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Invited Review

Chemical Abundances and Kinematics in Globular Clusters and Local Group Dwarf Galaxies and Their Implications for Formation Theories of the Galactic Halo

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ABSTRACT. We review Galactic halo formation theories and supporting evidence, in particular, kinematics and detailed chemical abundances of stars in some relevant globular clusters as well as Local Group dwarf galaxies. Outer halo red HB clusters tend to have large eccentricities and inhabit the area of the Lee diagram populated by dwarf spheroidal stars, favoring an extragalactic origin. Old globular clusters show the full range of eccentricities, while younger ones seem to have preferentially high eccentricities, again hinting at their extragalactic origin. However, the three outer halo second parameter clusters with well-determined orbits indicate they come from three independent systems. We compare detailed abundances of a variety of elements between the halo and all dwarf galaxies studied to date, including both dwarf spheroidals and irregulars. The salient feature is that halo abundances are essentially unique. In particular, the general α vs. $[\text{Fe}/\text{H}]$ pattern of 12 of the 13 galaxies studied are similar to each other and very different from the Milky Way. Sgr appears to be the only possible exception. At the metal-poor end the extragalactic sample is only slightly deficient compared to the halo but begins to diverge by $[\text{Fe}/\text{H}] \sim -2$ and the difference is particularly striking for stars with $[\text{Fe}/\text{H}] \sim -1$. Only Sgr, the most massive dSph, has some stars similar in α -abundance to Galactic stars at intermediate metallicities, even the most extreme low- α subset most likely to have been accreted. It appears very unlikely that a significant fraction of the metal-rich halo could have come from disrupted dSphs of low mass. However, at least some of the metal-poor halo may have come from typical dSphs, and a portion of the intermediate metallicity and metal-rich halo may have come from very massive systems like Sgr. This argues against the standard hierarchical galaxy formation scenario and the Searle-Zinn paradigm for the formation of the Galactic halo via accretion of “fragments” composed of stars like those we see in typical present-day dSphs. The chemical differences between the dwarfs and the halo are due to a combination of a low star formation efficiency and a high galactic wind efficiency in the former. AGB stars are also more important in the chemical evolution of the dwarfs. The formation problem may be solved if the majority of halo stars formed within a few, very massive satellites accreted very early. However, any such satellites must either be accreted *much* earlier than postulated, before the onset of SNe Ia, or star formation must be prevented to occur in them until only shortly before they are accreted. The intrinsic scatter in many elements, particularly the α -elements, indicates that the halo was also mixed on a surprisingly short timescale, a further problem for hierarchical formation theories.

Online material: color figures

1. INTRODUCTION

To terribly distort a famous phrase: our Galaxy exists, therefore it formed. But how? When? What fossils can we find that

might yield clues to this process, and what means do we have at our disposal to interpret these clues? What theories have been formulated to explain these clues and how do these theories hold up to current evidence? We review current Galactic halo formation theories and supporting evidence, in particular, clues derived from kinematics and detailed chemical abun-

¹ Derived in part from the Henry Norris Russell Lecture delivered at the Seattle Meeting of the American Astronomical Society in 2003 January.

dances of individual stars in some relevant globular clusters as well as Local Group dwarf galaxies.

Let us first look at formation theories. There are two major grand-design scenarios for the formation of the halo of our Galaxy. These models can apply to the Galaxy as a whole but we concentrate on their application to the Galactic halo.

1.1. The Monolithic Collapse Model

In 1962 Eggen et al. (1962, hereafter ELS62) proposed a model of the formation of the Galaxy in which a general monolithic gravitational collapse of matter brought together the baryons now observed as a spherical halo and continued on to form the disk. Since the infalling material had never (or hardly ever) been processed through stars it must have been extremely metal-poor, at least initially. They argued that the time-scale for the collapse was short compared to a Galactic rotation time ($\sim 2 \times 10^8$ yr), allowing for the orbital eccentricities to vary in a potential not yet in equilibrium, but sufficiently long on an evolutionary timescale so that massive stars forming in the collapsing gas could live out their lives and enrich the gas with heavy elements. Subsequent generations of stars had different chemical compositions, in particular, enhanced metallicity, and different kinematics, as the orbits changed from very elliptical with high energy to nearly circular, confined to the developing plane. Hence, they predicted a gradient in metallicity and kinematics in the halo. Evidence supporting this was given by the correlation of orbital eccentricity, total angular momentum, and velocity perpendicular to the disk with metallicity of halo field stars. In addition, included in the halo are especially dense stellar concentrations: the globular clusters (GCs). If they continued to form during the collapse, then the ELS62 scenario predicts that they should also show a metallicity gradient and that they should be coeval (to within the timescale of the collapse). However, such data were beyond the observational limits available at that time.

1.2. The Merger/Hierarchical Accretion Model

Searle & Zinn (1978, hereafter SZ78) measured and compiled the most up-to-date and reliable Fe abundances and horizontal branch morphologies available at the time for some 50 GCs and investigated these properties as a function of galactocentric distance, R_{GC} . Surprisingly, they found no radial abundance gradient in the cluster system in the outer halo, with the dividing line at about the solar $R_{GC} \sim 8$ kpc. They also found significant differences in HB morphology between inner and outer halo GCs.

It is of interest to revisit their work with current data. The metallicity scale has subsequently changed dramatically as has our ability to measure metallicity and the number of clusters with reliable metallicities and color-magnitude diagrams from which to derive HB morphology now includes almost all of the ~ 150 known Galactic GCs. In addition, distances are much more robust. In Figure 1 we plot cluster metallicity against

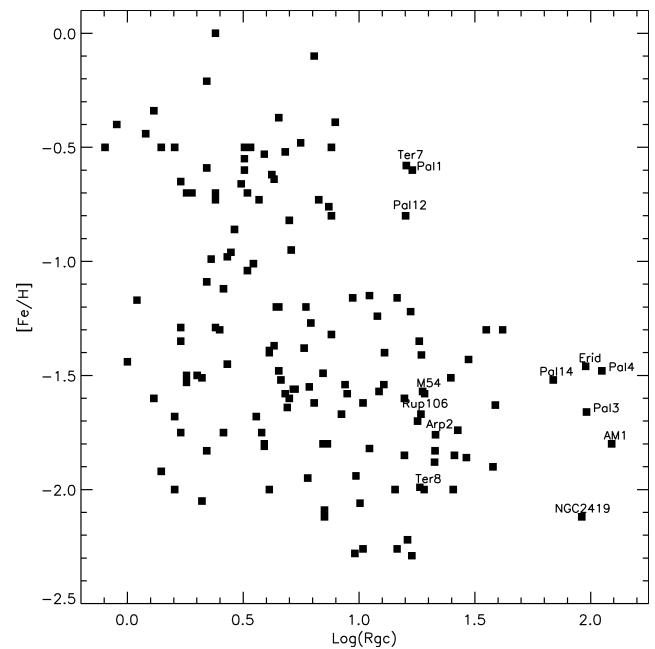


FIG. 1.—Metallicity of GCs as tabulated by Harris (2003) plotted against the log of their distances from the Galactic center in kiloparsecs. The break at 40 kpc is evident followed by six very distant GCs located at similar distances to the nearer dSph systems. Various clusters are identified.

galactocentric radius, and in Figure 2 we duplicate the SZ78 plot of HB morphology versus $[Fe/H]$ for their same four radial bins, using the database maintained by Harris (2003). Here, we use the modern quantitative definition of HB morphology: $(B - R)/(B + V + R)$, where B , V , and R are the number of blue, variable, and red stars on the horizontal branch. The modern data bear out the same conclusions drawn by SZ78: beyond $R_{GC} \sim 8$ kpc, there is no metallicity gradient in the GC system. Second, the inner halo GCs show a very tight relation between metallicity and HB type, while the outermost halo GCs have a broad range of HB type at a given $[Fe/H]$ (e.g., -1.5).

There are a number of GCs in the outermost bin in Figure 2 that have unusually red horizontal branches despite their low metallicities, a long-standing conundrum referred to as the “second parameter problem” (Sandage & Wildey 1967). The large spread in horizontal branch type is best understood, as suggested by SZ78, as a difference in age with the red HB outer halo GCs several Gyr younger than their blue HB cousins at large radii as well as the inner halo clusters, although the solution to the second parameter problem is still controversial and may involve other factors such as He abundance, internal dynamics, or mass loss (e.g., Chaboyer et al. 1996; Stetson et al. 1996; Catelan et al. 2001). Note that the inner/outer halo dichotomy now finally appears to be well-supported by field stars as well (Carollo et al. 2007).

The lack of an outer halo GC metallicity gradient and the differences in HB morphology between inner and outer halo

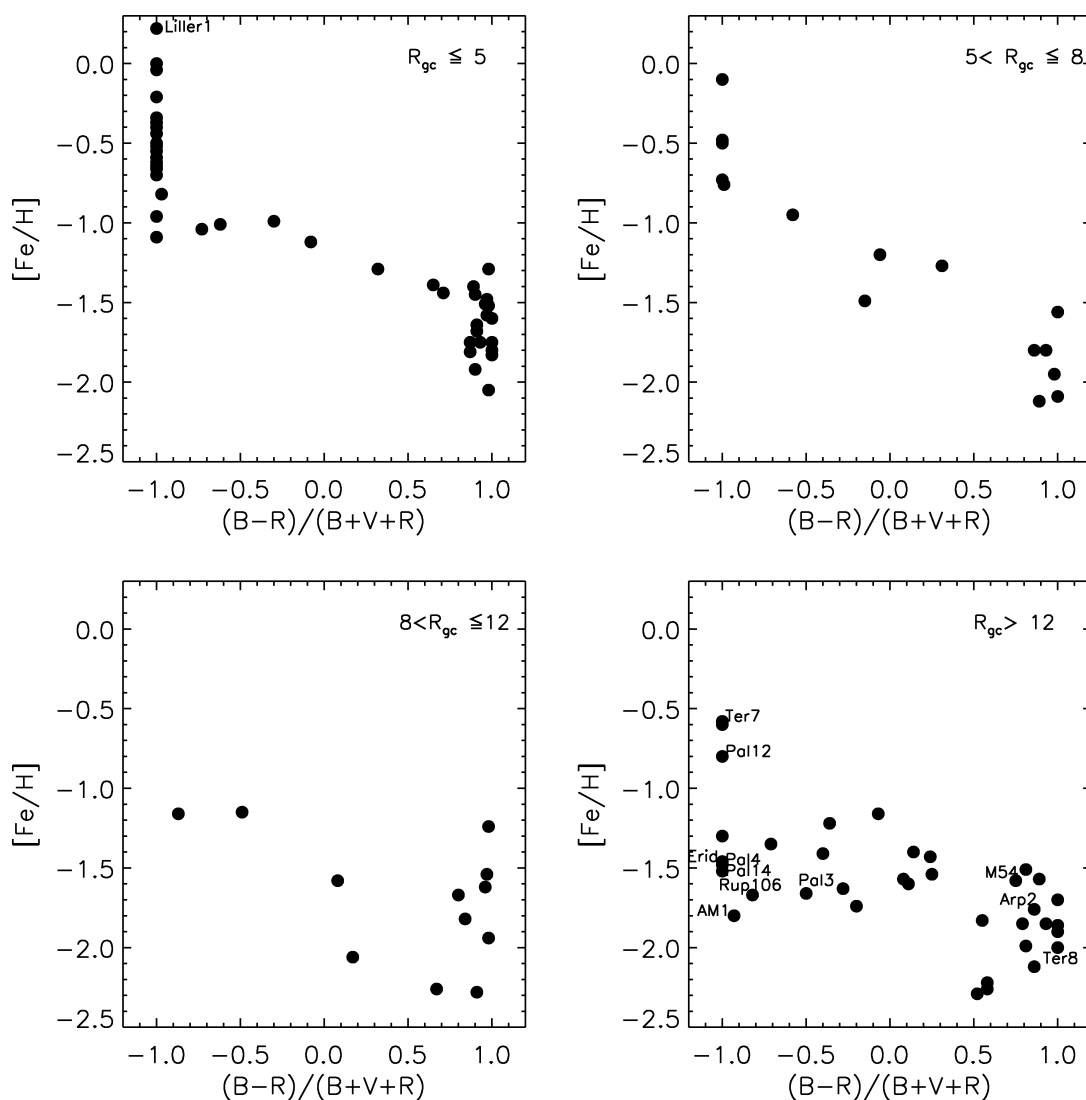


FIG. 2.—Dependence of metallicity on the color distribution of horizontal branch stars for GCs divided into four groups according to their distance from the Galactic center, following SZ78. Beyond 8 kpc there are no clusters with $[Fe/H] > -1.0$ except for Ter 7 and Pal 12, which are associated with the Sgr system. NGC 2419 is located in the bottom right diagram at (0.86, -2.12).

GCs, which they interpreted as a larger age spread in the latter (>1 Gyr) than the former, led SZ78 to suggest a model in which the outer halo formed over a longer time via the capture or accretion of external systems. They coined the term “fragments” for these postulated Galactic building blocks. Zinn (1993) developed this concept further, finding that dividing the halo GCs into two groups according to their HB morphology also yielded distinct spatial distributions, rotational velocities, and velocity dispersions, thus leading to the distinction of “old” versus “younger” halo. One also speaks now of the “dissipative” versus “accreted” halo, in which the former component was formed along the lines suggested by ELS62 and the latter à la SZ78 (e.g., Gratton et al. 2003). These ideas have been thoroughly reviewed by Freeman & Bland-Hawthorne (2002).

Note that the clusters in the Galactic bulge are now considered to be of a different bulge population from the halo clusters (e.g., Minniti 1995).

The SZ78 scenario has been given a firm cosmological footing in recent years. Modern cosmological theories based on the currently favored Λ CDM paradigm posit hierarchical structure formation on all physical scales (e.g., White & Rees 1978; Navarro et al. 1997). They predict that all galaxies, including the Milky Way, form as part of a local overdensity in the primordial matter distribution and grow via the accretion of numerous smaller building blocks (SZ78 fragments), which themselves formed similarly.

As originally noted by SZ78 and later by Zinn (1980), obvious candidates for these building blocks are the present-day

dwarf spheroidal (dSph) and dwarf irregular (dIrr) galaxies. Such galaxies are the most numerous in the universe and the dSphs in particular are found to surround both the Milky Way and M31 in large numbers (although their numbers fall by an order of magnitude or more to match those predicted by Λ CDM theories [Klypin et al. 1999]). There are undoubtedly other faint dwarfs left to be found, e.g., the Sloan Digital Sky Survey has very recently turned up a number of new dSph companions to the Milky Way (Willman et al. 2005; Kleyna et al. 2005; Belokurov 2006b; Zucker et al. 2006a, 2006b, 2006c), but it is unlikely that the numbers required by Λ CDM theories really exist, although the most recent estimate (Simon & Geha 2007) suggests that there are only a factor of ~ 4 too few dwarf galaxies currently known). Many of them are known to contain at least a sizeable fraction of stars that are similar to those in the halo, namely old and metal-poor. Graphic proof that accretion of such galaxies does indeed occur has existed ever since the discovery of the Sagittarius dSph (Sgr; Ibata et al. 1994), which is clearly being assimilated by the Galaxy along with its coterie of GCs. Not only are Sgr field stars now forming part of the MW halo, but its several GCs are also now becoming part of the Milky Way's GC system. It is also theorized that a significant fraction of halo field stars were once members of a GC. Indeed, we now know that GCs do indeed disrupt, the most beautiful example being that of Pal 5 (Odenkirchen et al. 2003).

1.3. The Search for Building Blocks: Comparing Observations with Theory

One can think of a number of observational tests to probe the predictions of different galactic formation theories. An obvious test is to directly compare the stellar populations of the surviving dSph or dIrr systems with that of the halo. If the halo is indeed made up in large part by dissolved systems initially like the dSphs or dIrrs we see today, one would expect to find many similarities in their stellar populations.

One way to do this is to compare the CMDs in detail and try to set limits on the percentage of present day dSph populations that may have contributed to the halo. By comparing the turnoff colors in these systems, Unavane et al. (1996) first set a surprisingly low upper limit of $\sim 10\%$ on this contribution, as the intermediate-age stars generally found in dSphs are lacking in the halo. This was the first strong hint that at least the present-day dSphs may not be the generic galactic building blocks they are often imagined to be.

Another more stringent but observationally more difficult approach is a direct comparison of the detailed chemical compositions of stars from the two environments, based on high-resolution spectroscopy. Clearly, if the halo formed from dSphs or dIrrs or objects like them, their chemical makeups should be similar. Such a study has been dubbed "chemical tagging" by Freeman & Bland-Hawthorn (2002). The catchphrase "near-field cosmology" also applies, as we are probing cosmological galaxy

formation theories using the nearest galaxies as our testbeds. The value of such a comparison was recognized long ago and served as one of the key science drivers for the installation of high-resolution spectrographs on the new generation of 6–10 m telescopes, as even the brightest stars in the older populations in even the nearest galaxies were really beyond the reach of high-resolution spectrographs on 4 m telescopes. In the context of this review, when referring to abundances of individual elements other than simply "[Fe/H]," we restrict ourselves to data with a resolution $R \gtrsim 20,000$, in which the chemical abundances of individual elements in a single star have been derived from a detailed model atmosphere and/or spectrum synthesis analysis. (NB, for historical purposes, "metallicity" refers to the Fe abundance, i.e., [Fe/H] and we adhere to this). For this purpose, high S/N data (≥ 50) is certainly preferable. Of course, spatial and kinematic, as well as chemical, data are needed to really disentangle the predictions of different theories (e.g., Venn et al. 2004; Font et al. 2006a, 2006b). In this review we mainly focus on high-resolution abundance results but also discuss some recent kinematic evidence.

In addition to providing a key observational test for galactic formation models, detailed chemical abundances of our nearest galactic neighbors also allow us to reconstruct their own chemical evolution history, investigating the relative contributions over time to different elements by supernovae Type Ia (SNe Ia), SNe II, AGB stars, etc., as well as to help constrain their star formation history. The dSphs are also believed to be local analogs to damped Ly α galaxies and/or the many distant faint blue galaxies seen in very deep images.

After the installation of instruments like UVES on the VLT and HiRes on Keck, the field of extragalactic chemical abundances has really taken off. Detailed abundances now exist for at least a few stars in each of the classical dSphs associated with the Milky Way (except for Leo II) as well as for several of the nearest dIrrs, thanks in large part to the efforts of M. Shetrone, K. Venn, E. Tolstoy, V. Hill, J. Johnson, P. Bonifacio, T. Smecker-Hane, A. McWilliam, and collaborators, and of course the Magellanic Clouds, although surprisingly, the amount of high-quality data for older Large Magellanic Cloud (LMC) stars is very limited and indeed virtually nonexistent for the SMC. We note that this is still very hard work; the brightest target stars are typically $V \sim 17$, and even with good seeing on an 8 m telescope and an efficient spectrograph, they require several hours to achieve adequate signal-to-noise ratio (S/N) at high resolution. In addition, many new studies have been carried out on major samples of halo stars which provide a much better sample of our own Galaxy to compare to. The results have had major implications on our understanding of how our Galaxy, as well as other galaxies, might have formed. This field will continue to expand rapidly in the near future, especially with the recent implementation of multiplexing spectrographs such as FLAMES on the VLT and MIKE and MOE + IMACS on Magellan. These new instruments will further revolutionize this field, yielding orders of magnitude more

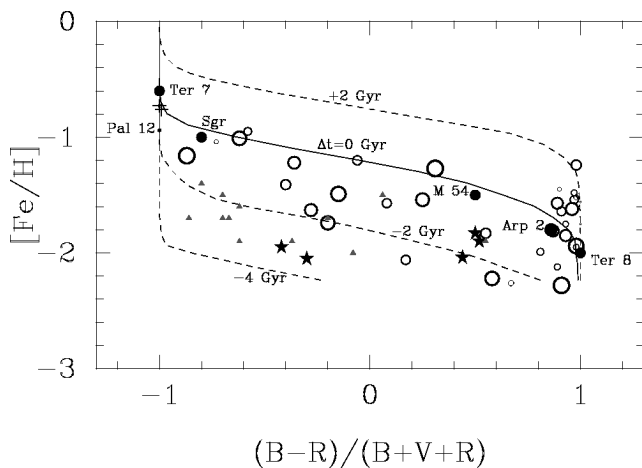


FIG. 3.—Metallicities as a function of HB type (Lee diagram) for Galactic GCs (circles), Fornax dwarf spheroidal clusters (star symbols) and mean values for dwarf spheroidals (triangles). For the Galactic GCs, the symbol size is proportional to the eccentricity. Sgr's clusters are represented with filled symbols and labeled. Equal age lines from Lee et al. (2002) are also shown. [See the electronic edition of *PASP* for a color version of this figure.]

stars per galaxy. Nevertheless, we feel that a summary of our current knowledge in this field is timely, and hence this review, although we fully expect many of the details to be outdated in short order. We generally restrict ourselves to papers published or in preprint form by mid-2007.

The paper is organized as follows: We start by investigating outer halo GCs in the context of their possible extragalactic origin. We next discuss the first galaxy known to have been (or is being) captured by the Galaxy, the Sgr dSph. We then compare detailed abundances of a variety of important elements, including O, Mg, Si, Ca, Ti, Na, Fe, Ba, and Eu in several different galaxies. We follow with a long discussion of the implications for formation scenarios of the particularly important α -element abundances in nearby galaxies compared to those in the halo. We close by enumerating some of the problems associated with the latest galaxy formation theories as applied to our halo.

2. GLOBULAR CLUSTERS OF THE OUTER HALO

In order to test the SZ78/hierarchical merger idea that at least the outer halo was accreted from fragments, by comparing abundances in the halo with those in potential building block galaxies, we need to not only examine abundances in other galaxies but also representatives of the outer halo. We take the same working definition of the “outer halo” as SZ78: $R_{GC} > 8$ kpc. Several recent studies have explored abundances in halo field stars and GCs, e.g., Venn et al. (2004), Beers & Christlieb (2005). We present a brief review of the properties of outer halo GCs, including not only abundances but also orbital eccentricities which are now available for some of these objects.

Let us first return to Figure 1 and focus on the more distant

clusters. The bulk of the outer halo GCs have $[Fe/H]$ between -1.2 and -2.3 . Note the significant gap in the GC radial distribution in which no clusters are found between ~ 40 and 70 kpc (Zinn 1985). In the far halo, beyond the gap, there are six clusters, with galactocentric distances extending to more than 100 kpc, entering the realm of the nearest dSphs, which (excepting Sgr) have $R_{GC} \sim 70\text{--}90$ kpc (Mateo 1998). Five of these clusters have $[Fe/H]$ between -1.4 and -1.8 , while a single cluster, NGC 2419, has $[Fe/H] = -2.14$. A glance at Figure 2 reveals that, of these six very distant outer halo clusters, all except NGC 2419 have very red HBs.

These five outer halo, RHB clusters, Pal 3, 4, 14, Eridanus, and AM 1, are then excellent candidates for accreted clusters, especially if age is the second parameter. In order to investigate this further, it would be of great interest to determine their kinematics and orbits. Unfortunately, because of their great distances their proper motions are not yet known so we do not know their orbital eccentricities, but it is likely that they do not have penetrating orbits or they would have lost sufficient members so as to no longer be recognizable, except possibly by their debris streams.

However, with the galactic orbits of many other GCs in hand (Dinescu et al. 1999, and further updates) we can prepare plots like Figure 2, but now including eccentricity. In Figure 3 we plot the metallicity against HB type in what has been called a Lee diagram (Lee et al. 1994) for GCs with known eccentricities, with the symbol size proportional to the eccentricity. Two disk clusters, 47 Tuc and NGC 6838, are marked with crosses, and Pal 12 is labeled. For comparison, we also plot Sgr and its four main-body clusters (filled circles) and the Fornax clusters (star symbols; for these clusters the symbol size is not related to the eccentricity, which is unknown). In addition, we include known mean values for the field populations of dSphs (small triangles), with values taken from Grebel et al. (2003) and Harbeck et al. (2001). Again, eccentricity values are not known for these galaxies. According to Lee et al. (1994), curves of equal age may be drawn in this diagram. We have done this, using the isochrones from Lee et al. (2002). The full range in age is about ± 2 Gyr, some of which may be due to the uncertainties in the whole process. Blue HB clusters at a given low metallicity (or “first parameter” clusters) appear to have the full range of eccentricities, while red HB clusters at a given low metallicity (or second parameter clusters) seem to have preferentially large eccentricities. These latter clusters also fall in the same general region of the diagram as the general populations of the dSphs. Both of these facts are evidence in favor of an extragalactic origin for the second parameter clusters.

The GCs of Fornax range from $HB = -0.4$ to $+0.5$, although their apparent $[Fe/H]$ range is only from -2.1 to -1.8 . Fornax appears to have its own second parameter problem (Smith et al. 1996). For the dSph companions of M31 the HB values are all near -0.7 , with $[Fe/H]$ ranging from -1.5 to -2.0 , which is within the uncertainties of photometric metallicities. Why they should all be so similar while the dSph

systems surrounding our Galaxy and their associated GCs are so different is an intriguing question.

The large range in age and metallicity of the GCs and dSph systems shows the large range of conditions that must have been present as these systems formed. We should remember, however, that the GCs and dSph systems that we see today are the ones that, if they were captured, have not yet been totally assimilated into the halo. Their stellar content, as well as their orbits, may differ from those of similar systems that were captured earlier in the history of our galaxy, and were primarily responsible for contributing their stars to the current halo. Perhaps it should be no surprise that halo stars have compositions more like dSph systems when their $[\text{Fe}/\text{H}]$ values were close to -2 rather than their present values nearer to $[\text{Fe}/\text{H}]$ of -1 (see § 5).

De Angeli et al. (2005) derive precise relative GC ages from homogeneous photometric data sets: ground-based and *Hubble Space Telescope* (*HST*). We plot the ages determined from this study on the Carretta & Gratton (1997) metallicity scale as a function of orbital eccentricities in Figure 4. The two disk clusters 47 Tuc and NGC 6838 are indicated with star symbols in this plot. Old clusters show the full range of eccentricities, while younger ones seem to have preferentially high eccentricities. Two well-known second parameter clusters are not present in the age-eccentricity plot: NGC 7006 and Pal 13. These two clusters also have high eccentricities, 0.69 and 0.76, respectively. Finally, ω Cen, a system widely accepted to be the nucleus of a captured dwarf elliptical galaxy, has a high orbital eccentricity (0.57). More importantly, to match ω Cen's present orbital characteristics, Tsuchiya et al. (2003, 2004) show that its progenitor started with an orbital eccentricity of 0.9.

If indeed the majority of second parameter clusters (or the younger clusters) were born in satellite systems of the Milky Way, their orbit shapes indicate that these systems were rapidly destroyed due to their penetration into the inner denser regions of the Galaxy. Only satellite systems with low orbital eccentricities could have survived. Fornax is such an example. It has an orbital eccentricity of 0.27 ± 0.16 (Dinescu et al. 2004; see however Piatek et al. [2002] for a different proper-motion determination which corresponds to an eccentricity of 0.52). The LMC too has a low-eccentricity orbit (~ 0.35), while that of Sgr is rather moderate (0.53; e.g., Dinescu et al. 2001, 2005).

If the assumption that second parameter clusters were captured is correct, one can envision testing the hypothesis that the outer halo was assembled from just a few massive satellites, as recent models predict (Robertson et al. 2005; see § 5). Specifically, by quantifying the amount of phase-space association of distant GCs, once accurate proper motions are determined for a good number of these clusters, e.g., from the *Space Interferometry Mission PlanetQuest* (*SIM PlanetQuest*) or *Gaia* projects, one can set constraints on the generic number of SZ78 fragments/satellites that made up the halo. We note here an initial attempt along these lines. There are three second param-

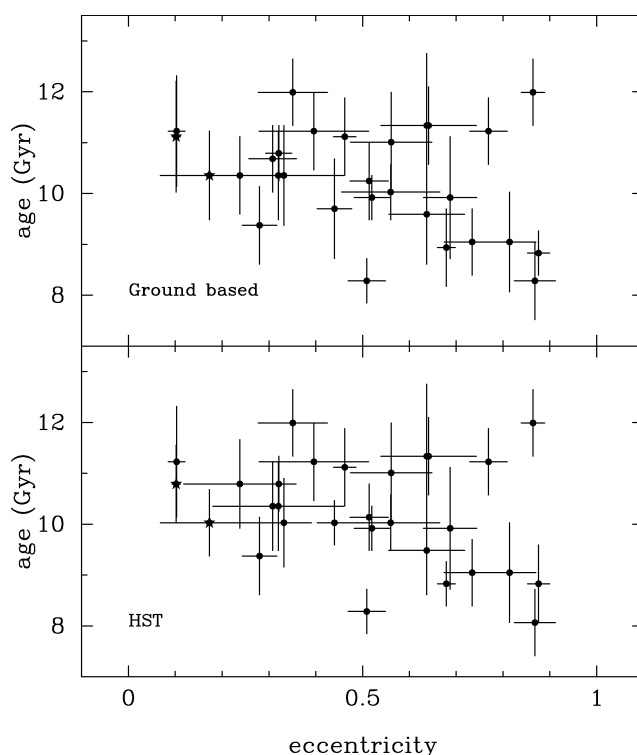


FIG. 4.—Ages for Galactic GCs from De Angeli et al. (2005) as a function of orbital eccentricity for two age data sets: ground based (*top*) and *HST* (*bottom*). Two metal rich clusters ($[\text{Fe}/\text{H}] > -0.8$) are represented with star symbols.

eter clusters with well-determined orbits: Pal 13, NGC 7006, and NGC 5466. These three clusters have high-energy orbits (i.e., they belong to the outer halo), and their orbits are highly eccentric. They are thus good candidates to have been produced in the SZ78 fragments which were later captured and disrupted. Their orbits however indicate that they come from three independent systems. If the outer halo was indeed made out of only a few very massive systems, one would expect better phase-space association than is demonstrated by these clusters, but of course the numbers are still very small.

3. THE SAGITTARIUS SYSTEM

Ibata et al. (1994) noted a large number of stars of magnitude about 17 and fainter in a direction toward the Galactic center that appeared to be at about the same distance and radial velocity. The Sgr system is now known to extend over many degrees and to show multiple tidal tails that are extremely long (Belokurov et al. 2006a). In addition to the main body of the Sgr system there are four nearby GCs that appear to be comoving with Sgr and at a similar distance. These are M54, Terzan 7, Terzan 8, and Arp 2 (Da Costa & Armandroff 1995). The relatively young GC Pal 12, somewhat further away, seems also to be comoving with the system (Dinescu et al. 2000) and

is now generally believed to be a Sgr member (Cohen 2004; Sbordone et al. 2007), as is Whiting 1 (Carraro et al. 2007). M54 is one of the most massive GCs in the Galaxy and was probably the nucleus of Sgr when it was a more independent entity than it is now, possibly a nucleated dwarf galaxy (Sarajedini & Layden 1995). Two properties of these GCs are very revealing of the star formation and evolution of small system age and chemical composition.

3.1. Ages and Overall Metallicities in Sgr and Its GCs

To first order, CMDs provide information on both the age and metallicity of a GC. Ages can be estimated by the luminosity of the turnoff. The estimate of a system's age can be complicated by the presence of stars of either several discrete ages or a range of ages and/or compositions. Once an age for a component of a system has been established, a rough idea of its overall metallicity can be estimated from the absolute magnitude (and color) of the brightest red giants. These procedures have been known for half a century (Sandage, 1953; Hoyle & Schwarzschild 1955), and greatly refined by many authors over the years. Our best current estimates of the ages and metallicities (based on both photometric and spectroscopic studies) of Sgr and its GCs are: Sgr: 1–13 Gyr, -1.6 to $+0.1$; M54: 13 Gyr, -1.55 ; Terzan 8: 13 Gyr, -2.0 ; Arp 2: 11 Gyr, -1.8 ; Terzan 7: 7.5 Gyr, -0.6 ; Pal 12: 6.5 Gyr, -0.8 ; Whiting 1: 6.5 Gyr, -0.65 (taken mostly from Harris 2003). The range of ages and metallicities both within Sgr and its clusters is remarkably large. Sgr itself seems to have stars with a range of ages from 12 or 13 Gyr down to about 1 Gyr with metallicities that range from $[\text{Fe}/\text{H}] \sim -1.5$ to solar (Layden & Sarajedini 2000; Smecker-Hane & McWilliam 2002; Bonifacio et al. 2004; Monaco et al. 2005). The GCs do not show internal spreads of age or metallicity, but show large differences in these quantities when compared with each other. M54, the likely nucleus of Sgr, is 13 Gyr old with $[\text{Fe}/\text{H}] = -1.55$ (Brown et al. 1999). Terzan 8 is as old as Sgr and M54 and even more metal-poor. Arp 2 is similarly metal-poor but likely a few Gyr younger. On the other hand, Terzan 7, Pal 12 and Whiting 1 are many Gyr younger and much more metal-rich. These are three of the few definitively young GCs of the halo. The positions of Terzan 7 and Pal 12 in the Lee diagram are shown in Figure 3. Despite their wide range in ages and metallicities, the Sgr systems appear to fall along the $\Delta t = 0$ Gyr line. However, Ter 7 and Pal 12 could have any age from 0 to -4 Gyr while Arp 2 and Ter 8 could lie anywhere from -2 to $+2$ Gyr. As Figure 3 shows, clusters with $(B - R)/(B + V + R)$ near -1 and $+1$ cannot have their ages determined from their position in Figure 3.

These wide ranges of age and metallicity raise significant questions regarding their past histories. It is unclear how Sgr, a dSph or perhaps originally a nucleated dE galaxy, could have retained sufficient interstellar matter for continuous or intermittent star formation over a period of 10 Gyr and cluster

formation over 6.5 Gyr, half of its lifetime. SN ejecta cannot be retained by the gravitational field of a small galaxy (although see Marcolini et al. 2006), but perhaps Sgr was above the minimum mass required. The only nongravitational way to retain such high-velocity material is by running it into ambient interstellar matter, whereby its kinetic energy can be converted to thermal energy in a shockwave and then radiated away. Even that process will not work for ever as momentum transfer to the interstellar clouds will eventually blow them out of the system. We just do not know how such systems could have “reinvented themselves” every few Gyr. This problem pervades the dSph systems (Table 6 of Mateo 1998). However, this problem is actually least severe for Sgr, the most massive dSph.

3.2. Comparing Chemical Abundances in Sagittarius and Its GCs

To treat Sgr and its GCs as a single evolving system, we plot the mean $[\text{X}/\text{Fe}]$ values for elements X against $[\text{Fe}/\text{H}]$ in Figure 5 for M54, Pal 12, Ter 7, and Sgr itself (five, four, three, and ~ 25 stars, respectively). There are no high-resolution results for Ter 8, Arp 2, or Whiting 1 as of this writing. The data are from Brown et al. (1999), Cohen (2004), Tautvaisiene et al. (2004), Smecker-Hane & McWilliam (2002), and Bonifacio et al. (2004). For Na/O with a likely significant range within one of the systems we use the high end for the O and the low end for the Na to handle possible internal depletion of O and enhancement of Na.

Most species do not show a metallicity trend. The mean values of $[\text{X}/\text{Fe}]$ are approximately -0.25 for Na, $+0.1$ for O, 0.0 for the α -elements (Mg, Si, Ca, and Ti), -0.15 for the light s -process elements Y and Zr, and $+0.5$ for the r -process element Eu. For the heavy s -process elements Ba and La there is a well established trend from near 0.0 at $[\text{Fe}/\text{H}] = -1.5$ to $+0.4$ at $[\text{Fe}/\text{H}] = -0.5$. A similar although stronger trend in the heavy s -process elements has been seen in ω Cen (Vanture et al. 1994; Norris & Da Costa 1995; see Fig. 11).

In Figure 6 we show the mean abundances of various species in each of the Sgr system's GCs and for the most metal-rich stars in Sgr itself. For the abscissa we use the age assigned to each system. Starting with oxygen, we see that $[\text{O}/\text{Fe}]$ has remained constant from the time of star formation in M54 until recent star formation in Sgr. The slightly discrepant value for Ter 7 may well be due to random errors when the O abundance depends on only one line (which must be corrected for atmospheric absorption) in a few stars. Note that Sbordone et al. (2007) have derived a slightly lower mean value of 0.18 from four stars; $[\alpha/\text{Fe}]$, which is determined more reliably, descends from $+0.2$ to 0.0 or -0.1 from 13.5 Gyr to about 2 Gyr ago. Evidently, the ratio of SNe II to SNe Ia did not change very much during that interval. For Sgr and its GCs, $[\alpha/\text{Fe}]$ is low compared to the halo and nearly independent of $[\text{Fe}/\text{H}]$ (but does show an indication of a small age gradient). We discuss this further in § 5. Turning to $[\text{Na}/\text{Fe}]$, we see that it descends

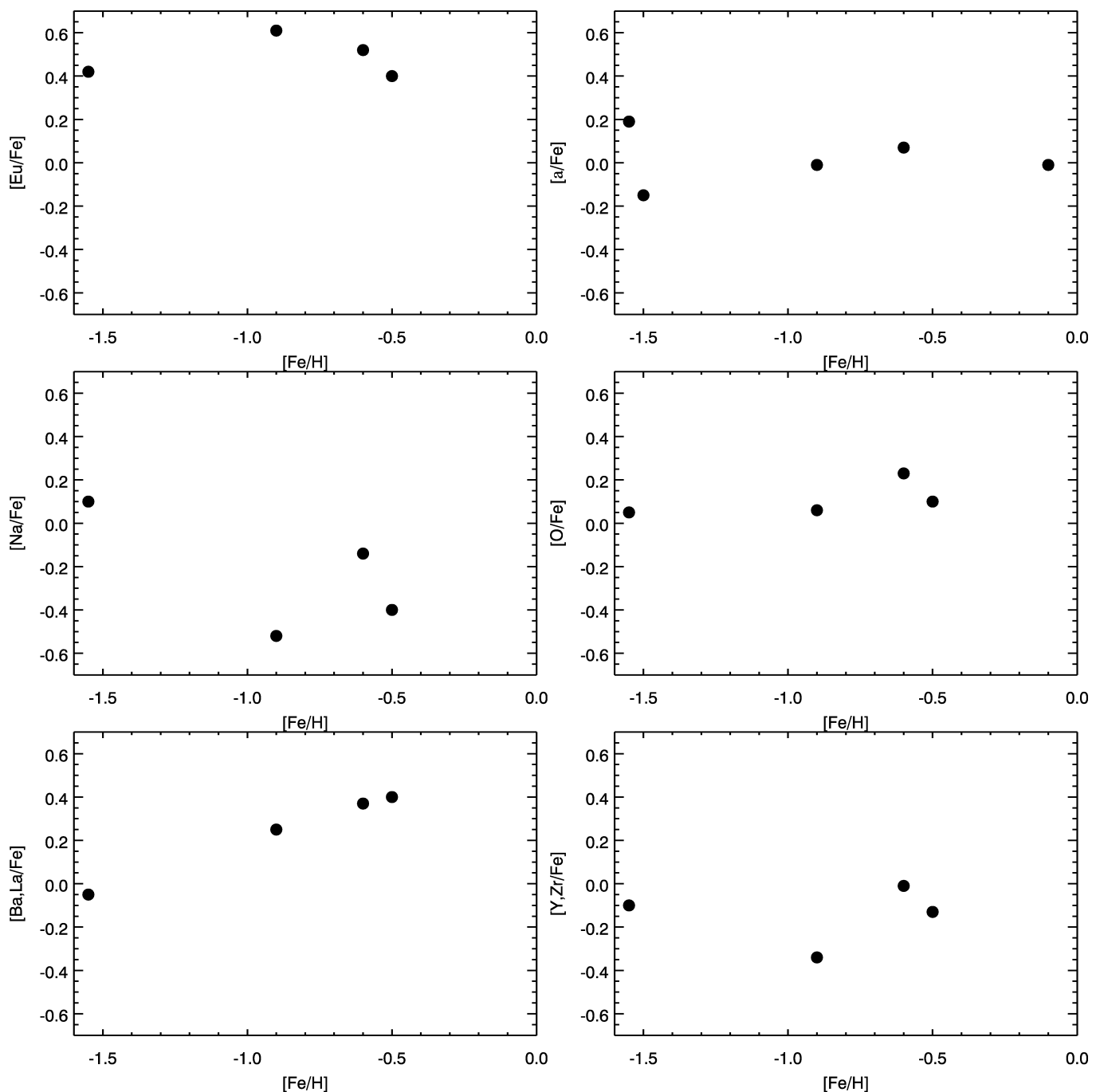


FIG. 5.—Trends of abundance of various elements or element groups with $[\text{Fe}/\text{H}]$ in the various systems that are associated with the Sagittarius Galaxy.

from $+0.1$ to -0.4 as Fe built up more rapidly than did Na. The light s -process elements, represented by Y and Zr do not show a significant trend, but the difference between Ter 7 and Pal 12 is intriguing, as it is for Na. The heavy s -process elements, Ba and La, show a strong increase with time, while the r -process species, Eu, has remained high, near $[\text{Eu}/\text{Fe}] = +0.5$ for all systems. Both the heavy s - and r -process patterns are similar to what is seen in many halo stars.

4. DETAILED CHEMICAL EVIDENCE FROM EXTRAGALACTIC SYSTEMS

4.1. Chemical Tagging

Detailed abundance distributions containing strategic elements are very useful as a tool for comparing the chemical compositions of the dwarf galaxies with the compositions of Galactic halo, thick disk, and thin disk stars. The elemental

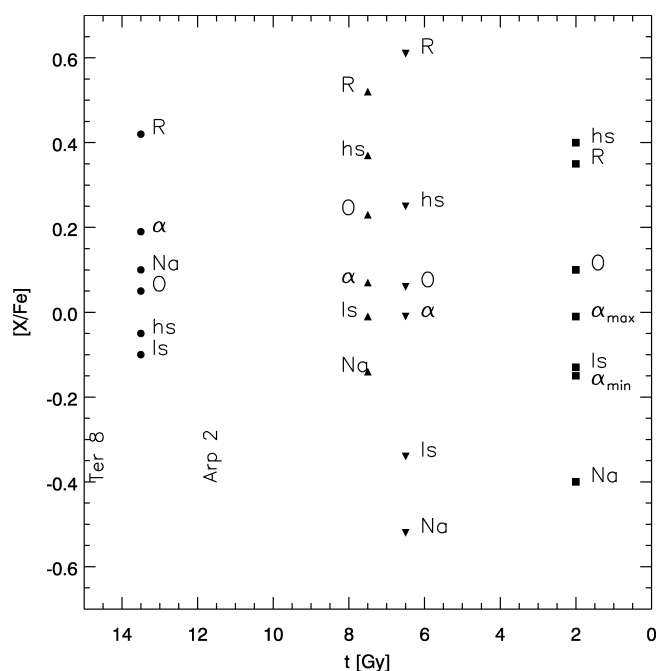


FIG. 6.—Trends of abundance of various elements or element groups with age in the various systems that are associated with the Sagittarius Galaxy.

abundances of Galactic populations have been rather well-studied for many key elements; these abundances are available and well-sampled from solar metallicities down to $[\text{Fe}/\text{H}]$ of about -4.0 . Galactic studies that are used as comparisons here are Edvardsson et al. (1993) and Reddy et al. (2003) for the thin disk, while Prochaska et al. (2000) and Reddy et al. (2006) provide abundance distributions for thick disk stars. At lower metallicities, recent fairly large surveys of abundances in halo stars include Fulbright (2000), Johnson (2002), Fulbright & Johnson (2003), and Cayrel et al. (2004). The work by McWilliam et al. (1995) is useful for including stars having extremely low metallicities ($[\text{Fe}/\text{H}] < -3.0$). This section focuses on a comparison of field stars; however, there are a number of GCs in the metallicity range from $[\text{Fe}/\text{H}] = -1$ to -2 . Below $[\text{Fe}/\text{H}] = -2$, the number of halo stars diminishes steadily toward $[\text{Fe}/\text{H}] = -4$ with several intriguing objects that show $[\text{Fe}/\text{H}] < -5.0$. Only a few GCs have $[\text{Fe}/\text{H}] < -2$, and none are known below -2.5 .

Abundances in some dwarf galaxies of the Local Group are compared to Galactic abundances from the studies described above. In particular, the studies by Shetrone et al. (1998, 2001, 2003) and Geisler et al. (2005) of dwarf spheroidals are used, as well as the LMC studies by Smith et al. (2002), Hill et al. (2000), and Korn et al. (2002) and those of the Sgr galaxy by Smecker-Hane & McWilliam (1999), McWilliam et al. (2003), and McWilliam & Smecker-Hane (2005a). Table 6 of Mateo (1998) shows $[\text{Fe}/\text{H}]$ values for old populations of 28 Local Group galaxies ranging from -2.2 to -1.0 . The distribution is similar to that of the Galactic GCs with a median at

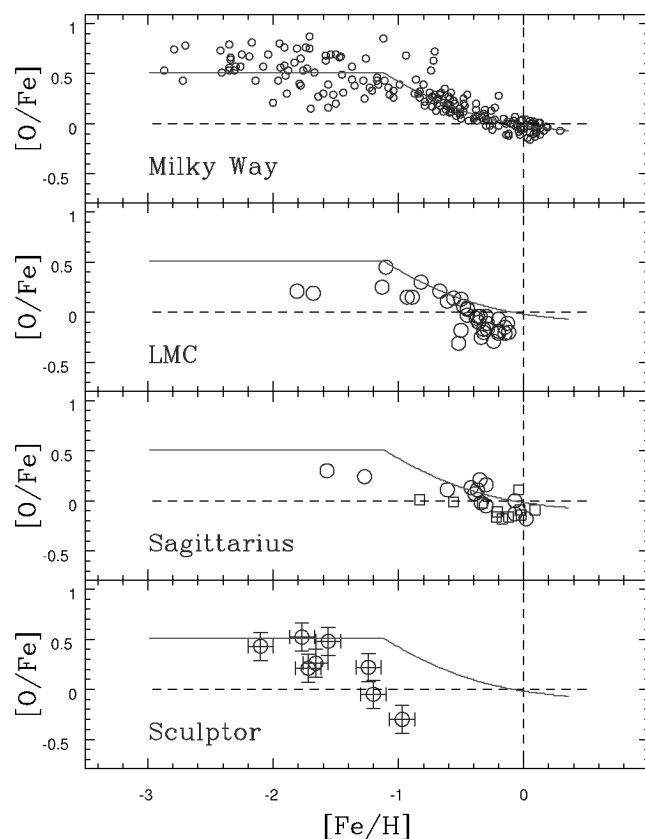


FIG. 7.— $[\text{O}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ for samples of stars in four different galaxies. The solid curve is a model fit described in the text. O abundances in the extragalactic samples are generally depleted with respect to their Galactic counterparts. [See the electronic edition of *PASP* for a color version of this figure.]

-1.55 . All of the Local Group galaxies have a range of metallicities and virtually all also have a range of ages, a phenomenon seen for certain among the GCs only in ω Cen, which is a likely capture. Several recent papers have shown that the dwarf systems show significant ranges not only in $[\text{Fe}/\text{H}]$ but also in the ratios of various elements to iron (Shetrone et al. 2003; Geisler et al. 2005). The comparison of Galactic and dwarf galaxy populations relies primarily on how the ratios of various elements to iron (expressed as $[\text{X}/\text{Fe}]$) depend on the overall metallicity, as defined by $[\text{Fe}/\text{H}]$. These ratios reveal details about how different galactic systems enriched themselves as the overall metallicity increased.

Our comparison begins by investigating the behavior of oxygen, a quintessential product of massive star enrichment and dispersal via SNe II that tracks the formation of massive stars. Figure 7 shows the behavior of $[\text{O}/\text{Fe}]$, as determined from either the 6300 \AA line or the infrared vibration-rotation OH lines, for the Milky Way, the LMC, the Sagittarius dwarf galaxy, and Sculptor (hereafter Scl). This first comparison of $[\text{O}/\text{Fe}]$ is restricted to these three satellite galaxies as these are the ones that have had the largest numbers of member stars analyzed.

The top panel in Figure 7 summarizes results for stellar members of the Milky Way thin disk, thick disk, and halo. The general structure of $[\text{O}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ for Milky Way populations is now reasonably well-defined; values of $[\text{O}/\text{Fe}]$ are larger for the metal-poor halo stars with typical values being $+0.5$ for $[\text{Fe}/\text{H}] \leq -1.0$. There may be a slight slope such that $[\text{O}/\text{Fe}]$ increases with decreasing $[\text{Fe}/\text{H}]$, but such a slope if present is not large (being less than about 0.10 dex per dex). At $[\text{Fe}/\text{H}] \sim -1.0$, $[\text{O}/\text{Fe}]$ begins to decrease and reaches a value of 0.0 at about solar $[\text{Fe}/\text{H}]$. The elevated values of $[\text{O}/\text{Fe}]$ for metal-poor stars can be understood as both O and Fe being produced as a result of SNe II with the masses being distributed along a standard initial mass function (IMF; e.g., yields from Woosley & Weaver [1995] would predict $[\text{O}/\text{Fe}] \sim +0.3$ to $+0.6$, with uncertainty due primarily to the mass cut for Fe production), while the decreasing $[\text{O}/\text{Fe}]$ for higher metallicities occurs as SNe Ia inject mainly Fe into the interstellar medium.

The solid curve in the top panel of Figure 7 is a simple model of chemical evolution for the Milky Way in which oxygen and iron from SNe II and SNe Ia are added to gas. This model is taken from the paper by Smith et al. (2002) in their study of the LMC. The model is described in their paper, but is simply a numerical model in which yields of O and Fe from SNe II and SNe Ia are added at certain rates into a mass of gas that is undergoing continuous star formation. The numerical model from Smith et al. is similar in its assumptions to the analytical models of Pagel & Tautvaisiene (1995). In this model oxygen yields are taken from Woosley & Weaver (1995) and convolved with a Salpeter mass function. Based on results from Timmes et al. (1995), the Fe yield from SNe II was set to $0.15 M_{\odot}$ per event; these numbers produce a value of $[\text{O}/\text{Fe}] = +0.5$ from the mass-convolved SNe II. The downturn in $[\text{O}/\text{Fe}]$ at $[\text{Fe}/\text{H}] \sim -1.0$ (as is observed) was produced with an average SN II rate of one per 100 yr and SNe Ia beginning after 1.2 Gyr at a rate of 1/3 that of SNe II, with each SN Ia event producing $0.7 M_{\odot}$ of Fe. Of course such a model is not unique and is an oversimplification; however, it does a fair job of fitting the Galactic trend and this model relation can serve as a fiducial curve in comparison to the dwarf galaxies.

The second, third, and fourth panels of Figure 7 summarize current results for the LMC, the Sgr galaxy, and Scl, respectively. Superimposed on each dwarf galaxy $[\text{O}/\text{Fe}]$ – $[\text{Fe}/\text{H}]$ relation is the fiducial model constructed for the Milky Way. There is a consistent trend in each of the dwarf galaxies to exhibit lower values of $[\text{O}/\text{Fe}]$ relative to the Milky Way as $[\text{Fe}/\text{H}]$ increases. Both the LMC and Sgr have quite similar relations, with only moderately low $[\text{O}/\text{Fe}]$ values compared to the Galactic curve. Scl, on the other hand, is strikingly different from the Milky Way, with $[\text{O}/\text{Fe}]$ values beginning a precipitous decline at a low overall metallicity ($[\text{Fe}/\text{H}] \sim -1.7$).

We next comment on the other commonly studied α -elements, Mg, Si, Ca, and Ti, in turn. Here we concentrate on the two galaxies with the best existing data: Scl (Shetrone et al. 2003, hereafter S03; Geisler et al. 2005, hereafter G05) and

the LMC (Johnson et al. 2006, hereafter J06; Pompeia et al. 2007, hereafter P07).

The Scl stars were selected to cover as much of the well-known metallicity spread in that galaxy as possible, and current results (Tolstoy et al. 2001, 2004) indicate success in this regard. As noted before, good high-resolution abundances for a variety of elements for older MC stars are sorely lacking. The best studies to date with such abundances are those of J06, who observed 10 giants in a total of four old LMC clusters covering a range of metallicities from ~ -1.2 to -2.2 , and the FLAMES study of P07, who investigate abundances of ~ 60 giants ranging in metallicity from -1.7 to -0.3 . We include here only the LMC stars that overlap in metallicity with the Scl sample.

Figures 8a–8d shows the behavior for these four elements. Note that typical halo abundances are $\sim +0.4$ for each element over this metallicity range. In general, the Scl and LMC stars are significantly depleted in all four α -terms with respect to their Galactic counterparts at similar metallicity, as already noted by S03, G05, J06, and P07. The exceptions in general are the more metal-poor stars which tend to be very similar to the halo or only slightly depleted. The depletion is largest for the most metal-rich stars. The detailed α -abundance distributions for these two very different external galaxies (one a dSph and the other a Magellanic irregular) are quite similar. In addition, one can draw a single line in the Mg and Ca plots that does a good job of fitting both galaxies with no evidence for kinks. The slope of this line is very similar to that shown in our Galaxy for the transition from the pure halo (at low $[\text{Fe}/\text{H}]$) to pure disk (at high $[\text{Fe}/\text{H}]$), but is offset to lower metallicities in the dwarfs. However, there are some important differences between the behavior of these two galaxies in these diagrams. With the exception of a single star in Mg, the largest enhancements occur in the LMC. In Mg and Si, Scl has several stars that are more depleted than any LMC stars. Thus, the LMC stars are in general less distinct from their halo counterparts than Scl stars. We return to the α -elements in more detail in § 5.

Moving from the α -elements, the next element considered as a comparison species is sodium. This element is selected as it is well-represented in the dwarf galaxy results to date and its behavior looks different than in the Milky Way in certain respects (S03). Sodium provides somewhat different insights into chemical evolution than oxygen and the other α -elements; although it is primarily a product of SNe II in most stellar populations, its yield is metallicity dependent. The main source of Na is carbon-burning; however, it is also both produced and destroyed by proton captures. The final yield from SNe II then depends on the p/n ratio, which is itself a function of metallicity, decreasing as the overall metallicity increases. In Figure 9 Na is combined with O, and $[\text{Na}/\text{Fe}]$ is plotted versus $[\text{O}/\text{Fe}]$. Galactic results are shown as the small black symbols, with the thin disk represented by asterisks, the thick disk by open squares, and the halo by open circles. The dwarf galaxies are

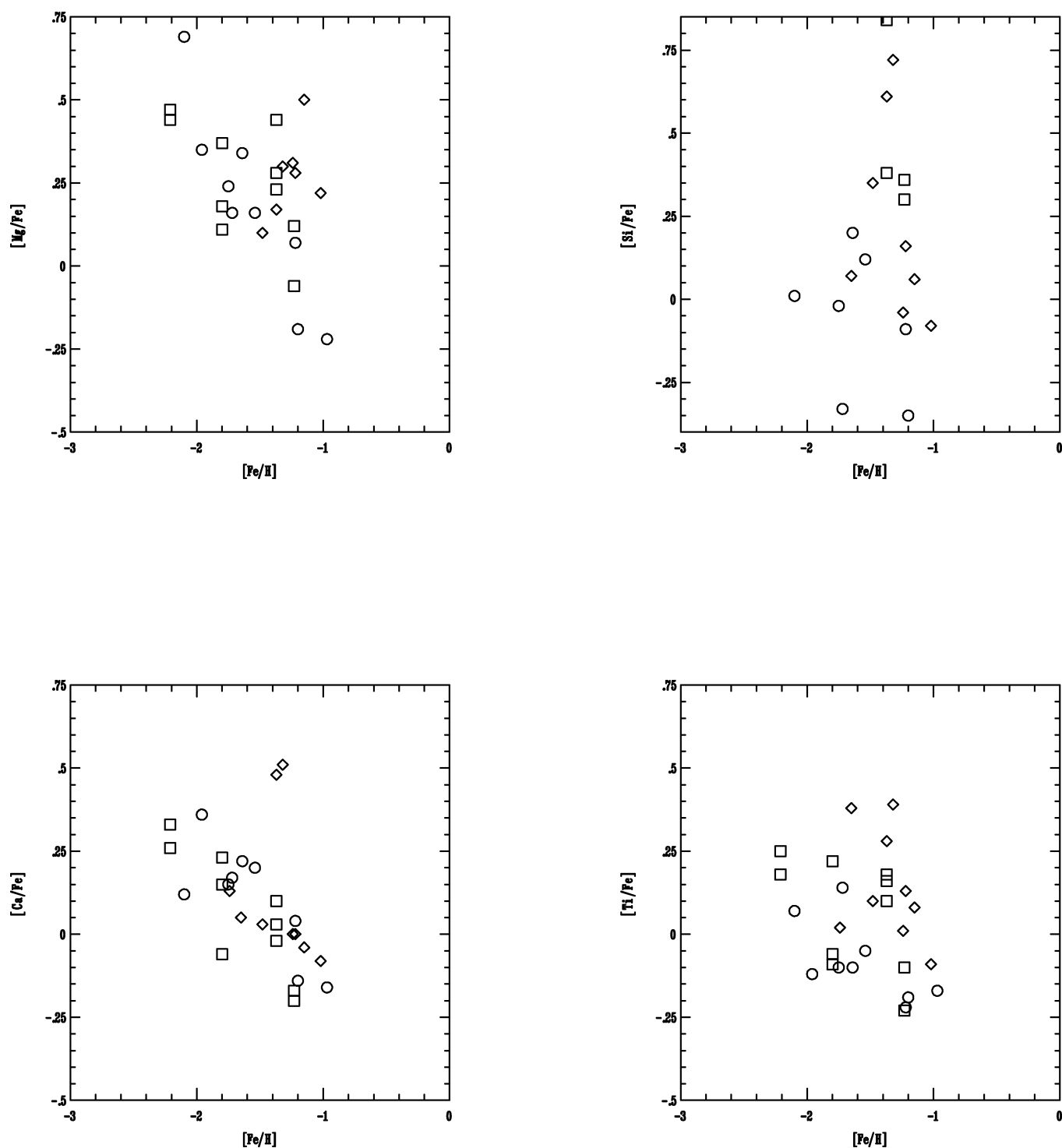


FIG. 8.—Mg, Si, Ca, and Ti abundances vs. $[\text{Fe}/\text{H}]$ for giants in Scl (*circles*) and 2 LMC samples (J06 clusters: *squares*; P07 field stars: *diamonds*).

the gray solid points. In this diagram, the dwarf galaxies clearly segregate, on average, from the Milky Way results. The solid lines are schematic representations of what sort of chemical evolution would occur in simple, extreme examples. Starting

at an elevated value of $[\text{O}/\text{Fe}]$ and lower $[\text{Na}/\text{Fe}]$ (as would be expected in a metal-poor environment that had been dominated chemically by SNe II ejecta) the vertical line is what could be expected approximately from pure SNe II ejecta being

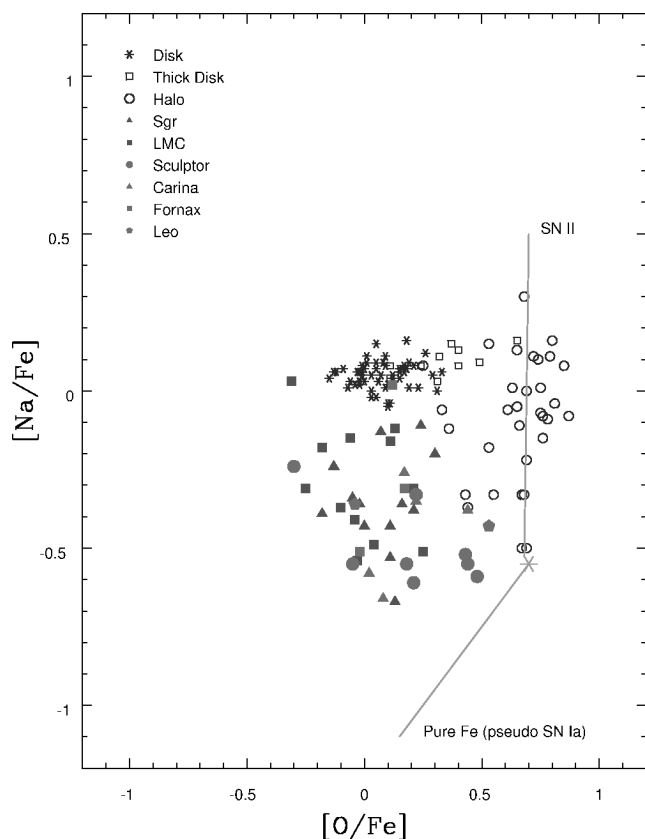


FIG. 9.—[Na/Fe] vs. [O/Fe] for stars in the Galaxy (*black symbols*) and various extragalactic samples (*gray*; see key). Solid lines represent schematic representations of contributions expected from pure SNe II and SNe Ia. [See the electronic edition of *PASP* for a color version of this figure.]

instantaneously recycled into new massive stars; the oxygen and iron yields are not terribly metallicity sensitive, while the sodium yield increases as the metallicity increases, and p/n decreases. By-and-large the Milky Way halo stars follow such a pattern. The solid line leading toward equally decreasing values of [O/Fe] and [Na/Fe] would result from the addition of pure Fe and is meant to mimic approximately the contribution from pure SNe Ia ejecta. Within this diagram, the differences between the dwarf galaxies and the Milky Way populations can again be understood as being dominated by a population of low-metallicity SNe II (where such stars would form from the much slower increase in metallicity due to inefficient star formation) and a higher proportion of SNe Ia. Very few Galactic halo stars overlap the dwarf galaxy results in Figure 9.

The above illustrated abundance ratios demonstrate that different galactic environments produce distinct behaviors in how [X/Fe] varies from one element to another. Using iron as a fiducial element, however, can complicate certain comparisons, as Fe has substantial contributions from both core-collapse SNe II and the longer lived binary SNe Ia. The differences, as

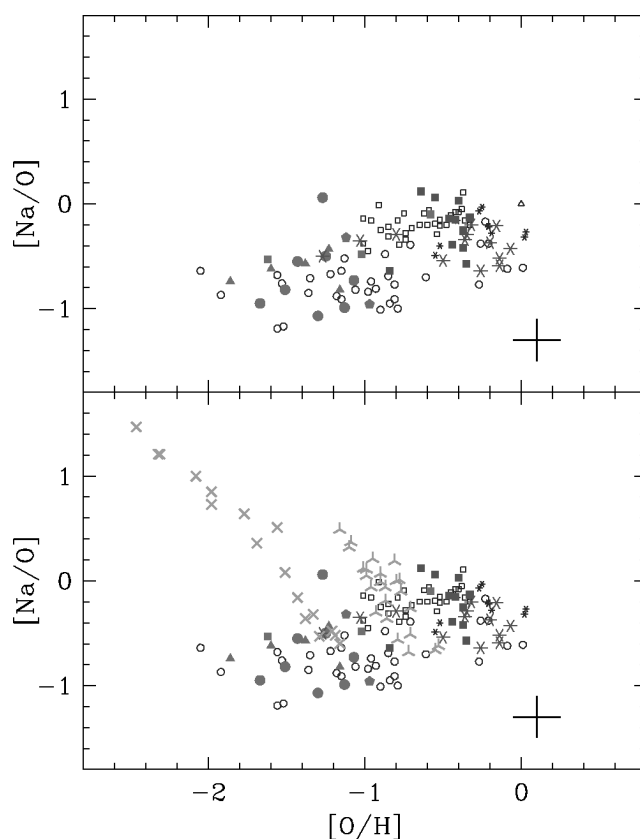


FIG. 10.—[Na/O] vs. [O/H] for (*top*) field stars in the Milky Way and dwarf galaxies (symbols as in Fig. 9) and (*bottom*) as in the top panel but also including stars from two GCs in light gray: M13 (*crosses*) and M4 (*three-pronged symbol*). [See the electronic edition of *PASP* for a color version of this figure.]

discussed above and below, quite probably are dominated by differing star formation rates or the efficiency at which a galaxy can convert its gaseous reservoir into stars, as well as the presence and strength of galactic winds. It can be useful to also investigate abundance ratios that more nearly isolate elemental yields from a single source. Such a comparison is attempted in Figure 10, where oxygen, not iron, is used as the main metallicity indicator. In this figure values of [Na/O] are plotted versus [O/H]. In the top panel only field stars from the Milky Way populations and the dwarf galaxies are shown. In this case, unlike Figure 9 (where dwarf galaxies segregate clearly from the Milky Way populations), the dwarf galaxy points fall within the Galactic halo stars. Predicted model yields (e.g., Woosley & Weaver 1995) produce increasing [Na/O] values as [O/H] (or overall stellar metallicity) increases, as is seen in the top panel of Figure 10. This demonstrates that in the field star populations of both the Milky Way and the dwarf galaxies, Na and O production are dominated by SNe II. In GCs, the Na/O ratio varies wildly due to proton captures that reduce O and enhance Na. The location of these processes remains uncertain,

but possibly occurs in a previous generation of massive asymptotic giant branch (AGB) stars (Ventura & D'Antona 2005).

The bottom panel of Figure 10 plots the same field-star points as in the top panel, but also includes results for two well-studied GCs: M13 and M4 (with M13 being the lower metallicity cluster). The abundances for the M13 stars were taken from the paper by Kraft et al. (1997) and for M4 from Ivans et al. (1999). In the case of the GCs the well-established Na-O anticorrelation stands out, with a larger Na-O abundance variation in M13 than in M4. These abundance variations have been established even in unevolved main-sequence stars in GCs and point to some type of chemical evolution which occurs in the early environment of these clusters. The abundance variations also include F, Al, and Mg and point to a nucleosynthetic site driven by proton captures at temperatures of roughly 5×10^7 K (e.g., Kraft et al. 1997). It is clear here, however, that GC-like chemical evolution in stellar populations can be isolated by using only Na and O.

The elements heavier than iron that are produced primarily by neutron captures, either the *r*- or *s*-process, can be adequately represented by two key elements, barium and europium. Barium is an *s*-process product, with about 85% of its solar system abundance due to the *s*-process, while europium is an excellent proxy for measuring *r*-process contributions as some 97% of solar system Eu nuclei arose from *r*-process nucleosynthesis (Burris et al. 2000). Most *s*-process elements are created as a by-product of neutron captures that are driven by thermal pulses in AGB stars, while the *r*-process neutron captures occur during SNe II (for a review of the neutron-capture elements and their relation to stellar evolution, see Wallerstein et al. 1997). The abundance ratio of Ba/Eu is thus an approximate measure of the relative importance of AGB star chemical contributions, relative to SNe II.

Figure 11 summarizes results for [Ba/Eu] as a function of [Fe/H] for various stellar populations from the Milky Way, a sample of dwarf spheroidals, and the captured system ω Cen. The long-dashed horizontal lines represent values for [Ba/Eu] for pure *r*-process (bottom line) and pure *s*-process barium and europium abundances as set by the solar system *r*- and *s*-process fractions.

Low-metallicity Milky Way stars exhibit subsolar [Ba/Eu] values, closer to the pure *r*-process mixture, and this is indicative of higher fractions of SN II material characterizing the old Galactic halo population. A significant fraction of Galactic halo stars show only *r*-process Ba/Eu ratios in the interval of [Fe/H] ~ -3 to -2 . As [Fe/H] increases, there is a gradual increase in [Ba/Eu] up to [Fe/H] ~ -1.0 followed by a steep increase as [Fe/H] approaches the solar value. This increase in [Ba/Eu] reflects the increasing contributions from AGB stars as chemical evolution proceeds in the Milky Way.

The dwarf galaxy stars follow a different trend from the Galactic members. The extreme system is ω Cen, where [Ba/Eu] increases by a factor of 20–25 as [Fe/H] increases from

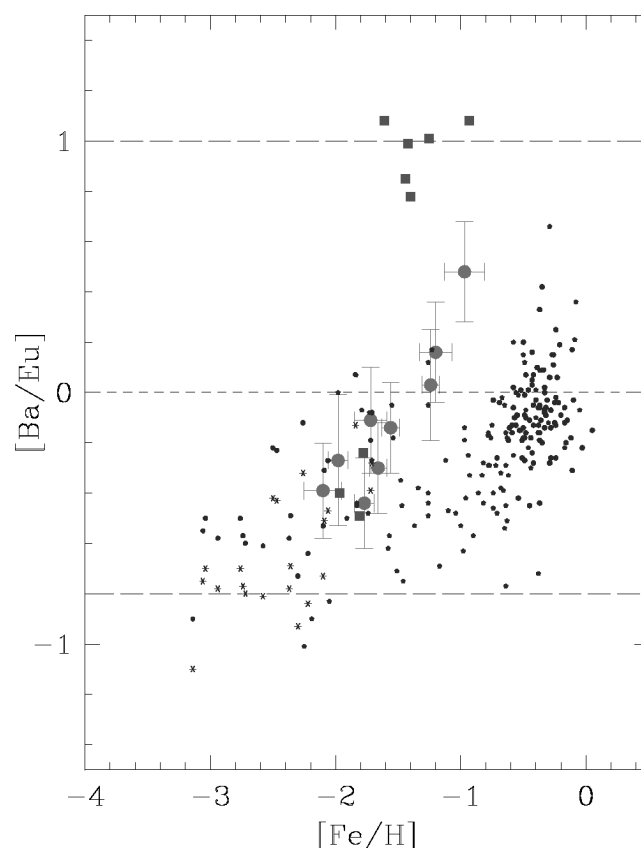


FIG. 11.—[Ba/Eu] vs. [Fe/H] for Galactic stars (same symbols as Fig. 9), dSph stars, Scl (large gray circles) and ω Cen (dark gray squares). The dashed lines show expected abundances for pure *r*-process (bottom) and pure *s*-process (top). [See the electronic edition of PASP for a color version of this figure.]

-2.0 to -1.5 . The more metal-rich stars in ω Cen exhibit a heavy-element abundance distribution that is dominated by a pure *s*-process origin, i.e., chemical evolution dominated by AGB stars. The dwarf spheroidal systems shown in Figure 11 follow a trend that is in-between ω Cen and the Milky Way, indicating that AGB stars are more important in the chemical evolution of these small galaxies, but not to the extreme found in ω Cen.

5. DISCUSSION

5.1. The Problem

We return to a more detailed discussion of the α -elements, which are particularly important both observationally and theoretically. For the purposes of this discussion, we include O as well as Mg, Si, Ca, and Ti, since their nucleosynthetic origins and abundance behaviors are generally similar (although differences may exist in detail [e.g., Shetrone 2004], but uncovering clear trends requires another level of observational complexity) and in order to compare with previous work, e.g., Nissen & Schuster (1997, hereafter NS97) and Gratton et al.

(2003). We refer here to the “[α /Fe]” abundance or simply the α -abundance as the mean of [O/Fe], [Mg/Fe], [Si/Fe], [Ca/Fe], and [Ti/Fe] (or whichever of these is available if not all are determined, where we require a minimum of three elements).

An intriguing trend for dSph stars to have lower α -abundances than in the halo was first noted by Shetrone et al. (2001, hereafter S01) and given more weight by the observations of additional dSphs by S03. In that work and in Tolstoy et al. (2003, hereafter T03), they combined their data for giants in seven dSphs including their sample of five Scl stars and found that over the metallicity interval from ~ -1 to -3 , the dSph α -abundances are typically 0.1–0.3 dex lower than in the Galaxy at the same metallicity and use this as a strong argument against the standard Searle-Zinn scenario for the formation of the Galactic halo from dSph-like objects. G05 added an additional four Scl stars which confirmed these results.

We can now examine this issue in much more detail and with larger samples by adding the new data on abundances in giants in the Sgr dSph from Smecker-Hane & McWilliam (2002), Bonifacio et al. (2004), and Monaco et al. (2005), in Ursa Minor (Sadakane et al. 2004), and the initial results for the first FLAMES dSph study (Tolstoy 2005, hereafter T05), who derives α -abundances for almost 100 stars in Scl. These latter are still preliminary, so we here only refer to her Figure 4. We also include the first results from similar observations of a few stars each in several Local Group dIrr galaxies, including NGC 6822 (Venn et al. 2001), WLM (Venn et al. 2003), Sextans A (Kaufer et al. 2004), and IC 1613 (Tautvaišienė et al. 2007) as well as LMC cluster stars (J06, P07). We also average the O, Mg, Si, Ca, and Ti abundances, which yields a single parameter describing α -abundances and has smaller internal errors, allowing one to see any possible trends more clearly. Finally, we can use new data from Fulbright (2002), Stephens & Boesgaard (2002), Gratton et al. (2003), Ivans et al. (2003), Cayrel et al. (2004), and Jonsell et al. (2005) to improve on the sample of Galactic comparison stars.

In Figure 12 we show the full current dSph, dIrr, LMC and halo data sets. Gray symbols denote the various Galactic samples, described below. We include the Scl stars from S03 and G05 as the black asterisks. The black stars are the Fornax dSph and the black filled circles are stars in other dSphs studied by S01 and S03. Dark gray filled circles are the Sgr sample of Smecker-Hane & McWilliam (2002), and the dark gray stars are the Sgr samples of Bonifacio et al. (2004), Monaco et al. (2005), and Sbordone et al. (2007). The gray triangles are from the LMC clusters studied by J06, the gray squares from the LMC field stars of P07 and the gray triangles are from the various dIrr studies. We have also searched the literature to include high-resolution studies of halo stars, especially those that have attempted to investigate abundances of stars that are the most likely to have been accreted, based on their kinematics. We first use the data of NS97. They studied a number of stars in the halo and thick disk and found an interesting group of halo stars with

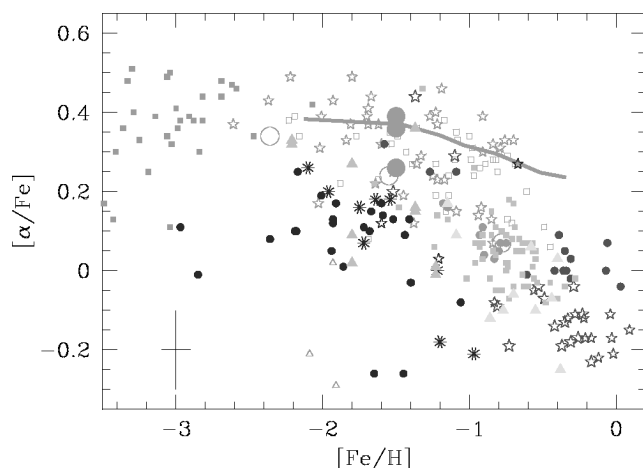


FIG. 12.—[α /Fe] vs. [Fe/H] for a variety of halo and extragalactic samples (see text for full explanation). Light gray symbols represent halo samples, black are for low-mass dSphs, dark gray for Sgr, light gray for the LMC, and light gray for dIrrs. In detail, solid light gray curve and light gray stars; Gratton et al. (2003) dissipative collapse and accreted halo stars, respectively; small light gray filled circles; NS97 low- α stars; mean values for the three F02 components as the large light gray filled circles; mean points for three different metallicity bins from Stephens & Boesgaard (2002); large light gray open circles; Ivans et al. (2003); light gray triangles; Cayrel et al. (2004); light gray filled squares; Jonsell et al. (2005); light gray open squares. The black stars are the Fornax dSph and the black filled circles are stars in other dSphs studied by S01 and S03. Black asterisks are from the Scl dSph studies of S03 and G05. Dark gray filled circles are the Sgr sample of Smecker-Hane & McWilliam (2002) and the dark gray stars are the Sgr samples of Bonifacio et al. (2004) and Monaco et al. (2005). The light gray triangles indicate the LMC clusters studied by J06 and the light gray squares LMC field stars from Pompeia et al. (2007). Observations of stars in dwarf irregular galaxies, including NGC 6822 (Venn et al. 2001), WLM (Venn et al. 2003), Sextans A (Kaufer et al. 2004), and IC 1613 (Tautvaišienė et al. 2007), are indicated as the light gray filled triangles. [See the electronic edition of *PASP* for a color version of this figure.]

significantly lower [α /Fe] than other stars of the same metallicity. These “low- α ” stars also have different kinematics and NS97 suggested they are good candidates for stars having been accreted from dwarf galaxies with a different chemical evolution history than that of the general halo. We also add data from Gratton et al. (2003), who have essentially repeated the NS97 analysis but with a significantly enlarged sample. They divide their halo stars into two kinematic samples: those with significant galactic rotation which they term the dissipative collapse component and those without rotation or with counterrotation, which they refer to as the accreted component. They find a significantly lower α -abundance at a given [Fe/H] for the second component relative to the first. Figure 12 includes the Gratton et al. (smoothed) mean for their large sample of dissipative collapse component stars as the solid curve, which is meant to represent the “normal” halo, their accreted component stars as the gray stars and the NS97 low- α stars as the small gray filled circles. Fulbright (2002, hereafter F02) studied a large number of “ α -poor” halo

stars. F02 found that the α -abundances correlated well with kinematics such that the most extreme α -poor stars had the largest Galactic rest-frame velocities, after dividing his sample into three velocity bins, with ~ 60 stars per bin. The largest velocity stars should be the closest known Galactic counterparts to the dSph stars. We show the mean values for his three components as the large gray filled circles, plotted at their mean values, where the point with the largest α -abundance is the lowest velocity bin and the smallest α -abundance is for the largest velocity stars. Stephens & Boesgaard (2002) derived detailed abundances for 56 halo stars kinematically selected to be the most likely candidates for being accreted, possessing either a very large apogalactic distance, a very large maximum distance above the plane, and/or a very large retrograde orbital velocity. Their mean points for three different metallicity bins, with from 3–32 stars per bin, are given as the large gray open circles. Ivans et al. (2003) investigated abundances in three stars known previously to have low- α abundances; these are shown as the gray triangles. Cayrel et al. (2004) have begun a large-scale study of abundances in very metal-poor stars, the First Stars project, and their initial results are given as the gray filled squares. The Jonsell et al. (2005) sample of 43 halo stars are the open gray squares.

Let us first look at the Scl sample, as it is by far the largest available to date for an external system, thanks especially to the FLAMES data. If there are any differences between galaxies, it is best to study them individually. The scatter seen in the Scl stars, including the T05 plot, is rather small except at the metal-poor end, where there are only a few stars. Note that the S03 and G05 small sample of stars nicely delineates the main features. There are several striking features about the Scl sample: the first is the clear trend of decreasing α -abundance with metallicity, with a uniform, continuous decrease. This is the first time that such a trend has been seen so clearly in a dSph. A decrease also occurs in the Galaxy but starting only at a metallicity > -1 . The second striking feature is that all Scl stars except for a handful of the most metal-poor FLAMES giants are depleted in their α -abundance relative to the Galaxy. At the metal-poor end the two samples merge but begin to diverge by $[\text{Fe}/\text{H}] \sim -2$ and the difference with the Galaxy is particularly striking for the most metal-rich stars, which are some 0.5 dex lower in $[\alpha/\text{Fe}]$ than their Galactic counterparts. Based on a large-scale Ca triplet study (Tolstoy et al. 2001), we are confident that the full metallicity range of this galaxy is represented. Unfortunately, then, we cannot say whether the α -abundances continue to drop at the highest metallicities or are higher at the lowest metallicities as there are simply no, or very few, stars at these metallicities in Scl.

Next we look at the full ensemble of galaxies depicted here. It was already clear from the work of S01, S03, and G05 that the dSphs have depleted α -abundances compared to the typical halo star and the present data set shows this even more clearly. They also pointed out the very interesting fact that the different

dSphs display very similar behavior in this diagram, despite their widely varied star formation histories. However, we can now point to the very important exception of Sgr, which does display unique behavior in this diagram.

Are there *any* stars in our halo that have abundances like those in dSphs? Until now, there was little overlap in the metallicities of dSph stars from the samples of Shetrone and collaborators with those of the low- α stars of NS97. But the G05 and Tolstoy et al. (2004) metal-rich Scl stars and the Sgr stars, as well as the addition of the Gratton et al. (2003) sample, now remove this problem and show some fascinating trends. Starting at the most metal-poor end, there are still only 2 stars observed at high resolution in dSphs with $[\text{Fe}/\text{H}] < -2.4$. These two stars have depleted α -terms, although note that there is at least one star in the Cayrel “First Stars” sample with similar metallicity and depletion. For $-2.4 \lesssim [\text{Fe}/\text{H}] \lesssim -1.6$, the bulk of the dSphs stars have depleted α -elements, although a few Scl FLAMES stars appear similar to the halo. There is a very occasional halo star that falls among the bulk of the dSph stars. One such star is the extreme halo star BD +80245, which has $[\text{Fe}/\text{H}] = -1.86$ and $[\alpha/\text{Fe}] = -0.29$ (Carney et al. 1997; Ivans et al. 2003). This places it near several of the most extreme low- α dSph stars (at slightly higher metallicities). However, this star lies one or two orders of magnitude below dSph stars in its Ba and Eu abundances, arguing against their common origin. From $-1.6 \lesssim [\text{Fe}/\text{H}] \lesssim -1.0$, the situation is grim indeed; there is essentially no overlap between the two samples, with the difference being very substantial, with the very notable exception of Sgr. Sgr alone actually shows quite good agreement (with a slight depletion) with the halo for the six stars for which good abundances exist. Clearly, it would be extremely useful to observe more metal-poor stars in Sgr to see if this trend continues. What is distinct about Sgr is of course that it is the most massive dSph known, with a mass at least several times greater than the next most massive dSph, Fornax, and many times larger than the other dSphs. Finally, only Sgr has stars more metal-rich than $[\text{Fe}/\text{H}] = -1$ with the exception of a single Fornax giant which is very halo-like. However, here we have a small problem; there appears to be an offset of about 0.15–0.2 dex between the α -abundances of Sgr stars at a given metallicity derived by Smecker-Hane & McWilliam and those of the Italian group (Bonifacio et al. 2004; Monaco et al. 2005; Sbordone et al. 2007). Note that this offset does *not* exist for the (small number) of metal-poor stars. We are uncertain as to the origin of this offset (see Monaco et al. for more details). We take the abundances at their face values. The data of Smecker-Hane & McWilliam suggest there may be some overlap with the most extreme low- α , high-metallicity halo stars, while the Sgr stars measured by the Italians continue the trend shown by the other dSphs of low relative α -abundances, although of course by the time we reach solar metallicity in the Galaxy, the mean α -abundance is also solar, and thus, even the Italian results show only a minor depletion of

~ 0.15 dex at this metallicity. These results build on those derived by Venn et al. (2004), who carried out a very detailed comparative study of the chemistry in different Galactic components, separated by their kinematics, and dSphs.

Thus, it appears that only the most massive dSph has stars similar in α -abundance to Galactic stars, even the most extreme low- α subset most likely to have been accreted. There appear to be very few stars in the less massive, more typical dSphs that overlap in this property with any stars in the Galaxy. This may be due to the likely possibility that Sgr was a dE galaxy rather than a dSph (Monaco et al. 2005). The difference in α -abundance with the Galactic mean for all dSphs except Sgr is *larger* at higher metallicity, i.e., $[\text{Fe}/\text{H}] \sim -1$, than at the lower metallicities previously well explored by S01 and S03. This is contrary to the suggestion by S03 that, although the metal-poor halo could not be made up of stars like those seen in dSphs, up to 1/2 of the metal-rich halo could have originated in such objects. Our analysis allows us to demonstrate that it appears very unlikely that a significant fraction of the metal-rich halo could have come from disrupted dSphs of low mass similar to those studied herein. However, it does appear possible from this diagram that at least some of the metal-poor halo may have come from typical dSphs, and that a portion of the intermediate-metallicity and metal-rich halo may have come from the accretion of very massive systems like Sgr.

However, McWilliam et al. (2003) and McWilliam & Smecker-Hane (2005b) show that Sgr stars have a unique Mn/Fe and Cu/Fe signature and also that at the metal-rich end, Sgr stars are depleted by ~ 0.4 dex in Na and Al with respect to their Galactic counterparts. Sbordone et al. (2007) confirm these findings and extend them to other elements including Sc, V, Co, Ni, and Zn. It is of paramount importance to clarify the abundances in Sgr stars already measured and obtain new data, especially for its most metal-poor red giants.

We can help to fill in this critical metal-rich zone for comparison to the halo by using recent high-resolution abundances derived for a small number of blue or red supergiants in each of several Local Group dwarf irregular (dIrr) galaxies. It is often assumed that the dIrrs are the counterparts of dSphs which have managed to retain their gas. Venn et al. (2001, 2003) and Kaufer et al. (2004) provide detailed abundances for several stars in NGC 6822, WLM, and Sex A, respectively, and we have included new results on IC 1613 (Tautvaisiene et al. 2007). These stars are shown as the gray triangles in Figure 12. We also add the LMC cluster results from J06 as gray triangles and the LMC field stars from P07 as gray squares. We see that the dIrr stars (granted only a small number) appear to be rather uniform in their behavior. The dIrrs, as first noted by Venn et al. (2003), as well as the LMC stars (as expected from Fig. 8), follow the general trend of the dSph stars very well, although the two most metal-poor dIrr stars, at $[\text{Fe}/\text{H}] \sim -1.2$ (in Sex A), are not as α -depleted as the stars from the low-mass dSphs, lying between them and the Sgr stars of comparable metallicity, but still depleted with respect to the bulk of the halo.

We are led to the rather amazing conclusion that the general α versus $[\text{Fe}/\text{H}]$ pattern of 12 of the 13 galaxies studied so far besides our own are similar to each other and very different from the Milky Way. Sgr appears to be the only possible exception.

These comparisons add renewed weight to the arguments first made by S01 and subsequently by F02, S03, T03 and G05 that the chemical compositions of stars present now in typical low-mass dSphs are distinct from those in the Galactic halo and disk. Our analysis adds to this argument by enlarging the sample and independently confirming this trend, and extending the metallicity regime to which this applies to higher metallicity; viz. we argue against the possibility suggested by S03 that some 50% of the metal-rich halo may have come from disrupted dSphs. In addition, however, we suggest that high-mass dwarf systems like Sgr may potentially be the source of some of the halo.

A comparison with GCs shows that there are a few α -poor systems such as Pal 12 (Cohen 2004) and Ruprecht 106 (Brown et al. 1997). However, the strongly retrograde GC NGC 3201 does not show an α -deficiency (Gonzalez & Wallerstein 1998). For ω Cen, the abundance history is extremely complex (Norris & Da Costa 1995). For the GCs associated with the Sgr system, Terzan 7 has a slightly lower $[\alpha/\text{Fe}]$ value at $[\text{Fe}/\text{H}] = -0.6$ than the Galactic field stars. Similarly, M54 (Brown et al. 1999) shows a mean $[\alpha/\text{Fe}]$ value of $+0.2$, about half of the value for field stars of similar metallicity, viz. $[\text{Fe}/\text{H}] = -1.55$. In general, however, GC stars and halo field stars have very similar chemical properties (except for the notorious Na-O-Al behavior in some GCs) and therefore shared the same chemical evolution history, which was different from that of typical dSphs (Pritzl et al. 2005).

The major implication of this of course is that the standard hierarchical galaxy formation scenario and the Searle-Zinn paradigm for the formation of the outer Galactic halo via accretion of “fragments” composed of stars like those we see in typical present-day dSphs is ruled out by the disjoint chemical signatures. We refer to this as “the problem.”

Can we tell if a given star in the halo originated from a dSph? As emphasized by S01 and S03 and further corroborated by this paper, dSph stars have broadly similar abundance patterns which are generally quite different from those found so far in our Galaxy. The distinct abundance signature of dSph stars, as well as kinematic differences expected for a disrupted system, suggest that it would be a rather unambiguous task to determine if a given star or stellar structure may have originated from a dSph like those studied here. An obvious first starting point is to search for metal-poor stars ($[\text{Fe}/\text{H}] < -1$) with $[\alpha/\text{Fe}] < 0.05$, as also suggested by Font et al. (2006a, 2006b). Sgr stars could still be missed by this criterion. But McWilliam et al. (2003) and McWilliam & Smecker-Hane (2005b) suggest even Sgr stars could be distinguished by using their unique $[\text{Mn}/\text{Fe}]$ and $[\text{Cu}/\text{Fe}]$ signatures.

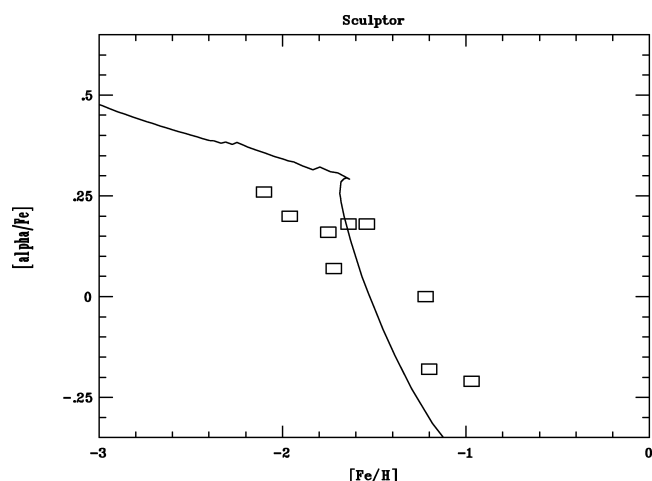


FIG. 13.— $[\alpha/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ for Scl dSph giants (squares) compared to the theoretical predictions of LF04 (solid curve).

5.2. Explaining the Problem

The uniformity of the chemical abundance patterns in dSphs (S01; S03; T03; this work) suggest a fairly uniform chemical evolution, despite the rather large range of star formation histories (e.g., Mateo 1998). Here we explore chemical evolution scenarios in dSphs and how their evolution appears to have differed from that experienced in our Galaxy. We would especially like to understand the reason for the distinct chemical abundances seen today between halo and dSph stars, in particular, the α -elements, as described in § 5.1. A great deal of progress has been made in very recent years which allows us to now understand the origin of these abundance differences.

The canonical description of Galactic chemical enrichment dates back to Tinsley (1979). She describes the abundance patterns expected due to the varying ratio of SNe II to SNe Ia during the lifetime of the Galaxy. SNe II arise from massive stars with main-sequence lifetimes $<10^8$ yr and have ejecta rich in the α -elements as well as Na and probably Eu. SNe Ia come from mass transfer onto a white dwarf, which explode after they pass the Chandrasekhar limit, typically at least 1 Gyr after formation. Their primary ejecta are Fe-peak elements. Thus, in an initial low-metallicity environment characterized by a standard IMF, the second generation of stars will exhibit enhanced α -abundances (compared to solar), with $[\alpha/\text{Fe}] \sim 0.4$, the standard SNe II ratio. As the Fe abundance slowly builds up, the α -abundances will remain enhanced at about this level until the lower mass SNe Ia begin to explode, ≥ 1 Gyr after the first episode of star formation. Thereafter, $[\alpha/\text{Fe}]$ will begin to decrease. This produces a “knee” in $[\alpha/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ at an $[\text{Fe}/\text{H}]$ that depends on the chemical evolution rate (basically the star formation rate and yield). If the star formation rate (SFR) is rapid, the galaxy will have achieved a relatively higher $[\text{Fe}/\text{H}]$ within a given time than would a system like a

dSph experiencing a lower SFR or an early burst followed by a long quiescence (e.g., Gilmore & Wyse 1991).

A complication arising in dSphs that is still unsolved is how such a dwarf galaxy was able to retain the products of powerful SNe II ejecta so that they could be incorporated in the next generation of stars, as a galactic wind is expected to be generated which could efficiently blow out any remaining gas (although, see Marcolini et al. 2006). Clearly, the loss of processed stellar ejecta (via a galactic wind), or infall of matter, can also influence the shape of the $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$ relation and also prevent star formation.

In the Milky Way, the SFR was relatively rapid and the Galaxy produced α -enhanced stars and enriched itself to $[\text{Fe}/\text{H}] \sim -1$ within the timescale for the first SNe Ia to go off, subsequently producing the knee seen in Figure 7. In Scl, the best observed dSph, we see a similar process: although it is not really clear what the general behavior for metal-poor stars is, they are certainly α -enhanced and may have a relatively shallow decrease in α with metallicity followed by an apparent knee at higher metallicity and a subsequent steeper decline of $[\alpha/\text{Fe}]$. The main difference with the halo is that the knee occurs at a much lower metallicity than in the Galaxy, ~ -1.7 .

The most straightforward interpretation of the $[\text{Fe}/\text{H}]$ value of the knee is that Scl had a lower SFR than in the Galaxy and only achieved an $[\text{Fe}/\text{H}]$ of ~ -1.7 before the onset of SNe Ia explosions. It is well known qualitatively that dSphs must have a lower SFR (e.g., Gilmore & Wyse 1991). Lanfranchi & Matteucci (2004, hereafter LF04) have modeled these effects in detail and find that the chemical differences between the dSphs and the halo are easily and simply understood as due to a combination of a low star formation efficiency (\sim SFR) and a high galactic wind efficiency in the former. They carry out chemical evolution models with a variety of parameters and try and match the observed abundances, star formation histories, and age-metallicity relations for the Local Group dSphs. They find that in every case except for Sgr, a very good match is derived when the star formation efficiencies are very low and the wind efficiencies are high. Sgr requires a substantially higher star formation efficiency. They predict both a depressed metal-poor plateau as well as the metal-poor knee. The knee is due both to the onset of SNe Ia as well as the occurrence of the galactic wind which blows out much of the available remaining gas and halts further star formation and subsequent SNe II. For example, the O, Mg, Si, and Ca abundances of Scl available to them (those of S03) are well fit by a star formation efficiency of 0.05 – 0.5 Gyr^{-1} and a high wind efficiency. We now add the G05 α -data for Scl and have combined the predictions for individual elements from the best-fit Scl model of LF04 into a single- α curve. The results are shown in Figure 13. Again, we include in our discussion a comparison with the FLAMES results of T05. The predicted knee at $[\text{Fe}/\text{H}] = -1.6$ is very pronounced and fits the data reasonably well, especially when the FLAMES results are included. The smaller slope at lower metallicity is not as clearly defined by

the data, which show a larger spread in this metallicity regime. The steep slope at higher metallicity fits the data, although the data show a somewhat shallower decrease. The overall agreement is reasonable and lends credence to the LF04 analysis. We note that their models also do quite well in fitting the sparser data for other dSphs. However, note that the Scl data could be fit even better by a model producing a constant decline in $[\alpha/\text{Fe}]$ with $[\text{Fe}/\text{H}]$.

The success of their model in explaining the α -abundances prompted Lanfranchi et al. (2006) to also apply it to the evolution of Ba and Eu in dSphs. Using the same best-fit parameters found for the α -abundances, i.e., star formation efficiency and galactic wind efficiency, they find similar good fits to these important heavier elements in the dSphs with the best data available, including Scl. We reproduce here as Figure 14 their figure for Scl, but have included two additional stars that they did not which show an excellent fit to the data. They find the same kind of knee as for the α -elements, at the same metallicity and for the same reasons. Again, the roles of SFR and galactic winds are critical. Both elements are produced early on in the lifetime of a galaxy in relatively constant amounts by SNe II, yielding the horizontal line at low metallicity. However, when SNe Ia begin to kick in after about 1 Gyr of evolution, a galactic wind is generated which stops further star formation and hence SNe II. Thus, no more Eu is produced, but Ba slowly begins to rise as the contribution from AGB stars becomes important. A similar rise is again seen in the Galaxy but at higher metallicity (see Fig. 11) due to the higher SFR there.

Thus, we are led to a simple explanation for the differences in abundance behavior that we see between the halo and its nearest galactic neighbors: the halo experienced much quicker chemical evolution due to its higher SFR, and the dSphs, at least the typical low-mass ones, experienced strong galactic winds which suppressed further massive star formation after SNe Ia began to explode. The latest models of Lanfranchi and collaborators account quite well for the observed differences.

However, such models do have at least one glaring failure: their predicted metallicity distribution does not mimic observations. Both the large samples derived from Ca triplet studies (Tolstoy et al. 2001) as well as the detailed $[\text{Fe}/\text{H}]$ values based on FLAMES results (Tolstoy et al. 2004) for Scl show that the observed metallicity distribution is essentially bimodal, with metal-poor and metal-rich components with the dividing line at $[\text{Fe}/\text{H}] = -1.7$. The metal-poor stars are more spatially extended and are kinematically hotter than the metal-rich stars. On the other hand, Lanfranchi & Matteucci produce only a single population with a peak at $[\text{Fe}/\text{H}] = -1.7$ and a broad dispersion. The discovery of multiple populations in even these simplest stellar conglomerates adds a new wrinkle to this whole area. Clearly, if there are two components, abundances need to be derived separately for each one. However, note that Kawata et al. (2006) find that a simple system with a continuous, albeit steep, metallicity gradient can lead to observations which suggest the system is instead discontinuous and bimodal.

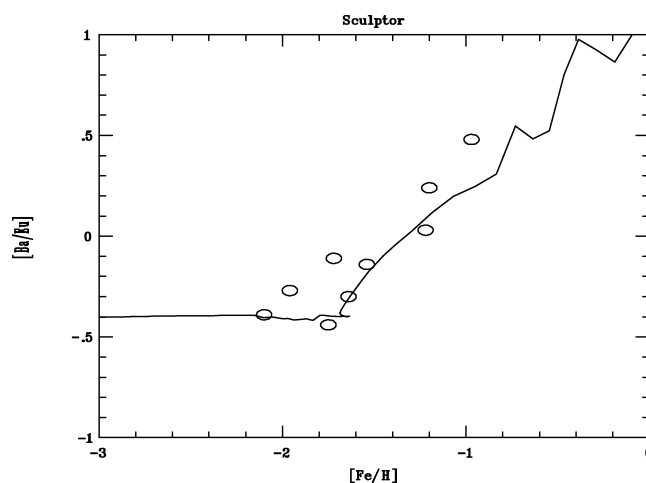


FIG. 14.— $[\text{Ba}/\text{Eu}]$ vs. $[\text{Fe}/\text{H}]$ for Scl dSph giants (circles) compared to the theoretical predictions of Lanfranchi et al. (2006; solid curve).

Clearly, more observations are required to investigate this possibility. In any case, we are now able to theoretically account for the observed chemical differences between the halo and dSphs.

5.3. Solving the Problem

We are still left with the very serious problem; we cannot build the halo out of the obvious dwarf galactic fragments, the objects that otherwise strongly favored cosmological theories suggest should be the basic building blocks of galactic structure. Can we solve this problem?

A series of recent papers have made great strides in presenting a very viable solution to the problem. These papers include Robertson et al. (2005, hereafter R05), Font et al. (2006a, 2006b), and Bullock & Johnston (2005). We mostly focus on the main arguments, presented in R05. They have combined chemical evolution models with cosmologically motivated mass accretion histories for the putative Milky Way dark halo and its satellites. They begin with representative examples of the type of dark matter halos expected to host a destroyed “stellar halo progenitor” dwarf, a surviving dIrr and a surviving dSph. They then include star formation and chemical evolution allowing for enrichment from SNe Ia and SNe II as well as stellar winds. Their solution to the problem relies on the Λ CDM prediction that the majority of halo stars formed within a few (~ 5), very massive ($\sim 5 \times 10^{10} M_{\odot}$) satellites accreted very early in the history of the Milky Way (~ 10 Gyr ago). Being massive, these satellites, before being assimilated, underwent rapid star formation. For the reasons developed above, such objects should then show approximately halo abundance patterns. They were subsequently accreted by the growing Galaxy, disrupted, and their stars then became the halo stars we see today. These massive dwarf systems were perhaps more like dEs than dSphs.

What about the dSphs? They argue that the dSphs we see today are *not* representative of the type of building block that was responsible for the bulk of the halo but instead are a biased population. They are “survivors,” objects which have lived most of their life in isolation and are only now (in the last few gigayears) being slowly assimilated by the Galaxy and are still pretty much intact. Thus, they have undergone the processes noted by LF04: low SFR and eventual onset of a galactic wind. They are also generally low mass. R05 find, as expected, that such galaxies end up with depleted α -abundances, in good agreement with the results of LF04 and the observations.

Let us look in detail at the three different objects that R05 model. The first is designed to represent a dIrr. It starts with a total dark halo mass of $6 \times 10^{10} M_{\odot}$ and ends with a final mass in stars of $4 \times 10^8 M_{\odot}$. This is similar to that of a typical dIrr like IC 1613. This object formed 11.6 Gyr ago and was accreted by the Galaxy 3.1 Gyr ago. It thus had 8.5 Gyr of star formation and chemical evolution in isolation, allowing the effects of SNe Ia and a galactic wind to shape its abundances. This object ends up having a relatively low SFR, forms few stars initially, and the majority of its stars form at relatively high metallicity ($\sim -0.6 < [\text{Fe}/\text{H}] < -1$) with $[\alpha/\text{Fe}] \sim$ solar, similar to the stars observed in present-day dIrrs.

Second, they study an object designed to mimic those expected to have formed the bulk of the halo. Its initial mass is identical to that of the above dIrr. Being of the same initial mass, it formed at the same time 11.6 Gyr ago. However, this object has two main differences with the dIrr: first (for reasons not specified by the authors), it forms stars initially very quickly. Second, it is accreted by the proto-Galaxy also very early, 9 Gyr ago. Thus, this object had only 2.6 Gyr of independence, at a high level of star formation. Under these conditions, they posit, or their models predict, that SNe Ia and galactic winds have little effect on the chemical evolution, leading to stars with enhanced α -abundances. Its gas enriches so that at the time of accretion a typical star has $[\text{Fe}/\text{H}] = -1.1$ and $[\alpha/\text{Fe}] \sim 0.2$. This system, with a total stellar mass very similar to that above, quickly disrupts after it is accreted and subsequently forms typical halo stars (although this is a little low in $[\alpha/\text{Fe}]$, which is more like 0.35 at this metallicity in the halo).

Their final object is modeled after a typical dSph. It has a dark halo mass of $6 \times 10^8 M_{\odot}$ and thus formed very early, 13.1 Gyr ago. Its final stellar mass is $1 \times 10^6 M_{\odot}$, 1 order of magnitude less than an object like Scl. It was accreted some 5 Gyr ago, so had 8 Gyr of isolation. As expected, such an object had a low SFR, experienced galactic winds, injection of SNe Ia and AGB material, and thus ends up with the knee in the $[\alpha/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ diagram at low metallicity and depressed α -abundances for metal-rich stars. The gas just prior to accretion has enriched to $[\text{Fe}/\text{H}] \sim -1.5$ and $[\alpha/\text{Fe}] \sim -0.1$. This is similar to what is seen in the low-mass dSphs.

Thus, R05 can successfully account for the abundances that we see in the halo and in dSphs and dIrrs and appear to have

rescued the SZ78/hierarchical formation scenarios. This is a very important step which certainly requires further modeling and observational confirmation.

6. SOME PROBLEMS WITH SOLVING THE PROBLEM

There are a couple of potential problems in the R05 analysis that we wish to point out. Note that in order to account for the halo abundances they need to have their halo progenitor form stars very quickly and efficiently after its formation. The dIrr progenitor formed at the same time with the same mass but did not have this initial burst of star formation. What is the reason for the different star formation histories of these otherwise originally identical objects? Possibly the halo progenitor had its star formation triggered by a close encounter with the proto-Galaxy very early.

More problematical is the question of timescales. We know from the results presented above that by an $[\text{Fe}/\text{H}] \sim -2$ a typical low-mass dSph like Scl starts showing the problem. For stars more metal-rich than this, the problem becomes increasingly severe. How long does the problem take to develop? The models of LF04 suggest *very quickly*; an object like Scl reaches this metallicity in less than 0.5 Gyr after star formation commences. The observational age–metallicity relation for Scl of T03 backs this up. Thus, any halo building block with a star formation and chemical evolution history roughly similar to that of Scl (presumably all of the typical dSphs) will show the problem unless they are accreted extremely early in their history, i.e., within 0.5 Gyr of their formation, i.e., onset of star formation in them. Of course, R05 argue that such galaxies only comprise a small fraction of halo constituents. But we have shown that this fraction must be *very low* given the essentially negligible overlap in abundances between the halo and low-mass dSphs for stars more metal-rich than ~ -2 . If even a relatively small number of typical dSphs were accreted into the halo one might expect that this discrepancy would not be as pronounced as it is.

What about more massive dwarf systems, like Sgr? Observations indicate that there is reasonably good agreement for stars up to $[\text{Fe}/\text{H}] \sim -1$, above which Sgr stars also start to show the problem. LF04 again find that Sgr should reach such a metallicity on a very short, similar (< 0.5 Gyr) timescale. So, although more massive dSphs may be able to make halo-like stars up to a metallicity of about -1 , the problem occurs for more metal-rich stars, and these stars will be present if the object is accreted more than ~ 0.5 Gyr after its formation (although perhaps these more metal-rich stars formed later than this, as suggested by some CMD studies). In their analysis, R05 found that the problem did not occur in their stellar halo progenitor because it had “only” 2.5 Gyr of evolution before being accreted and this apparently was not enough time for the effects of SNe Ia and galactic winds to be important according to their models. However, real galaxies (at least Scl) and the

LF04 models suggest otherwise. Note that the usual assumption for the onset of SNe Ia is ~ 1 Gyr, so one would indeed expect their effects to be significant after 2.5 Gyr.

We are thus led to suggest that the R05 scenario, although very promising, may require some fine tuning, especially with regards to timescales, in order to prevent the problem from arising. In particular, satellite galaxies must either be accreted *much* earlier than postulated in R05 (within ~ 0.5 Gyr after their formation) or somehow star formation must be prevented to occur in them after their formation until only shortly before they are accreted. However, note that all dSphs and dIrrs had at least some star formation at the very earliest epochs. The R05 solution relies on having only a few very massive halos accreted “very early,” but in fact these massive halos must be accreted within a very short time after their formation. If dSph-like objects were accreted to form much of the halo, they must have been accreted very early, before the onset of SNe Ia. Thus, we may be left with a hybrid scenario where the Galaxy may have collapsed as well as accreted fragments a la Searle & Zinn (1978) but on an ELS62-like timescale.

6.1. Other Considerations

We close with a few brief remarks about other important factors or results related to our general topic. First, virtually all of the field stars that have been observed at high resolution to date to form our knowledge of the composition of the halo currently inhabit only a very small region of the halo centered on the Sun. How representative of the full halo is this region? Much wider area surveys are required to reveal this and are being planned. Lee & Carney (2002) suggested that although the mean α -abundances may be uniform, there may be a gradient in $[\text{Si}/\text{Ti}]$ in old halo GCs. However, Pritzl et al. (2005) compiled high-resolution abundances for 45 GCs and compared them to halo field stars and those of dSphs. They found no evidence for any chemical gradients, in particular $[\text{Si}/\text{Ti}]$, and indeed found that the detailed abundances of the GC and field stars were very similar and that they then must have shared the same evolutionary history. Cohen & Melendez (2005) found that the detailed abundances of stars in the distant outer halo GC NGC 7492 were the same as those in the inner halo GCs M3 and M13, corroborating the Pritzl et al. result.

This raises the general question of the homogeneity of the halo. The early results of McWilliam et al. (1995) confirmed the general expectation that at very low metallicities one should start seeing substantial differences in element ratios due to stochastic events related to the mixing of one or only a few SNe of different mass and hence nucleosynthetic output. However, as more and more data are acquired, of better resolution, S/N, and sample size (e.g., the First Stars results of Cayrel et al. 2004; Arnone et al. 2005; Beers & Christlieb 2005), the intrinsic scatter in many elements, particularly the α -terms, is approaching the observational errors, which are reaching very low levels. Arnone

et al. find that, with a very careful analysis of very similar stars, that the cosmic scatter in Mg was < 0.06 dex over a sample of 23 main-sequence halo stars in the range $-3.4 < [\text{Fe}/\text{H}] < -2.2$. This is truly an amazing result. Standard Galactic chemical evolution models (e.g., Argast et al. 2002) predict that there should be essentially no mixing and therefore substantial scatter at $[\text{Fe}/\text{H}] = -3$, with a total range in, e.g., the Mg abundance at this metallicity of 1 dex and a standard deviation of 0.4 dex, with the scatter decreasing with metallicity and disappearing by $[\text{Fe}/\text{H}] = -2$. The real halo, however, is much more homogeneous than this, with a cosmic scatter (at least in Mg) 1 order of magnitude lower than expected. They find that the halo must have been very well mixed within ~ 30 Myr after its formation, the estimated time for the metallicity to reach -3 . This is an extremely short timescale. Andersen et al. (2007) estimate that at least 30 SNe II must have exploded to produce the homogeneity in the Mg abundances seen at $[\text{Fe}/\text{H}] = -3$. Either the mixing time for the halo was much shorter than generally assumed, or the intrinsic variations in abundance ratios of SNe II of different mass and energy are much smaller than generally assumed. Also note that Melendez & Cohen (2007) have argued that the halo formed on a timescale of ~ 0.3 Gyr based on the absence of a contribution from intermediate-mass AGB stars to halo Mg isotope ratios.

This point raises an additional problem for SZ78/hierarchical formation scenarios. The halo now not only needed to have accreted but also to have mixed on a very short timescale. In fact, as pointed out by Gilmore & Wyse (2004), such a remarkable homogeneity of the halo already seems to rule out a large number of merger/accretion events. One expects that each fragment/satellite galaxy should have its own distinct chemical history, albeit similar in many details, and it seems incredibly contrived to imagine many or even a few of these coming together on such a short timescale and giving rise to such a uniform halo, unless of course they were mostly gaseous at the time of accretion.

Initial results of several ESO Large Programs devoted to the study of kinematics and abundances in dSphs are now appearing and will certainly revolutionize this field. One of the first has important implications for this review; Helmi et al. (2006) report on their Ca triplet metallicities for several hundred stars in each of four dSphs. They find *no* stars with $[\text{Fe}/\text{H}] < -3$ and that the metal-poor tail of the dSph metallicity distribution is thus significantly different from that of the halo. However, Λ CDM chemical evolution models (Prantzos et al. 2006) generally predict that the majority of low-metallicity halo stars should come from low-mass, dSph-like progenitors. This throws an extra wrench into halo building block theories.

A further argument against the SZ78 scenario comes from comparing the Oosterhoff types of RR Lyraes in the halo (field and GCs) and dSphs. While Galactic RR Lyraes very nicely separate into two classes, Oo types I and II, with mean periods of 0.55 and 0.65 days, those in the dSphs generally lie in

between these two types (Catelan 2006). It appears virtually impossible to obtain the clear separation seen in the halo from the concatenation of a variety of objects with generally intermediate properties.

It seems most likely from the above considerations that if the SZ78/hierarchical formation models are correct, that the bulk of the halo came from the disruption of only a small number of very massive building blocks very early in the history of the universe, as suggested by R05 but much earlier than they envisioned. Not only should such massive fragments contain the chemistry most like that seen now in the halo, but they are also the ones that will host their own GCs. Of the present day dSphs, only the two most massive, Fornax and Sgr, possess GCs. Since it is often suggested that many of the halo GCs, especially those in the outer halo, were accreted, one requires rather massive dwarf galaxies to provide these GCs, as Sgr is now doing. Interestingly, Fornax GCs have abundances very similar to typical halo GCs (Letarte et al. 2006); however, as seen in § 3, the Sgr GCs show the problem. Thus, although the Galaxy was not “Sculptor-ed” (see G05), it may well have been “Fornax-ed” or possibly “Sagittarius-ed.”

Indeed, perhaps GCs themselves are the missing halo building blocks. They certainly contain the right stellar populations, abundances, etc., by definition. Many theorists have argued that a substantial fraction of halo field stars are the disrupted remnants of former GCs; e.g., Kroupa & Boily (2002) studied the dynamical evolution of clusters and suggested that the halo field stars were the disrupted lower mass clusters of an initial cluster population and the remaining intact GCs form the massive end.

Finally, we note that the classical, tacit assumption that the Milky Way is a typical spiral galaxy may indeed not be correct. Recent evidence is beginning to suggest that the Milky Way may in fact be quite unrepresentative. For a given mass, the Galaxy lies $\geq 1\sigma$ below the mean of comparable local spirals in terms of its angular momentum, disk radius, and metallicity in its outer regions (Hammer et al. 2007). They suggest that this is because the Milky Way has had an exceptionally quiet

merger history, while most spirals have undergone significantly more mergers and that M31 is a much more typical spiral. Clearly, the suitability of our own Galaxy as a representative prototype is of utmost importance and needs to be clarified. We also still have much to learn about the nature of our own halo. A very recent paper (Carollo et al. 2007) presents the clearest evidence to date from studies of individual stars that the halo is composed of two subcomponents, with different spatial and metallicity distributions and kinematics, as first suggested by Zinn (1985) from GC studies. There is certainly much more to discover about our Milky Way, in which the current and future generations of surveys will play a leading role.

A quote by Shapley (1943), in announcing the discovery (Shapley 1938) of a new class of objects called dSphs, is as relevant today, in the context of galaxy formation ideas, as it was originally regarding the nature of galaxies, “the discovery of dSphs (Scl and Fornax) is upsetting, because it implies that our former knowledge and assumptions concerning the average galaxy may need serious modification...Two hazy patches on a photograph have put us in a fog.” We hope this review has shed a little light on this fog and suggested some new avenues of research where the fog persists or has thickened.

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