The Complex Chemical Abundances and Evolution of the Sagittarius Dwarf Spheroidal Galaxy

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ABSTRACT

We report on the chemical abundances derived from high-dispersion spectra of 14 red giant stars in the Sagittarius dwarf spheroidal (Sgr dSph) galaxy. The stars span a wide range of metallicities, $-1.6 \leq [\text{Fe/H}] \leq -0.1$ dex, and exhibit very unusual abundance variations. For metal-poor stars with $[\text{Fe/H}] < -1$, $[\alpha/\text{Fe}] \approx +0.3$ similar to Galactic halo stars, but for more metal-rich stars the relationship of $[\alpha/\text{Fe}]$ as a function of $[\text{Fe/H}]$ is lower than that of the Galactic disk by 0.1 dex. The light elements $[\text{Al/Fe}]$ and $[\text{Na/Fe}]$ are sub-solar by an even larger amount, approximately 0.4 dex. The pattern of neutron-capture heavy elements, as indicated by $[\text{La/Fe}]$ and $[\text{La/Eu}]$, shows an increasing $s$-process component with increasing $[\text{Fe/H}]$, up to $[\text{La/Fe}] \sim +0.7$ dex for the most metal-rich Sgr dSph stars. The large $[\text{La/Y}]$ ratios show that the $s$-process enrichments came from the metal-poor population. We can best understand the observed abundances with a model in which the Sgr dSph formed stars over a many Gyr and lost a significant fraction of its gas during its evolution. Low-mass, metal-poor, AGB stars polluted the more metal-rich stars with $s$-process elements, and type Ia SN from low-mass progenitors enriched the ISM with iron-peak metals. The type II/type Ia SN ratio was smaller than in the Galactic disk, presumably due to a slower star formation rate; this resulted in the observed low $[\alpha/\text{Fe}]$, $[\text{Al/Fe}]$ and $[\text{Na/Fe}]$ ratios. The fact that Sgr stars span such a wide range in metallicity leads us to conclude that their age spread is even larger than previously inferred. We derive ages for these red giants using the Padova models (Girardi et al. 2000). The ages span $\sim 0.5$ to 13 Gyr, which implies a very long duration of star formation in the central regions of the Sgr dSph.

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1. Introduction

The Sagittarius dwarf spheroidal galaxy (Sgr dSph) is currently being ripped apart and accreted onto the Milky Way (Ibata et al. 1997, and references therein). Tidal debris from the Sgr dSph appears to litter the Galaxy tracing out Sgr’s orbit (Dohm-Palmer et al. 2000, Newberg et al. 2002). How many and how frequently have mergers of dSphs effected the evolution of the Galaxy? When did they occur? We can answer these questions by determining the distributions of ages and chemical abundances in dSphs and comparing them with those of Galactic stars (Unavane, Wyse & Gilmore 1996, Shetrone, Côté, & Sargent 2001, Fulbright 2002). Abundance ratios such as $[\alpha/\text{Fe}]$, where examples of $\alpha$-elements are O, Mg, Si, Ca, Ti, provide powerful constraints on how much of the Galactic halo could have been formed in dSph-sized fragments because halo stars have $[\alpha/\text{Fe}]$ that is independent of metallicity and approximately equal to the theoretical average yield of type II supernovae (SNe). (For reviews see Wheeler et al. 1989, McWilliam 1997). Type II SNe explode very quickly $\sim 10^7$ yrs after stars form, while type Ia SNe explode afterward from $10^8$ yr to many Gyr after stars form. Thus the Galactic halo has been inferred to have formed quickly because only ejecta from short-lived type II SNe, and not from long-lived type Ia SNe, were incorporated into most halo stars.

Instead of having short formation timescales, we now know that many of the dSphs in the Local Group have had surprisingly complex star-formation rates despite their small mass ($10^7$ to $10^8 M_\odot$) and current lack of gas (see Smecker-Hane & McWilliam 1999, and Grebel 2000 for recent reviews). Color-magnitude diagrams show the Sgr dSph stars have a wide range in age, $\sim 1$ to 15 Gyr, and a wide range in metallicities from $-2 \leq [\text{Fe/H}] \leq -0.7$ (Bellazzini et al. 1999, Layden & Sarajedini 2000). Such complex evolution should leave obvious signatures in the abundance ratios of the stars (Gilmore & Wyse 1991). Will Sgr dSph stars contain a mix of Type Ia and II ejecta? Yes, if the dSph can recycle ejecta over long timescales as supported by the observed ranges in age and metallicity. No, if the first Type II SNe disrupt the interstellar medium in less than 0.1 Gyr and clear the way for subsequent SNe ejecta to escape in galactic winds, or if dSphs accrete fresh gas that fuels star formation at later times. Therefore, determining the abundance ratios in Sgr dSph stars also gives us unprecedented information on its evolution. The abundance ratios of the metal-poor stars tell us the initial mass function of the massive stars that exploded as Type II SNe, which is critical for estimating the energy available to power galactic winds. By
modeling the measured abundances as a function of metallicity or age, we can constrain the rate of enrichment from Type Ia and II SNe, star-formation rate, and the inflow/outflow of gas from the dSph.

We have obtained high dispersion spectroscopy of 14 red giants stars in the Sgr dSph and derived abundances for 20 elements. In a companion paper, we will present details of the target stars, observations, measured equivalent widths, and abundance analysis. In this paper we report on our results for Fe, α-elements, Al, Na, and neutron capture elements (La, Y, Eu). In addition, we derive ages for the stars by comparing their inferred bolometric luminosity and effective temperature to Padova stellar evolutionary models (Girardi et al. 2000).

2. Observations

High resolution ($R \approx 34,000$) spectra of 14 Sgr dSph red giant stars were acquired with the Keck I 10-meter telescope and HIRES (Vogt et al. 1994) from 1996 to 1998; the typical S/N per extracted pixel was $\approx 50$. Program stars were selected to span the full range in color of red giant branch stars in order to probe the full range of metallicities. Our sample was selected from the two fields imaged by Sarajedini & Layden (1995, hereafter SL95) near the center of the Sgr dSph, and our stars were identified as members of the Sgr dSph based on radial velocities obtained by Ibata et al. (1997).

In Figure 1, we show the dereddened color-magnitude diagram of the Sgr dSph based on the SL95 photometry, where we have assumed a reddening of $E(V - I) = 0.18$ and distance modulus of $(m - M)_V = 17.65$ as derived by SL95. The 14 stars in our spectroscopic sample are marked by large circles. In order to show a fairer representation of the stellar population in the Sgr dSph, we have excluded stars that are within 2 arcmin of the center of M54, which is a globular cluster that is a member of the Sgr dSph. Readers should not confuse the sequence of stars located at $((V - I)_0, M_V) \approx (0.1, 0.75)$ with a strong young population; this sequence is the extended blue horizontal branch of M54. However, more extensive photometry by Bellazzini et al. (1999) and Layden & Sarajedini (2000) in which they statistically subtract out the Galactic foreground shows that a young, metal-rich, population does exist (for example, see Bellazzini et al.’s Figure 11). Note that the color-magnitude diagram is heavily contaminated by Galactic foreground dwarfs because the Sgr fields lie at low Galactic latitude, $b = -14^\circ$. The main sequence turnoff of the Galactic disk appears as a prominent vertical feature at $(V - I)_0 \approx 0.7$, and lower mass main-sequence dwarfs become more prominent in the diagram at fainter magnitudes and redder colors. For
reference, we have overplotted isochrones based on the newest Padova models (Girardi et al. 2000) for a variety of ages and metallicities.

3. Data Reduction and Chemical Abundance Analysis

Extraction and wavelength calibration of the spectra was performed with standard IRAF routines. Identification and measurement of the equivalent width (EW) of atomic lines was accomplished by use of the semi-automated routine GETJOB (McWilliam et al. 1995). Abundance analysis was performed using the synthesis program MOOG (Sneden 1973) and the 64-layer Kurucz (1993) model atmospheres. Model atmosphere parameters for the program stars (bolometric luminosity, \( M_{\text{bol}} \), effective temperature, \( T_{\text{eff}} \), and gravity, \( \log g \)) were derived from a combination of photometric and spectroscopic methods; complete details will be provided in our forthcoming paper. Abundances were derived by matching the observed line EW with synthesis predictions; appropriate hyperfine components were employed for affected lines when hfs constants were available. We adopt the solar abundances as given by Grevesse & Sauval (1998); \( \epsilon(\text{Fe}) = 7.50 \). As typically the case, systematic errors rather than random errors are the dominant source of error in our abundances. The typical 1–σ errors in the adopted stellar parameters are \( \sigma_{T_{\text{eff}}} = 70^\circ \text{K} \), \( \sigma_{M_{\text{bol}}} = 0.15 \text{ mag} \), and \( \sigma_{\log g} = 0.15 \text{ dex} \). This corresponds to typical 1–σ errors of \( \sigma_{[\text{Fe/H}]} = 0.07 \text{ dex} \), and \( \sigma_{[\alpha/\text{Fe}]} = 0.07 \text{ dex} \). Typical errors for other element ratios are show on the following plots.

4. Derivation of Ages

Ages were derived for each star by comparing the star’s bolometric luminosity and effective temperature with isochrones interpolated for the star’s derived metallicity using the Padova models (Girardi et al. 2000). We chose to do the interpolation of the age in the \( M_{\text{bol}} - T_{\text{eff}} \) plane in order to avoid additional uncertainties introduced by adopting a specific color-temperature transformation. Padova models from Girardi et al. (2000) were used to generate isochrones at given metallicities; Andrew Cole kindly provided these to us. The Padova models were calculated assuming a scaled solar element mix. Because our Sgr red giants show significant departures from solar element ratios, as we show below, we must take this into account when deriving their ages. The \( \alpha \) elements and Fe are the main sources of opacity. Salaris et al. (1993) show that an isochrone for a model of a given \([\text{Fe/H}]\) and \([\alpha/\text{Fe}]\) is nearly identical to that of a scaled solar model with an effective metallicity equal to

\[
[\text{Fe/H}]_{\text{eff}} = [\text{Fe/H}] + \log(0.638 \times 10^{[\alpha/\text{Fe}]} + 0.362).
\]
Fig. 1.— The color-magnitude diagram for the Sgr dSph (see text for details) with our spectroscopic targets shown as large circles. Our sample spans the full spread in color of red giant stars in order to probe the full range of metallicity. Isochrones based on the Padova models (Girardi et al. 2000) are shown as solid lines for a variety of age and metallicity combinations: in black is $[\text{Fe/H}] = -1.4$ and age = 13 Gyr, in blue is $[\text{Fe/H}] = -1.0$ and age = 5.0 Gyr, in green are $[\text{Fe/H}] = -0.4$ and ages = 1.0 and 3.3 Gyr, and in red is $[\text{Fe/H}] = -0.1$ and age = 0.7 Gyr. For the sake of clarity, evolutionary stages past the tip of the red giant branch are shown only for the two youngest models.
Therefore, we interpolated the age of a star by adopting a Padova model with its derived $[\text{Fe}/\text{H}]_{\text{eff}}$, where we used the average of the Si, Ca, and Ti abundances for $[\alpha/\text{Fe}]$, because these abundances are much better defined than the O abundance that is based on the EW of only one or two lines. Errors in the derived age of each star were calculated by propagating the typical $1-\sigma$ errors in $M_{\text{bol}}$, $T_{\text{eff}}$, $[\text{Fe}/\text{H}]$, and $[\alpha/\text{Fe}]$.

5. Results and Discussion

5.1. $[\text{Fe}/\text{H}]$ and Age Distribution

Figure 2 shows the age–$[\text{Fe}/\text{H}]$ relationship for our Sgr dSph stars. The metallicities range from $-1.6 \leq [\text{Fe}/\text{H}] \leq -0.05$. The stars in our sample are all radial velocity members; furthermore, the unusual chemical compositions (discussed below) indicates that they are not Galactic halo, bulge, or disk interlopers. Our high dispersion abundances confirm the existence of a solar metallicity component as suggested by the strengths of the Ca II near-infrared triplet lines in low dispersion spectra obtained by Ibata and collaborators (1996, private communication to TSH).

The metallicity spread in the Sgr dSph was inferred to be large, $-2.0 < [\text{Fe}/\text{H}] < -0.7$, based on the wide distribution in colors of its red giant stars (Bellazzini et al. 1999). Bellazzini et al. performed a VI-band photometric survey over a wide area in 3 different Sgr fields. For $\sim 100$ stars on the upper red giant branch, they derived metallicities by interpolating fiducial sequences of Galactic globular clusters. This provided the best way of separating Sgr stars from Galactic foreground dwarfs and the estimating the metallicity distribution from photometry alone. They concluded that 80–90% of Sgr stars were metal-poor, $[\text{Fe}/\text{H}] < -1$. However our spectroscopic metallicities for most Sgr stars are significantly higher than this. This discrepancy is understandable because of the degeneracy of age and metallicity in color-magnitude diagrams. The derived ages of our stars vary from $\sim 0.5$ to 15 Gyr, hence many Sgr stars are significantly younger than globular clusters. Significantly decreasing the age of these stars would have implied a much higher metallicity.

The age sensitivity of the red giant branch is small for ages $\gtrsim 3$ Gyr, and thus our derived ages for the stars older than this have large uncertainties. To compliment the field star data, we also show in Figure 2 data from 4 globular clusters that are members of the Sgr dSph (M54, Ter8, Arp2, Ter7). Cluster ages were taken from Layden & Sarajedini (2000) and are derived from the V magnitude of the cluster subgiant branch and placed on the age scale of the Bertelli et al. (1994) isochrones. The Bertelli et al. models were the precursors of the Padova models that we use to derive the ages of our Sgr field stars, and their
Fig. 2.— The age–[Fe/H] relationship for the Sgr dSph. Data for our red giant stars are shown as filled circles. Open circles show data for 4 globular clusters that belong to the Sgr dSph (see text for details).
absolute age scales are roughly similar. In order to compare with our field star metallicities derived from high-dispersion spectra, we adopt [Fe/H] = −1.55 for M54 as derived by Brown, Wallerstein & Gonzalez (1999) from high dispersion spectra of five M54 red giants. For the other clusters without high-dispersion spectroscopy, we use metallicities from the catalog of Rutledge et al. (1997) that are derived from the strengths of the Ca II infrared triplet lines in low dispersion spectra of red giants, but calibrated to the Carretta & Gratton [Fe/H] scale, which is based on high-dispersion spectroscopic abundances.

The spread in [Fe/H] and age of Sgr dSph stars indicates that star formation and chemical enrichment was prolonged, with a possible gap between metal-rich and metal-poor populations. It would be interesting to obtain high dispersion spectra of stars in Ter 7, the cluster inferred to be ~4 Gyr younger than the other globular clusters, as well as additional intermediate-aged and older field stars to flesh out the age-metallicity relationship. In Figure 2, the solid line shows the prediction from a simple chemical evolution model that assumes instantaneous recycling, a closed box, star formation has gone to completion at the present time (i.e., the mass of gas at 15 Gyr is zero) and a star formation rate that is constant in time. Layden & Sarajedini (2000) suggested such a model was a good fit to the age-metallicity relationship they derived from color-magnitude diagram analysis. A model with a yield of $p = 0.0033 = 0.17 Z_\odot$ is implied by our data although this model does not fit the data very well. Note that this yield is much lower than the yield inferred from stellar nucleosynthesis. For comparison, the yield in the Galactic bulge, which is reasonably well fit by a simple closed box model, is $p = 0.7 Z_\odot$ (Rich 1990) and that implied by the the metallicity distribution function of the Galactic disk indicates the yield is $p = 0.50 Z_\odot$ (Pagel & Patchett 1975). Such a low yield in Sgr implies that the closed box assumption is probably not valid. In a simple outflow model, where the outflow rate is assumed to be proportional to the star formation rate ($\nu \psi$, where $\psi$ is the star formation rate and $\nu$ is the dimensionless proportionality constant), the age-metallicity relationship is identical to that predicted by the closed box model with the effective yield being $p_{\text{eff}} = p/\nu$. Therefore, our Sgr results would imply $\nu \approx 3.5$ if the true yield is the same as that in the Galaxy and thus mass loss has been a significant factor in the evolution of the Sgr dSph.

### 5.2. Alpha Elements

In this paper, we discuss the element ratios [$\alpha$/Fe] where $\alpha$ is the average of Si, Ca, and Ti abundances. The O abundances are much more uncertain because they are based on only 1 or 2 lines.
Figure 3 shows that the most metal-poor Sgr dSph stars exhibit the enhanced \([\alpha/\text{Fe}]\) ratio seen in Galactic halo, near +0.3 dex; however, above \([\text{Fe/H}]\sim−1\), it is clear that the \(\alpha\)-elements are deficient relative to the solar neighborhood at any given \([\text{Fe/H}]\). The standard interpretation of this observation (e.g. Wheeler et al. 1989, McWilliam 1997) is that the ratio of type Ia/type II SNe material is larger in the Sgr dSph than the solar neighborhood above \([\text{Fe/H}] = −1\). This, in turn is likely due to a slower star formation rate, for example, a longer e-folding timescale, in the Sgr dSph. Such variation of \(\alpha\)-elements has long been predicted for low-mass systems (e.g. Matteucci & Brocato 1990, Gilmore & Wyse 1991). A similar result was found for disk stars with large Galactocentric radii in the study of Edvardsson et al. (1993), where it was concluded that the star formation proceeded at a slower pace for the outer disk than for the inner disk.

Note that the low metallicity stars in the Sgr dSph have \([\alpha/\text{Fe}]\) ratios similar to those of Galactic halo stars, and essentially equal to the theoretical yield of type II SNe, means that the upper mass end of the initial mass function in the dSphs is not significantly different than that of the Galaxy. This is a crucial point to establish because the upper-mass end of the initial mass function sets the amount of energy available to power galactic winds.

5.3. Aluminum and Sodium

In Figure 4 we show a comparison of \([\text{Al/Fe}]\) and \([\text{Na/Fe}]\) in the Sgr dSph with the results for solar neighborhood stars from Chen et al. (2000). The Sgr stars with \([\text{Fe/H}]<−1\) possess halo-like abundances of Al and Na, \([\text{Na/Fe}]\sim[\text{Al/Fe}]\sim0\).

A notable exception is star 1−73 with \([\text{Fe/H}] = −1.07\) that shows a large enhancement of Al, \([\text{Al/Fe}] = +1.1\) dex (so large that it is not plotted in Figure 4), a small enhancement in Na, \([\text{Na/Fe}] = +0.2\), and a large deficit of O, the upper-limit being \([\text{O/Fe}] < −0.8\). We suggest this is due to proton-burning in the stellar atmosphere altering the star’s primordial abundances, depleting O and creating Na and Al, similar to the pattern seen in some globular cluster red giants (e.g. Kraft et al. 1997). Note that this star’s derived metallicity is significantly different from the mean metallicity of M54 stars, \([\text{Fe/H}] = −1.55\) (Brown, Wallerstein & Gonzalez 1999). Thus we believe this star is a field star and not a cluster member, although its position on the sky and radial velocity are not significantly different from M54 stars. If this star is a field star then the fraction of Sgr field stars showing signs of proton burning is 7%, although the uncertainty is ±7%. This would significantly limit the amount of material from Sgr-like dwarfs that has been incorporated into the Galactic halo, because no field star (with 160 surveyed to date; Fulbright 2000) in the Galactic halo is observed to have undergone such processing. In the Galaxy, proton burning appears to be
Fig. 3.— Chemical abundances for red giants in the Sgr dSph (filled circles), where $\alpha$/Fe is the average of [Si/Fe], [Ca/Fe], and [Ti/Fe]. A typical error bar shown on the lower left. The average abundance of red giants in M54, a globular cluster in the Sgr dSph, from Brown, Wallerstein & Gonzalez (1999) is shown as the star symbol. The dashed line represents the mean trend in $\alpha$/Fe for stars in the solar neighborhood from Edvardsson et al. (1993).
Fig. 4.—a: A plot of [Al/Fe] versus [Fe/H]. b: A plot of [Na/Fe] versus [Fe/H]. Symbols are the same as in Fig. 3. Crosses represent abundances from Chen et al. (2000) for solar neighborhood F stars.
a phenomenon solely limited to some (but not all) Galactic globular cluster stars. Therefore additional searches for field Sgr stars with similar signs of proton-burning would be very interesting.

For the stars with $[\text{Fe/H}] > -1$ both Al and Na are deficient relative to the solar neighborhood trend by $\sim 0.4$ dex. While such low $[\text{Na/Fe}]$ and $[\text{Al/Fe}]$ ratios are not unheard-of in the Galaxy, they are extremely unusual, and never found in the metallicity range, $-0.6 \lesssim [\text{Fe/H}] \lesssim 0$, seen in the Sgr dSph stars.

Apart from re-processing Ne and Mg by proton burning reactions in stellar envelopes, Al and Na are synthesized by carbon and oxygen burning, which only occurs in massive stars destined to end as type II SNe. We suggest that the source of the Al and Na deficiencies seen in Sgr dSph stars is due to a paucity of nucleosynthesis products from massive stars. This is in qualitative agreement with the observed deficiency in $[\alpha/\text{Fe}]$ ratios. However, the Al and Na deficiencies are larger than the $\alpha$-element lacuna, which might be understood if type Ia SNe produce a small amount of $\alpha$-elements as suggested, for example, by Nomoto et al. (1984).

5.4. Neutron-Capture Elements

In Figure 5a we present the trend of $[\text{La/Fe}]$ with $[\text{Fe/H}]$; while the metal-poor stars appear quite normal in this plot, the metal-rich stars show a steady increase in La enhancement with increasing $[\text{Fe/H}]$, up to $[\text{La/Fe}] \sim +0.7$ dex. Except for very metal-poor stars, La is produced mostly by the s-process; the solar s-process fraction for La is estimated at 75% (Burris et al. 2000). To investigate the neutron source for La in the Sgr dSph stars we show the $[\text{La/Eu}]$ ratios in Figure 5b; it is clear that $[\text{La/Eu}]$ is increasingly dominated by the s-process at higher $[\text{Fe/H}]$. In particular, the three highest $[\text{Fe/H}]$ stars have super-solar $[\text{La/Eu}] \sim +0.3$ dex. Note that normally we would like to use the $[\text{Ba/Eu}]$ ratio, which is a more sensitive discriminator of s/r-process fractions; but the Ba lines in our spectra are so strong that they are on the flat portion of the curve of growth, and consequently not very sensitive to abundance. Since AGB stars are the dominant source of heavy s-process elements at Galactic disk metallicities (see Travaglio et al. 1999), the Sgr dSph heavy element abundance enhancements indicate a significant contribution from AGB nucleosynthesis, which increases with $[\text{Fe/H}]$.

In Figure 5c we present a plot of $[\text{La/Y}]$, showing that the light s-process element yttrium is not enhanced as much as the heavy s-process element lanthanum in the metal-rich Sgr dSph stars ($[\text{La/Y}] \sim +0.5$ dex). This is characteristic of metal-poor s-process environments
Fig. 5.— a: A plot of \([\text{La/Fe}]\) versus \([\text{Fe/H}]\). b: A plot of \([\text{La/Eu}]\) versus \([\text{Fe/H}]\). Dotted lines indicate the solar r-process ratio, and a pure s-process ratio from Malaney (1987). c: A plot of \([\text{La/Y}]\) versus \([\text{Fe/H}]\). Symbols are the same as in Fig. 3. Open squares represent chemical abundances of Galactic stars from Gratton & Sneden (1994).
(Busso et al. 1999). From Figure 16 of Busso et al. (1999), we estimate that the metallicity of the stars responsible for the s-process enhancement in the metal-rich Sgr dSph population was $[\text{Fe}/\text{H}] \leq -1.5$, or at a single, higher, metallicity, near $[\text{Fe}/\text{H}] = -0.6$ (due to the bi-valued nature of the heavy/light yield function). For AGB s-process nucleosynthesis in the metal-rich Sgr dSph stars with $[\text{Fe}/\text{H}] \sim -0.1$ the $[\text{La}/\text{Y}]$ ratios are expected to be $-0.2$ to $-0.3$ dex (Busso et al. 1999), much lower than the observed value near $+0.5$ dex. Note that the metal-poor Sgr dSph stars do not show the enhanced $[\text{La}/\text{Y}]$ ratios because of the importance of the r-process at $[\text{Fe}/\text{H}] \leq -1$.

The observation that the s-process elements came from a significantly more metal-poor astrophysical site than the stars themselves, rules out the possibility that the metal-rich Sgr dSph stars polluted their own atmospheres with s-process elements, or that s-process material was transferred from evolved companions; it also eliminates the instantaneous re-cycling assumption for the chemical evolution of the Sgr dSph. Self pollution is also excluded because none of the metal-rich Sgr dSph stars are luminous enough to be on the thermally-pulsing AGB (TP-AGB); the log $L/L_\odot$ range is 2.54 to 3.07, compared to the lowest TP-AGB onset luminosity of log $L/L_\odot$=3.1 from the calculations of Boothroyd & Sackmann (1988). Additional evidence against mass-transfer from an evolved companion comes from the frequency of such s-process enriched stars in the Galactic disk, at only 1 to 2% (MacConnell & Frye 1972); it seems very unlikely that all the metal-rich Sgr dSph stars could have come from such a rare population.

The observation that all the metal-rich Sgr dSph stars show a similar enhancement in the $[\text{La}/\text{Y}]$ ratio is evidence that the progenitor AGB stars responsible for the s-process elements were of a similar metallicity; the simplest explanation is that the progenitors were from the metal-poor population.

Since AGB s-processing occurs in the approximate mass range $1.2M_\odot < M < 5M_\odot$, we conclude that there was an extended period of star formation and chemical enrichment in the Sgr dSph which lasted from $\sim0.5$ to a few Gyr.

The metal-rich Sgr dSph stars, $[\text{Fe}/\text{H}] \gtrsim -0.7$, have derived ages from 0.5 to 3 Gyr, while the metal-poor stars range from 5 to 13 Gyr; this is consistent with the expectation that ages decrease with increasing $[\text{Fe}/\text{H}]$, and that the metal-poor population is similar to the Galactic halo. The derived ages are in qualitative agreement with a period of extended star formation as indicated by the abundances of neutron-capture elements.

We note that similar s-process enhancements have been seen in stars of the globular cluster Omega Cen (e.g. Smith et al. 2000), but at lower metallicity; those observations were attributed to AGB nucleosynthesis by $M < 3M_\odot$ stars.
Thus, the detailed abundances of neutron capture elements in the Sgr dSph indicate that the old, metal-poor, population was the dominant source of the heavy elements for the metal-rich population.

This is quite contrary to the situation in the solar neighborhood, where the G-dwarf problem is the observation of the absence of a significant metal-poor thin disk.

The unusual heavy element abundance patterns in metal-rich Sgr dSph stars are also consistent with considerable mass loss from the galaxy after the initial formation, as indicated by the $[\text{Fe/H}]$ distribution; if this were not the case, the high $[\text{La/Y}]$ ratios from the metal-poor component would have been overwhelmed by the products of a more populous metal-rich population.

5.5. Comparison with Other Studies

Bonifacio et al. (2000) derived chemical abundances for 2 red giants in the Sgr dSph from high-dispersion spectra obtained with UVES on the ESO 8.2-meter telescope. Their derived metallicities are $[\text{Fe/H}] = -0.28$ and $-0.21$, similar to our dominant group at high metallicity. The abundance ratios they derive fit very well onto the trends defined by our data. They note that the unusual abundances found for the high metallicity Sgr stars are very much like those seen in young supergiants in the Large and Small Magellanic Cloud (c.f., Hill 1997 and references therein). Therefore, our explanation of Sgr’s unusual abundance variations – namely, slow evolution of the star formation rate accompanied by mass loss and chemical enrichment of the young, metal-rich population by the old, metal-poor population – is probably applicable to the Magellanic Clouds.

It is curious that the youngest stars in the Sgr dSph have approximately the same metallicities, as measured by $[\text{Fe/H}]$, as the young stars in the LMC despite the fact that the total absolute magnitude, $M_V$, for the LMC is more than 5 magnitudes brighter than the Sgr dSph. Is this an artifact of star formation running to completion in Sgr dSph, or is that much of Sgr’s luminosity has already been stripped by tidal interactions with the Galaxy?

5.6. The Complex Evolution of the Sgr dSph

A detailed modeling of the age and metallicity relationship is outside the scope of the present data. Ideally, one would want to obtain spectroscopy for a large number of stars and simultaneously analyze the abundances and well-populated color-magnitude diagrams.
However we can glean more information about the evolution of the Sgr dSph by comparing our data to some simple models. In Figure 6, we plot the age and [$\alpha$/H] abundance, which is more likely to be a good candidate for the instantaneous recycling approximation than [Fe/H] because of the delayed explosion of type Ia SNe which generate significant amounts of Fe but little $\alpha$-elements. For each of the globular clusters, we have assumed [$\alpha$/Fe] = 0.21, which is the value found by Brown, Wallerstein & Gonzalez (1999) for M54.

Figure 6 illustrates the results of simple outflow chemical evolution model with instantaneous recycling. For comparison, they have all been normalized to pass through the same point. Each model assumes that star formation goes to completion at the present time of $t = 15$ Gyr, but adopts different prescriptions for the star formation rate, $\psi(t)$. The black line shows the prediction assuming $\psi$ is constant in time. Results for an exponentially decreasing star formation rate of the form $\psi(t) \propto e^{-t/\tau}$ are illustrated by the green line for $\tau = 5$ Gyr and the red line for $\tau = 1$ Gyr. A model with an increasing star formation rate of the form $\psi \propto t$ is illustrated by the red line. Note that none of these simple outflow models accurately reproduce the observed age-metallicity relationship, but the sharp increase in [$\alpha$/H] for ages $\lesssim 5$ Gyr would imply an increasing, as opposed to decreasing, star formation rate. The most plausible model might well involve a discontinuous star formation rate. Episodic star formation events have been found for a number of dSphs in the Local Group with the most stunning example being the Carina dSph (c.f., Hurley-Keller et al. 1998, Smecker-Hane & McWilliam 1999). Further work on the Sgr dSph will benefit greatly from new generations of spectrographs, such as the MIKE fiber-fed echelle spectrograph being developed for the 6.5-meter Magellan Telescopes, which will allow one to obtain high-dispersion spectra for $\sim 100$ stars simultaneously. Modeling of the color-magnitude diagrams, [Fe/H], and chemical abundance ratios promise to yield powerful constraints on the physical processes that regulated the complex evolution of dSphs.

6. Summary and Conclusions

Our observations of the Sgr dSph are consistent with prolonged chemical enrichment with significant mass loss. The radial velocities and chemical composition firmly establish our sample as bona fide Sgr dSph members with a metallicity range of $-1.6 \leq [\text{Fe/H}] \leq -0.05$ dex and a corresponding age range of $\sim 13$ to 0.5 Gyr.

While the composition of the metal-poor, [Fe/H] $<-1$, Sgr dSph stars resembles the Galactic halo stars, the metal-rich component shows a very unusual composition. The [$\alpha$/Fe] ratios are, on average, slightly sub-solar in the metal-rich sub-sample ([Fe/H] $\sim -0.3$ dex), which implies a low type II/type I SN ratio, and can most reasonably be understood as
Fig. 6.— The age–metallicity relationship for the Sgr dSph. Filled circles show the data for our 14 red giant stars. Open circles show data for 4 globular clusters that are members of the Sgr dSph. Simple chemical evolution models that assume instantaneous recycling are shown as solid lines. See text for details.
due to a relative paucity of type II SNe, consistent with expectations for a slow, or possibly episodic, star-formation rate.

In the metal-rich Sgr dSph stars the abundances of Al and Na are both deficient by $\sim 0.4$ dex, relative to iron, which has not previously been seen at this $[\text{Fe}/\text{H}]$. Since it is necessary for a star to go beyond carbon burning to produce large amounts of Al and Na (ignoring the re-distribution of Mg and Ne by proton burning), we interpret the observed Al and Na abundance deficiencies as a consequence of the low frequency of type II SNe.

Enhancements of neutron-capture heavy elements, which increase with $[\text{Fe}/\text{H}]$, and the s-process signature seen in the $[\text{La}/\text{Eu}]$ ratios, indicate the importance of AGB nucleosynthesis in the metal-rich Sgr dSph population. However, the $[\text{La}/\text{Y}]$ ratios suggest a nucleosynthetic origin from sites of much lower metallicity than the stars themselves. These observations may be understood if heavy elements in the metal-rich population were dominated by the low-mass, long-lived, AGB stars of the old, metal-poor population. The relatively long-lived AGB progenitors require that star formation in Sgr dSph took place over an extended period of time, at least 0.5 Gyr, and probably a few Gyr. This assertion is supported by age estimates for our sample of Sgr dSph stars, based on Padova isochrones, which span the range from 0.5 to 13 Gyr.

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