Fe/H] = –1.49) was formerly an LMC member as suggested by Lin & Richer (1992). However, it may be associated with the SMC as suggested Fusi Pecci et al. (1995), or with the CMa dwarf as discussed above.

5 ZINN HORIZONTAL BRANCH MORPHOLOGY

Zinn (1993) separated the halo GCs on the basis of their horizontal branch (HB) morphology at a given metallicity, and assumed that this effect was driven by age. The so-called 'young halo' GCs have red HBs at fixed metallicity, tend to be located at large galactocentric radii and reveal a mean retograde motion in contrast to the prograde orbits of the 'old halo'. These properties have led many to suggest that

the young halo GCs have been accreted (e.g. van den Bergh 1993). On the basis of their spatial distribution and sizes, Mackey & Gilmore (2004) suggested that ∼16%, or ∼11, of the old halo GCs were also accreted.

Using the classification of either bulge/disk (BD), young halo (YH) or old halo (OH) as listed by Mackey & van den Bergh (2005), we show the age-metallicity diagram coded by HB class in Fig. 6. We also include NGC 5139 (Omega Cen) that Catelan (2005) list a HB ratio of +0.89 for, which indicates an OH classification for its metallicity.

The figure shows a clear separation between BD GCs at high metallicity and the halo GCs. The young halo GCs indeed have younger ages on average compared to old halo GCs. A couple of GCs classified as OH are located at younger ages than typical OH GCs (i.e. NGC 6712 and NGC 6535).

If we assume that all of the OH GCs that follow the joint AMR are accreted, then the number is about a dozen GCs, consistent with the estimate of Mackey & Gilmore (2004).

Mackey & Gimore (2004) found that YH GCs shared many traits of GCs in nearby dwarf galaxies, however we find that the Sgr and CMa GCs reveal a range of HB classes (see Table 1). The Sgr dwarf contains mostly YH GCs but also includes two OH GCs (Terzan 8 and NGC 5634). The CMa dwarf GCs are mostly OH, except NGC 4590 (YH) and Rup 106 (YH) and Pal 1 (BD). Thus the GCs which we are most confident were accreted, cover a range of HB classes. This suggests HB class is only a crude accretion indicator at best.

6 EXTENDED HORIZONTAL BRANCH (EHB) GLOBULAR CLUSTERS

EHBs in GCs appear to be due to the presence of a helium-enhanced population of stars and hence are a strong indicator for the presence of multiple stellar populations (Norris 2004; Piotto et al. 2005). Such multiple populations could be the result of enhanced enrichment in the nuclei of dwarf galaxies which have subsequently been stripped and accreted (Lee et al. 2007; Bekki et al. 2007). Lee et al. (2007) determined that 15 out of 114 (13%) GCs examined have evidence for a strong EHB. They are: NGC 2419, 2808, 5139 (Omega Cen), 5986, 6093, 6205, 6266, 6273, 6388, 6441, 6656, 6715 (M54), 6752, 7078 and 7089. NGC 2419 and 5139 (Omega Cen) have previously been associated with dwarf galaxy nuclei (Mackey & van den Bergh 2005).

After excluding the Sgr 'nucleus' (NGC 6715) and the suspected equivalent for CMa (NGC 2808), the age and metallicity of the remaining 13 EHB GCs are shown in Fig. 7. The figure shows that the EHB GCs have a wide range of metallicities. They are on average slightly younger with ages 11-12 Gyr, for a given metallicity, than the general distribution. This may be a reflection of age as the second parameter effect. Otherwise they are consistent with both the joint and general AMRs. Without the presence of associated young GCs, it is difficult to identify possible accreted GCs in a sample of EHBs using an age-metallicity analysis.

7 RETROGRADE MOTION GCS

GCs on retrograde orbits are prime candidates for having been accreted from a satellite on an initially retrograde encounter with the Milky Way. Perhaps the most well known retrograde motion case is NGC 5139 (Omega Cen). Taking into account the potential of the Milky Way bar, Allen et al. (2006, 2008) calculated the z component of the orbital angular momentum for 54 GCs (about 1/3 of the Milky Way GC system). They found 16/54 (30%) to be on retrograde orbits for their model of the Milky Way potential. They are: NGC 288, 362, 2298, 3201, 5139 (Omega Cen), 5466, 6121, 6144, 6205, 6316, 6712, 6779, 6934, 7089, 7099 and Pal 13. All are available in our sample except NGC 6316 and Pal 13. We note that none of these 16 GCs belong to the CMa or Sgr systems, except NGC 2298. However the detection of retrograde motion for NGC 2298 is of low significance and we continue to include it in the CMa GC sample. The location of the remaining 13 GCs with respect to the joint AMR are shown in Fig. 8. Note that for many of the other GCs shown in this plot the orbital properties are unknown and remain unclassified.

Five of the retrograde GCs are consistent with both the joint and general AMRs. However several are only well-described by the joint AMR. They are NGC 288, 362, 3201, 5139 (Omega Cen) 6205, 6712, 6934, 7089.

NGC 5139 (Omega Cen) is thought to be the remnant nucleus of a dwarf galaxy (Freeman 1993). Does it have associated GCs? Dinescu et al. (1999) noted that NGC 362 and NGC 6779 shared a similarly strong retrograde motion with Omega Cen for a low inclination. Remarkably both Omega Cen and NGC 362 lie directly on the joint AMR, whereas NGC 6779 is very metal-poor. According to the best fit models of Bekki & Freeman (2003), the progenitor dwarf galaxy had a luminosity of $M_V \sim -14.5$. This is similar to the predicted luminosity of both the Sgr and CMa dwarf galaxies. Although, galaxy mass is only one of many parameters that may determine a galaxy's AMR (Lanfranchi & Matteucci 2004), we tentatively support the suggestion that NGC 362 and NGC 6779 may be associated with the disrupted dwarf galaxy whose nucleus is now NGC 5139 (Omega Cen). We conclude that a retrograde orbit is a useful discriminant of an accreted GC and that larger samples of GCs with such information will be a useful addition to Galactic archaeology studies.

8 FORNAX-LEO-SCULPTOR GREAT CIRCLE

A great circle in the sky connects the Fornax, Leo (I and II) and Sculptor (FLS) galaxies (Lynden-Bell & Lynden-Bell 1995). Several recently discovered dwarf galaxies lie within a few degrees of the FLS great circle. They include Coma, CVn II, CVn and the disrupting GC Segue I. The dwarf Sextans also lies nearby. The FLS great circle given by Fusi Pecci et al. (1995) passes close to several GCs. Once the GCs associated with CMa dwarf are excluded, the 11 GCs nearest to the orbit are: NGC 1261, 6426, 6864, Pal 3, Eridanus, Pal 14, NGC 5053, 5024, AM 1, Pal 15 and Pal 4. Our sample includes all except Pal 15.

In Fig. 9 we show the location of these 10 GCs, along with the ∼10 Gyr old field stars in the Fornax galaxy from

Coleman & de Jong (2008). Seven of the 10 GCs reveal ages younger by ∼3 Gyr than the general distribution, and consistent with the field stars that formed ∼10 Gyr ago in the Fornax galaxy. These GCs account for most of the remaining intermediate metallicity objects that deviate from the general distribution.

One possibility is that some of these GCs were tidally stripped from the Fornax galaxy as it crossed the orbit of the LMC (Dinescu et al. 2004). A second possibility is that these GCs came from the remains of a completely disrupted dwarf galaxy that shared the stream with half a dozen other satellites. The remnant nucleus of this possible dwarf may be NGC 5024 or NGC 5053, which are the 4th and 6th largest GCs for their luminosity respectively. The largest three are NGC 5139 (Omega Cen), NGC 6715 (M54) and NGC 2419 which are all potential remnant nuclei of dwarf galaxies (Mackey & van den Bergh 2005). We note that NGC 5053 reveals evidence of a tidal stream (Lauchner et al. 2006). Unfortunately, most of the potential FLS GCs do not have published proper motions and so their integrals of motion are not available. Exploring these GCs further requires more data.

9   GLOBULAR CLUSTERS ASSOCIATED WITH OTHER STREAMS

Recently, Newberg et al. (2009) found a thin stream of metal-poor stars with a low velocity dispersion that they suggest may have come from a progenitor dwarf galaxy. The GC NGC 5824 lies nearby in phase space and they suggest it may represent the remnant nucleus of the dwarf. Its half light size and luminosity place it close to the boundary line of Mackey & van den Bergh (2005). The location of NGC 5824 in Fig. 4 shows its age (=12.80 Gyr) and metallicity (=−1.60) are consistent with both the joint AMR and the general GC distribution.

Willett et al. (2009) have searched for GCs associated with their orbital fit to the Grillmair Dionatos stream, but none were found.

10   THE NUMBER OF ACCRETED GLOBULAR CLUSTERS AND DWARF GALAXIES

Previous work has attempted to quantify the number of accreted dwarf galaxies on the basis of the number of accreted GCs. For example, van den Bergh (2000) suggested 3-7 accreted Sgr-type dwarfs with 4-5 GCs each, for a grand total of ⩽35 accreted GCs. Whereas Mackey & Gilmore (2004) suggested a total of ∼41 GCs from ∼7 dwarf galaxies.

From our work, we associate 9 GCs with Sgr dwarf, 7 with CMa (although some are best described as 'probable' members), 4-8 GCs with retrograde motions which also have young ages for their metallicity (this rises to 16 if only their kinematics are considered), and potentially 7 associated with the NGC 5053 disrupted dwarf galaxy. This would still leave about 8 GCs with young ages for their (intermediate) metallicities. Thus we suggest 27-47 accreted GCs from 6-8 dwarf galaxies (which suggests that about half of the halo stellar mass has been accreted in this way). These numbers

Table 2. Milky Way Globular Clusters.

Name	Age (Gyr)	[Fe/H] (dex)	Source
NGC 0104	13.06	-0.78	1
NGC 0288	10.62	-1.14	1
NGC 0362	10.37	-1.09	1
NGC 1261	10.24	-1.08	1
NGC 2419	12.3	-2.14	3
NGC 3201	10.24	-1.24	1
NGC 4372	12.54	-1.88	2
NGC 4833	12.54	-1.71	1
NGC 5024	12.67	-1.86	1
NGC 5053	12.29	-1.98	1
NGC 5139	11.52	-1.35	1
NGC 5272	11.39	-1.34	1
NGC 5286	12.54	-1.41	1
NGC 5466	13.57	-2.20	1
NGC 5694	13.44	-1.74	2
NGC 5824	12.80	-1.60	2
NGC 5897	12.3	-1.73	3
NGC 5904	10.62	-1.12	1
NGC 5927	12.67	-0.64	1
NGC 5946	11.39	-1.22	2
NGC 5986	12.16	-1.35	1
NGC 6093	12.54	-1.47	1
NGC 6101	12.54	-1.76	1
NGC 6121	12.54	-1.05	1
NGC 6144	13.82	-1.56	1
NGC 6171	13.95	-0.95	1
NGC 6205	11.65	-1.33	1
NGC 6218	12.67	-1.14	1
NGC 6235	11.39	-1.18	2
NGC 6254	11.39	-1.25	1
NGC 6266	11.78	-1.02	2
NGC 6273	11.90	-1.53	2
NGC 6284	11.14	-1.13	2
NGC 6287	13.57	-1.91	2
NGC 6304	13.57	-0.66	1
NGC 6341	13.18	-2.16	1
NGC 6342	12.03	-0.69	2
NGC 6352	12.67	-0.70	1
NGC 6362	13.57	-0.99	1
NGC 6366	13.31	-0.73	1
NGC 6388	12.03	-0.77	1
NGC 6397	12.67	-1.76	1
NGC 6426	12.9	-2.11	3
NGC 6441	11.26	-0.60	1
NGC 6496	12.42	-0.70	1
NGC 6535	10.50	-1.51	1
NGC 6541	12.93	-1.53	1
NGC 6544	10.37	-1.20	2
NGC 6584	11.26	-1.30	1
NGC 6624	12.54	-0.70	1
NGC 6637	13.06	-0.78	1
NGC 6652	12.93	-0.97	1
NGC 6656	12.67	-1.49	1
NGC 6681	12.80	-1.35	1
NGC 6712	10.4	-0.94	3
NGC 6717	13.18	-1.09	1
NGC 6723	13.06	-0.96	1
NGC 6752	11.78	-1.24	1
NGC 6779	13.70	-2.00	1

Notes: 1 = Marin-Franch et al. (2009); 2 = de Angeli et al. (2005); 3 = Salaris & Weiss (1998); 4 = Dotter et al. (2008); 5 = Catelan et al. (2002).

Table 3. Table 2 (cont.)

Name	Age (Gyr)	[Fe/H] (dex)	Source
NGC 6809	12.29	-1.54	1
NGC 6838	13.70	-0.73	1
NGC 6864	9.98	-1.03	5
NGC 6934	11.14	-1.32	1
NGC 6981	10.88	-1.21	1
NGC 7078	12.93	-2.02	1
NGC 7089	11.78	-1.31	1
NGC 7099	12.93	-1.92	1
NGC 7492	12.0	-1.41	3
Pal 3	9.7	-1.39	3
Pal 4	9.5	-1.07	3
Pal 5	9.8	-1.24	3
Pal 14	10.5	-1.36	4
AM 1	11.1	-1.47	4
E3	12.80	-0.83	1
Eridanus	8.9	-1.20	3
Lyngå 7	14.46	-0.64	1

Notes: 1 = Marin-Franch et al. (2009); 2 = de Angeli et al. (2005); 3 = Salaris & Weiss (1998); 4 = Dotter et al. (2008); 5 = Catelan et al. (2002).

are likely a lower limit, as our sample (and the subsamples discussed here) represent only a fraction of the known GC system of the Milky Way.

11 CONCLUSIONS

We have supplemented new data from the HST/ACS by Marin-Franch et al. (2009) with deep colour-magnitude diagrams from the literature to form a high quality database of 93 Milky Way globular clusters (GCs) with age and metallicity estimates. Additional parameters, such as magnitude, half-light size, galactoccentric distance and horizontal branch class are available for most of the GCs and can be found in either Harris (1996) or Mackey & van den Bergh (2005). The Milky Way GC age-metallicity relation (AMR) reveals two distinct tracks – one has a near constant old age of ∼ 12.8 Gyr over the full metallicity range, the other is a track to younger ages at a given metallicity which appears at intermediate metallicities.

Using these new data, we revisit the age-metallicity relations of two dwarf galaxies thought to have been disrupted and accreted by the Milky Way – the Sagittarius (Sgr) and Canis Major (CMa) dwarf galaxies. We find that the GCs and open clusters associated with the suspected orbit of each dwarf galaxy produce a well-defined AMR. This supports claims that CMa is a disrupted dwarf and not merely an overdensity or warp in the Galactic disk. The joint Sgr plus CMa AMR indicates that both galaxies produced star clusters over ∼10 Gyr in a manner that is consistent with a simple closed box model for chemical enrichment. As well as confirming the secure clusters, we tentatively identify GCs AM4 and NGC 5634 with Sgr, plus NGC 4590, Pal 1 and Rup 106 with CMa dwarf. We find that Koposov 1 is unlikely to a member of the Sgr dwarf on the basis of its published age and metallicity. For other potential CMa GCs their age and metallicity did not provide a clear discriminator. We

associated a total of 9 GCs with Sgr and 7 with CMa. The GCs NGC 6715 (M54) and NGC 2808 (CMa) may be the remnant nuclei of the original host galaxy. The GC specific frequency of each galaxy appears to be quite high at ∼20, but is similar to the Fornax dSph galaxy.

Comparison with the AMRs of the Large and Small Magllenic Clouds reveals that the LMC has a similar AMR to the joint Sgr plus CMa AMR, whereas the SMC is less enriched for a given age.

Once the GCs associated with the Sgr and CMa dwarfs are removed from the distribution, the remaining GCs are mostly very old. The remaining sample is dominated by GCs formed in a rapid enrichment process on a timescale of less than 1 Gyr, suggesting that they are largely formed *in situ.* However, there are still some GCs with young ages for their (intermediate) metallicities. These are prime candidates for having been accreted along with their host dwarf galaxy.

We examined the horizontal branch morphology of GCs as originally studied by Zinn (1993). Using the recent classification of Mackey & van den Bergh (2005) we add NGC 6715 (M54) with an old halo classification and suggest NGC 6366 should be modified to bulge/disk. Although old halo GCs are often thought to be an *in situ* subpopulation, we find that several such GCs have young ages for their metallicity and note that several of the Sgr and CMa GCs have old halo classifications. Thus accreted GCs may have old (and young) halo horizontal branch morphologies.

Globular clusters with extended horizontal branches have been suggested to be the remnant nuclei of disrupted dwarfs. After removing NGC 6715 (the probable Sgr nucleus) and NGC 2808 (the possible CMa nucleus), we found these GCs to be slightly younger on average but otherwise they covered the full range in metallicity.

Retrograde motion is the signature of an object that has been accreted in the opposite rotational sense to the main bulk of the Galaxy's rotation, and there are 16 known GCs with such orbits. We find several of these also have young ages for their metallicity, i.e NGC 288, 362, 3201, 5139, 6205, 6712, 6934 and 7089. NGC 5139 (Omega Cen) has long been identified as a remnant nucleus of a dwarf galaxy. Interestingly, it and NGC 362 are consistent with an AMR similar to that of Sgr and CMa.

It has been known for some time that dwarf galaxies are not isotropically distributed but rather form great circles in the sky. The Fornax-Leo-Sculptor great circle (which includes several recently discovered faint dwarf galaxies) passes nearby to several GCs. After excluding the Sgr and CMa GCs, we examined the age-metallicity distribution for the 10 GCs nearest to the great circle. We find 7 of them to have young ages suggesting they were accreted.

On the basis of our age-metallicity analysis, we suggest that at least 27-47 GCs, from 6-8 dwarf galaxies, were accreted by the Milky Way over the course of its evolutionary history.

Currently scheduled for a 2012 launch, the GAIA spacecraft will determine accurate positions and space motions for most globular clusters, nearby dwarf galaxies and relic streams of stars. Once such data are available, we expect it to provide a new impetus to the field of Galactic archaeology and allow many of the suggestions made here to be tested.

12 ACKNOWLEDGEMENTS

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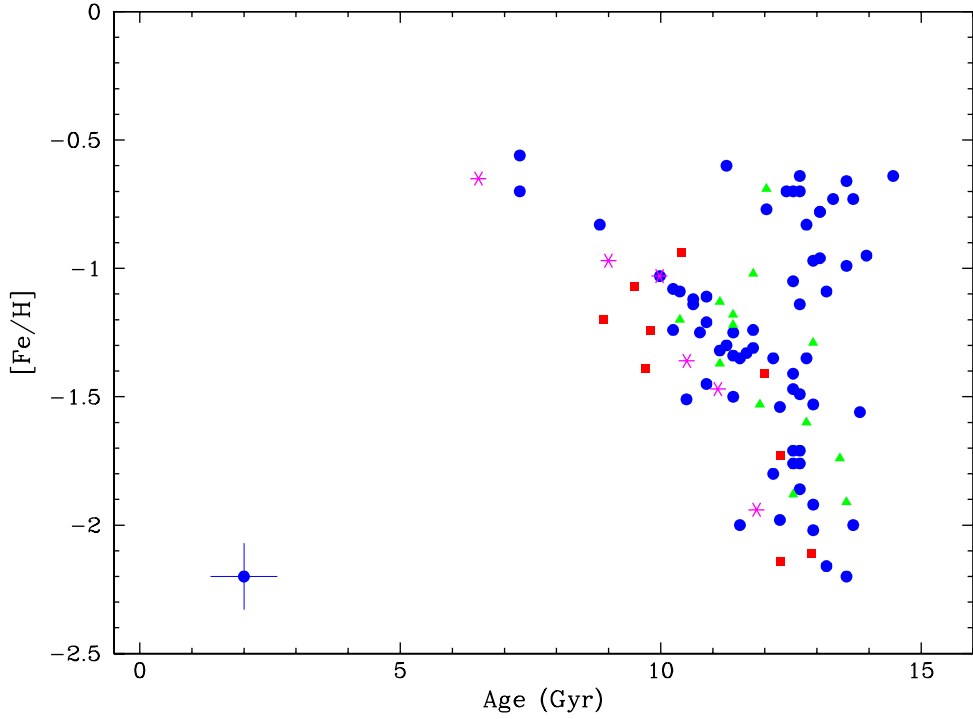Helmi A., White S. D. M., de Zeeuw P. T., Zhao H., 1999,

Figure 1. Globular cluster sample coded by source of data. Marin-Franch et al. (2009) are blue circles, Salaris & Weiss (1998) are red squares, de Angeli et al. (2005) are green triangles, Carraro (2009), Carraro et al. (2007), Bellazzini et al. (2002), Catelan et al. (2002) and Dotter et al. (2008) are purple stars. A typical error bar for the Marin-Franch et al. ACS data is shown lower left.
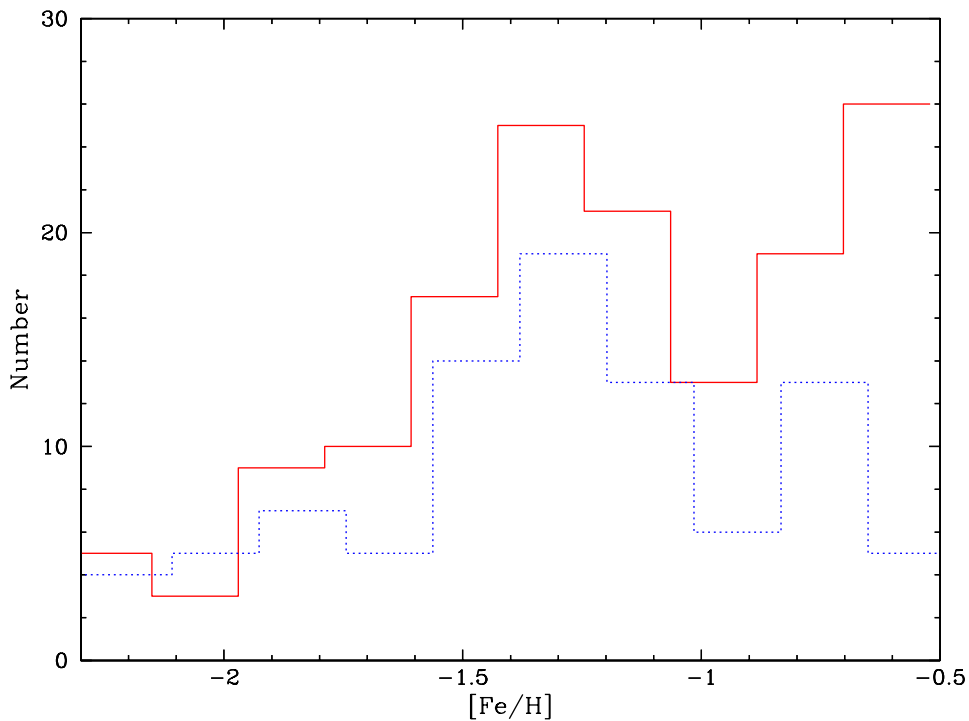

Figure 2. Histogram of globular cluster metallicities. The Milky Way distribution, converted into Carretta & Gratton (1997) metallicities, is shown by the solid red histogram. The distribution of our sample of 93 GCs is shown as a dotted blue histogram. Our sample is under-represented in metal-rich GCs compared to the full Milky Way distribution.
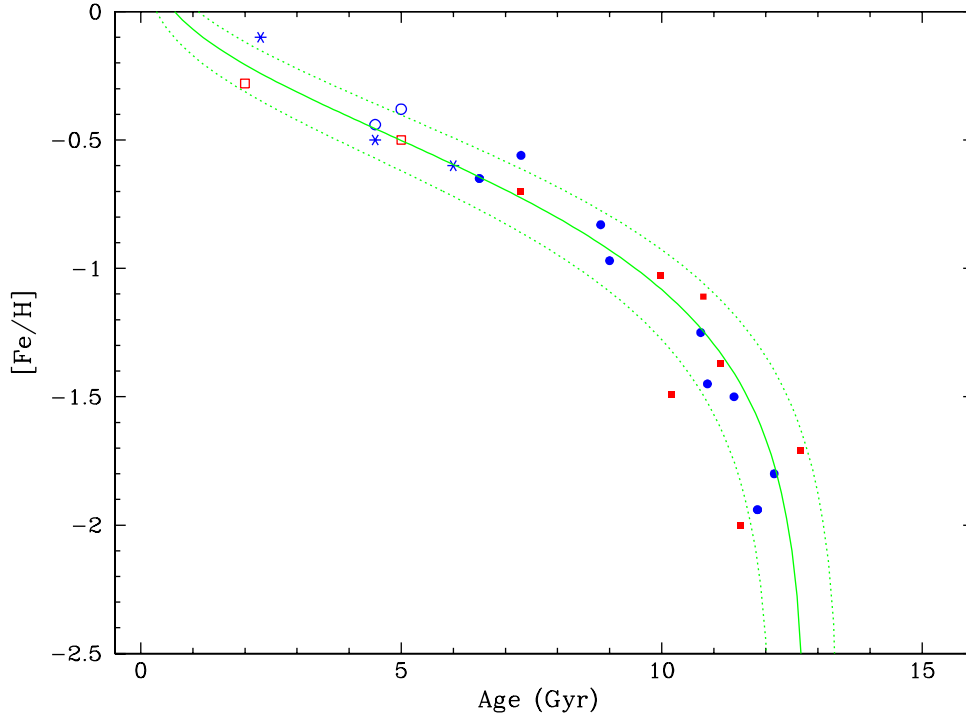
Figure 3. Joint age-metallicity relation for the Sgr and CMa dwarf galaxies. The Sgr dwarf data are blue circles and the CMa are red squares, with open symbols for open clusters and stars for field star populations. The green line is a simple closed box model with a continuous star formation rate to represent the joint Sgr and CMa age-metallicity relation (AMR).
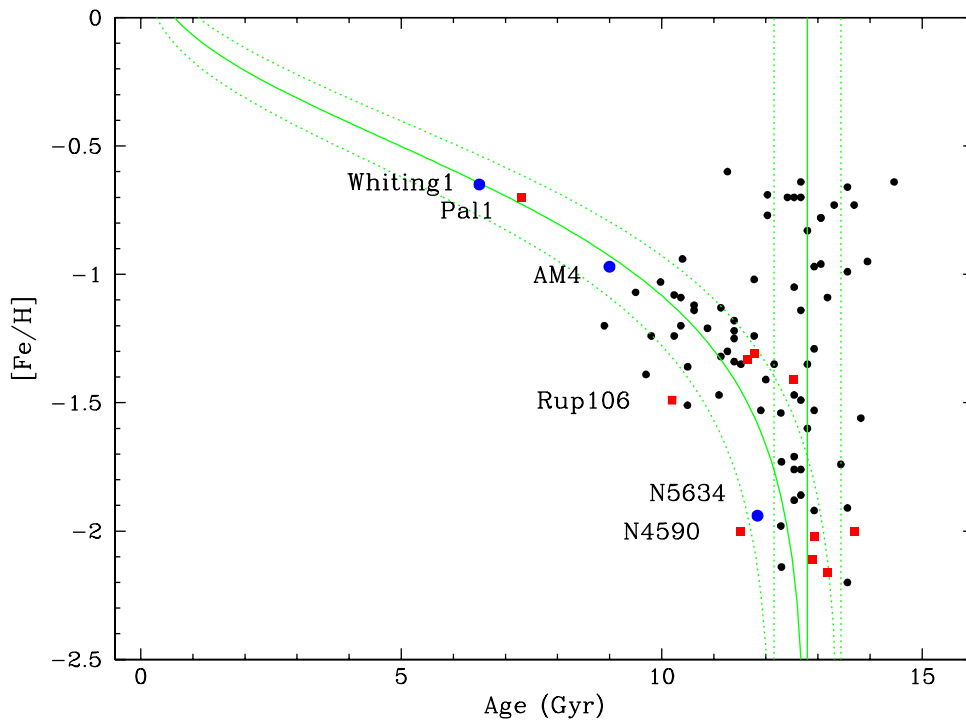

Figure 4. Possible globular clusters associated with the Sgr and CMa dwarf galaxies. The possible CMa globular clusters (red squares) all have a similar location in phase space to the predicted orbit of the CMa dwarf as determined by Martin et al. (2004). Three possible Sgr GCs (blue circles) are shown. The 6 additional GCs that we tentatively include in the Sgr and CMa GC systems are labelled. Green lines show the joint AMR and the AMR of the metal-poor GCs in the Milky Way from Marin-Franch et al. (2009).
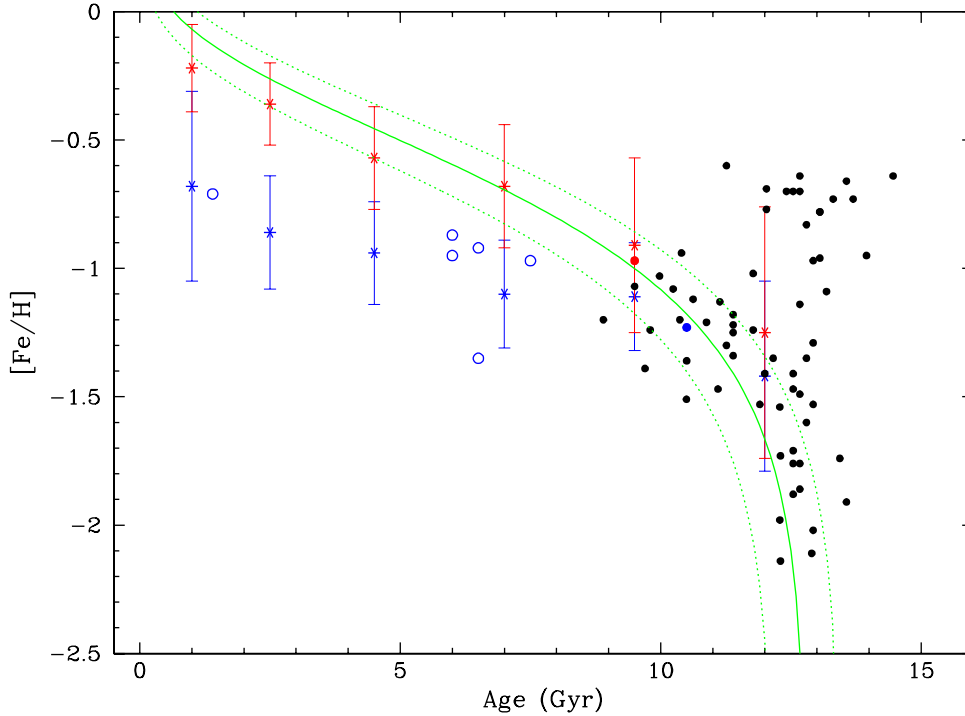
Figure 5. Age-metallicity relation of the Magellanic Clouds. The mean age and metallicity for the SMC (blue) and LMC disk (red) from Carrera et al. (2008a,b) are shown with error bars. SMC open and globular clusters from the ACS study of Glatt et al. (2008) are shown by open and filled blue circles. The old LMC GC (NGC 121) is shown by a filled red circle (age = 9.5 Gyr, [Fe/H] = −0.97). Milky Way globular clusters are shown by filled black circles. The Sgr and CMa joint AMR is shown but their GCs have been excluded from the plot.

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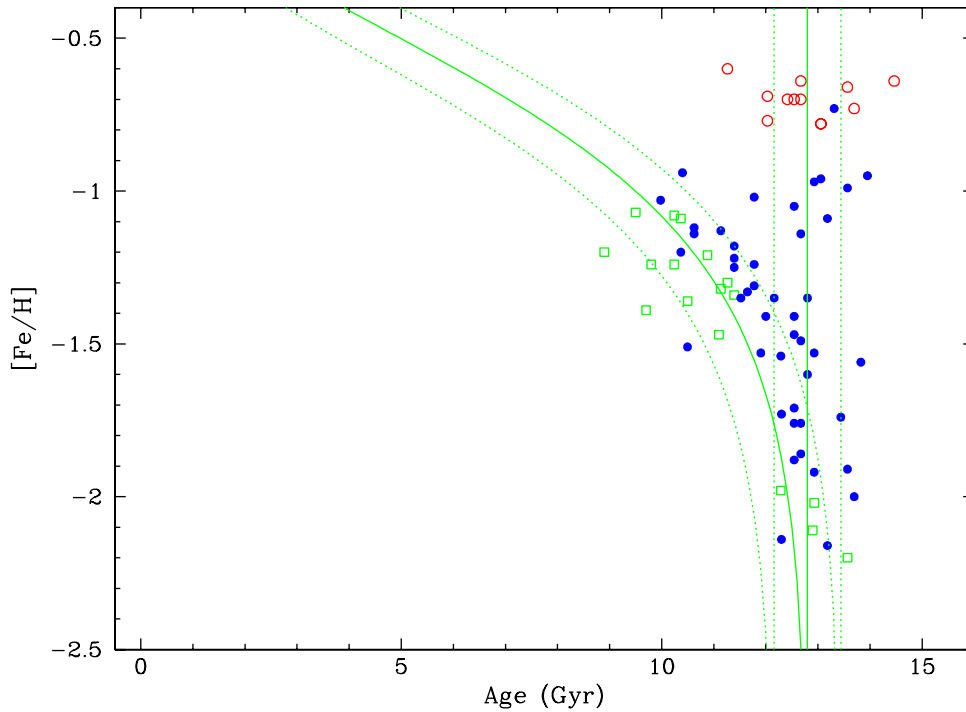
Figure 6. Globular clusters coded by horizontal branch (HB) class. Bulge/disk are red open circles, old halo are blue filled circles, young halo are green open squares. The y axis range has been reduced compared to previous plots. The Sgr and CMa joint AMR is shown but their GCs have been excluded from the plot. The AMR for metal-poor Milky Way GCs from Marin-Franch et al. (2009) is also shown.
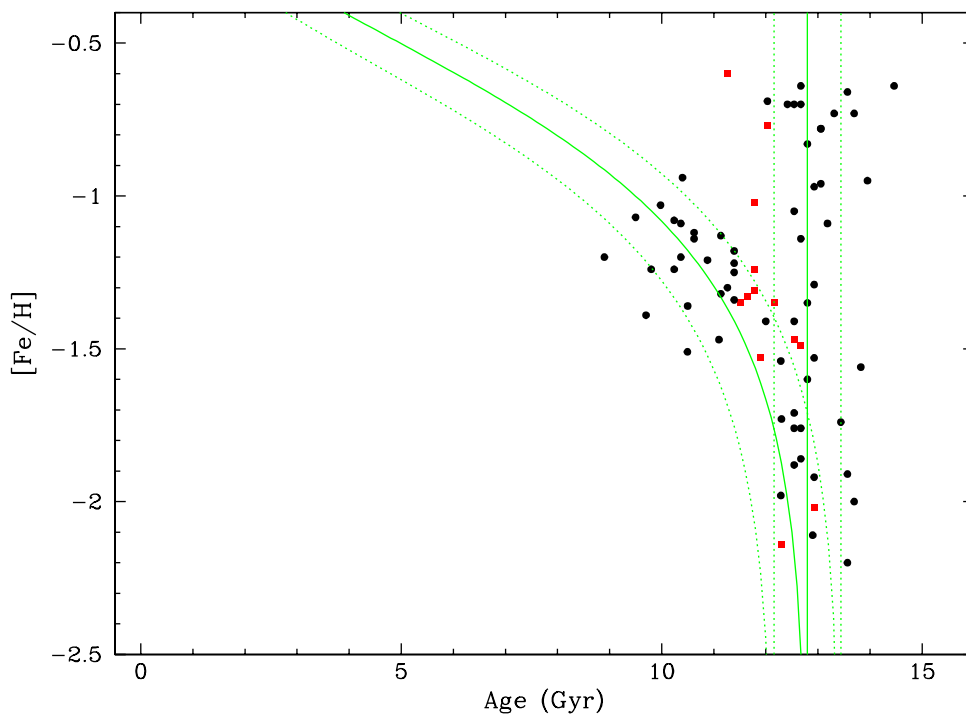

Figure 7. Globular clusters with Extended Horizontal Branch (EHB) stars. GCs with EHBs are shown as red squares. Green lines show the Sgr and CMa joint AMR (with their GCs excluded) and the metal-poor Milky Way GC AMR.
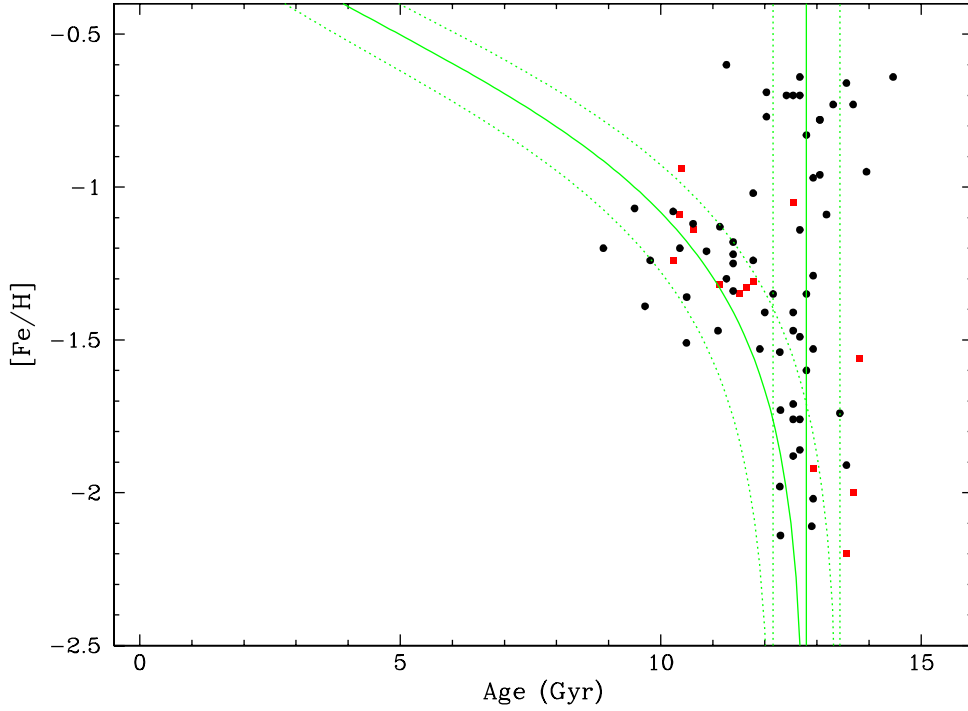
Figure 8. Globular clusters known to be on retrograde orbits. For many GCs shown the orbital properties are unknown. GCs with retrograde motions are shown as red squares. Green lines show the Sgr and CMa joint AMR (with their GCs excluded) and the metal-poor Milky Way GC AMR. Several of the retrograde motion GCs are found in the track to younger ages.
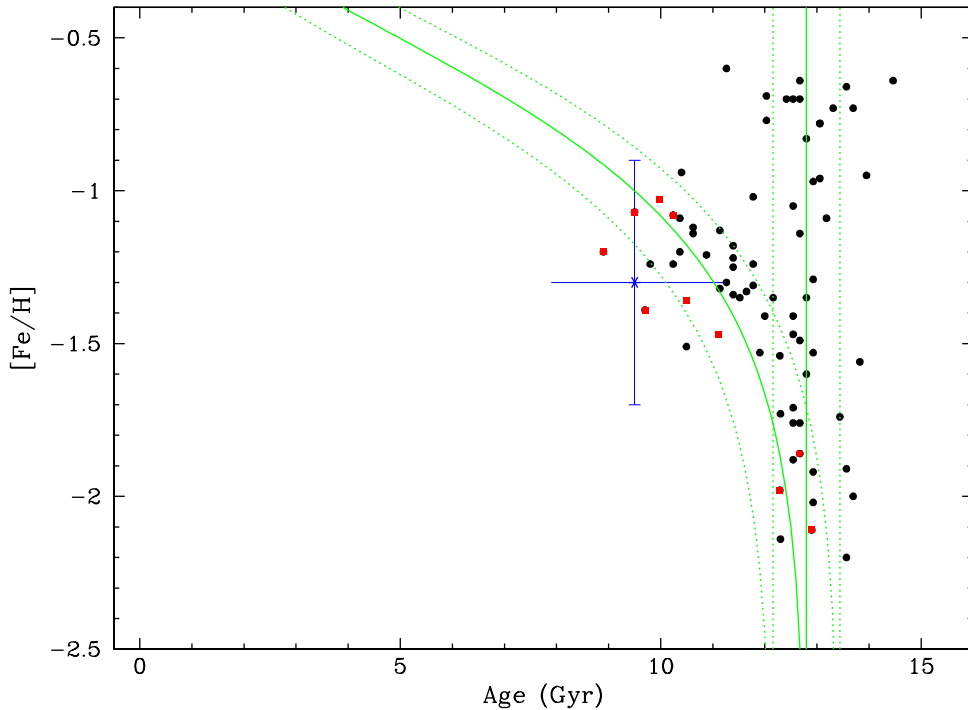

Figure 9. Globular clusters coincident with the Fornax-Leo-Sculptor great circle. The metallicity range of field stars formed in the Fornax galaxy ∼10 Gyr ago are shown by the blue cross. GCs that lie the FLS great circle are shown by red squares. Milky Way globular clusters are shown by filled black circles. Green lines show the Sgr and CMa joint AMR (with their GCs excluded) and the metal-poor Milky Way GC AMR.