Ages and Heavy Element Abundances from Very Metal-poor Stars in the Sagittarius Dwarf Galaxy*

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Abstract

Sagittarius (Sgr) is a massive disrupted dwarf spheroidal galaxy in the Milky Way halo that has undergone several stripping events. Previous chemical studies were restricted mainly to a few, metal-rich ([Fe/H] ≥ −1) stars that suggested a top-light initial mass function (IMF). Here we present the first high-resolution, very metal-poor ([Fe/H] = −1 to −3) sample of 13 giant stars in the main body of Sgr. We derive abundances of 13 elements, namely C, Ca, Co, Fe, Sr, Ba, La, Ce, Nd, Eu, Dy, Pb, and Th, that challenge the interpretation based on previous studies. Our abundances from Sgr mimic those of the metal-poor halo, and our most metal-poor star ([Fe/H] = −3) indicates a pure r-process pollution. abundances of Sr, Pb, and Th are presented for the first time in Sgr, allowing for age determination using nuclear cosmochronology. We calculate ages of 9 ± 2.5 Gyr. Most of the sample stars have been enriched by a range of asymptotic giant branch (AGB) stars with masses between 1.3 and 5 M_☉. Sgr J190651.47–320147.23 shows a large overabundance of Pb (2.05 dex) and a peculiar abundance pattern best fit by a 3 M_☉ AGB star. Based on star-to-star scatter and observed abundance patterns, a mixture of low- and high-mass AGB stars and supernovae (15–25 M_☉) is necessary to explain these patterns. The high level (0.29 ± 0.05 dex) of Ca indicates that massive supernovae must have existed and polluted the early ISM of Sgr before it lost its gas. This result is in contrast with a top-light IMF with no massive stars polluting Sgr.

Key words: galaxies: dwarf – galaxies: evolution – Galaxy: halo – nuclear reactions, nucleosynthesis, abundances – stars: abundances – stars: chemically peculiar

Supporting material: machine-readable table

1. Introduction

The Sagittarius dwarf spheroidal galaxy (Sgr dSph) is the nearest (26.3 kpc; Monaco et al. 2004), massive dwarf galaxy in the Milky Way (MW) and has been studied over two decades. It was discovered by Ibata et al. (1994), yet its most metal-poor component has remained unexplored until now, thereby limiting our past interpretation of the enrichment and formation of the MW and its satellites. Sgr is the third most massive satellite galaxy (2.1 × 10^7 M_☉—similar to Fornax dSph; McConnachie 2012) in the Local Group (LG) after the Large and Small Magellanic Clouds (LMC and SMC, respectively). The Sgr system is currently undergoing tidal stripping from the interaction with the MW, which has resulted in two large streams (an old, faint, and later stripped, brighter one; see, e.g., Majewski et al. 2003; Belokurov et al. 2014; Koposov et al. 2015). The old, faint stream was stripped when Sgr started falling into the MW ~ 9 Gyr ago, and the brighter one about 5–7 Gyr ago. The two streams are drawn from the main body of Sgr, which contains the massive globular cluster (GC) M54 as well as Ter7, Ter8, Arp2, and Pal12 (Cohen 2004; Sbordone et al. 2007). Several studies have found a bimodal metallicity distribution of Sgr and M54 typically around [Fe/H] = −1.5 and ~ −0.6 (Bellazzini et al. 2008; Carretta et al. 2010). According to Carretta et al. (2010) and de Boer et al. (2015), Sgr shows an “alpha-knee” at [Fe/H] = −1.3, which is consistent with the star formation history (SFH) of massive dwarf galaxies, and studying the SFH further they claim that the onset of the supernovae type Ia causing the occurrence of the knee happened 1–3 Gyr after the initial star formation.

Based on metallicity distribution functions, Sgr is found to have had an extended SFH, which was terminated by the stripping of the brighter stream leaving the main body behind with no or little gas as we observe today (McWilliam et al. 2013). Several globular clusters in the MW halo may have originated from Sgr (Law & Majewski 2010), and they have different [Fe/H], indicating that Sgr had a complex evolution, chemical enrichment, and metallicity distribution. It also points toward a very efficient stripping of GCs into the MW, which indicates the importance of such stripped systems as building blocks of the MW halo.

Several spectroscopic studies have focused on the chemistry of Sgr and have shown it to be different and easily separable from that of the MW. The “classical” difference of dSphs showing lower [$α$/Fe] than the MW is also seen in Sgr, at least in previous studies of Sgr stars more metal-rich than [Fe/H] ≥ −1.5 dex (see, e.g., the recent large APOGEE study by Hasselquist et al. 2017). This is well explained by the poorer gas reservoir retained in the weaker gravitational potential of dSphs compared to larger galaxies, resulting in smaller molecular clouds and in turn in lower mass supernovae

* Based on data obtained UVES/VLT ID: 083.B-0774, 075.B-0127.
and recovered for the 4; Trager et al. 1995 of the heavy elements our interpretation of the chemical evolution of Sgr. The actual tidal stripping and ram pressure exerted by the MW affect questions pertaining to the IMF and mass loss occurring during massive dwarf galaxies masses of AGB stars conformed by [Fe/H] > −1.55 dex. The proposed explanation for this chemical enrichment pattern is that no massive supernovae have existed in Sgr, leaving the IMF steep and top-light. The heavy element production was instead believed to be due to metal-poor, low-to-intermediate mass AGB stars confirmed by the large [La/Y] and [Ba/Y] ratio found in several studies (Sbordone et al. 2007; McWilliam et al. 2013). However, the large (235 stars belonging to M54 or the central nucleus of Sagittarius, Sgr, N), medium-resolution study by Mucciarelli et al. (2017) derived α-abundances in stars spanning a broad range of metallicities reaching [Fe/H] ~ −2 and recovered for the first time an α-enhancement.

Despite a number of high-resolution spectroscopic studies, the enrichment history of Sgr is yet not fully mapped, and open questions pertaining to the IMF and mass loss occurring during the tidal stripping and ram pressure exerted by the MW affect our interpretation of the chemical evolution of Sgr. The actual level of the Fe-peak elements is debated, as is the overall origin of the heavy elements (from both s- and r-processes) in various dwarf galaxies (Venn et al. 2004). Previous studies have placed constraints on the r-process sites in Sgr using, e.g., Eu/O-ratios in small-number, metal-rich samples (McWilliam et al. 2013). In spite of previous observations and analyses of Sgr, we still only know of one very, but not extremely, metal-poor star in the main body of this system. This has prevented an in-depth investigation of the nature and enrichment of the very early stages of this galaxy.

The combination of α, Fe-peak, and n-capture elements in our study allow for a reassessment of the nature of both the AGB stars and supernovae that enriched the very to extremely metal-poor Sgr stars. Finally, Th abundances were derived for a few stars in the sample with the highest signal-to-noise ratio in their spectra. This combination of elements allowed us to discuss the early formation of the Fe-peak and heavy elements in greater detail than previously done in addition to determining ages of the main body of Sgr. This led us to revise the interpretation from the previous studies dominated by more metal-rich stars that suffered from observational biases and limitations. Our results point toward a very early generation of massive (15–20 M☉) supernovae and AGB stars (∼5 M☉), polluting the early Sgr galaxy as seen in the MW and other massive dwarf galaxies (e.g., Koch et al. 2008; Pompeí et al. 2008).

In Section 2, the sample and data reduction are described, Section 3 presents the stellar parameters and how they are derived, Section 4 outlines the abundance analysis, and, in Sections 5–7, the results, discussions, and conclusions can be found.

## 2. Sample and Data Reduction

Observations were obtained using the high-resolution, cross-dispersed UV-Visual Echelle Spectrograph (UVES; Dekker et al. 2000) mounted at the unit 2 telescope (UT2/Keueyen) of the ESO Very Large Telescope (VLT) in Cerro Paranal, Chile.

Out of 13 stars, 12 were observed with setup dic1 and central wavelengths of 390 nm and 580 nm, for the blue and red arms, respectively. We adopted a 1′′ wide slit and 2 × 2 on-chip binning. All the stars were observed for ~2400–13000 s at an airmass between 1.0 and 1.3 in 2009 April and July. The very metal-poor star Sgr 2300225 was observed using a slightly different setup in an earlier run (in 2005 August). Here a slit of 1′′, 2 × 2 binning, and a dic1 setting centered on 390 and 564 nm were used. Details of the observations are provided in Table 1. Throughout the paper, we will refer to the stars using their full ID except from in figures where we adopt S (for Sgr) plus their shortened coordinate identifiers. However, the IDs for stars 2300225, 3600436, and 2300275 do not follow the same convention and are not coordinates. Other target IDs are from Giuffrida et al. (2010). The stars that are the objects of the present study were selected for a high-resolution follow-up of the metal-poor population of Sgr. The selection was based on the metallicity derived from FLAMES/Giraffe spectra (Zaggia et al. 2004; Bonifacio et al. 2006; Giuffrida et al. 2010).

The distance to the center of M54 is also listed in Table 1, showing that all the stars are clearly outside the tidal radius of M54 (7/4; Trager et al. 1995) but centrally located in Sgr. Hence, the stars are not part of M54 but the main body of Sgr (see Figure 1). The heliocentric radial velocities calculated using the cross-correlation in IRAF are between 127 and 167 km s$^{-1}$ for the individual stars. One to four frames were taken for each star, covering a maximum time span of about one day. Detected radial velocity variations between frames are generally small (below 0.7 km s$^{-1}$), being maximum for Sgr J190039.06–310720.53 and Sgr J190631.47–320147.23 with 1.0 km s$^{-1}$ and 1.4 km s$^{-1}$, respectively, and we therefore consider them single. Observations over a longer baseline in time would be needed to truly probe the binary nature of these stars.

The sample’s heliocentric corrected radial velocities are in good agreement with the average value of Sgr, N of 139.4 ± 10.0 km s$^{-1}$ (Bellazzini et al. 2008). Here we find an average of 143.6 ± 14.1 km s$^{-1}$ and when excluding Sgr J190651.47–320147.23 an average and standard deviation of 141.8 ± 13.0 km s$^{-1}$ is found.

### 2.1. Data Reduction

The data were reduced using the dedicated pipeline.7 Data reduction includes bias subtraction, flat-field correction, wavelength calibration, sky subtraction, and spectral rectification. Radial velocities were measured by the fxcor package in IRAF,8 using a synthetic spectrum of a typical giant star (Teff = 4500 K, log(g) = 2.0) as a template (see Table 2). Finally, the median coadded spectra were normalized using the continuum package in IRAF.

## 3. Stellar Parameters

Initial atmospheric parameters were obtained in the following way. First, T eff was derived from the 2MASS J–K color using the relation of Ramírez & Méloné (2005). Since this

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7 See http://www.eso.org/sci/software/pipelines/.

8 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
was only a first estimation, we did not adopt reddening correction. Surface gravities (log(g)) were obtained from the canonical equation:

$$\log \left( \frac{g}{g_\odot} \right) = \log \left( \frac{M}{M_\odot} \right) + 4 \log \left( \frac{T_{\text{eff}}}{T_\odot} \right) - \log \left( \frac{L}{L_\odot} \right),$$

where the mass M was assumed to be 1.0 $M_\odot$, and the luminosity $L/L_\odot$ was obtained from the absolute magnitude, $M_V$, assuming an apparent distance modulus of the Sagittarius dwarf spheroidal galaxy. The bolometric correction (BC) was derived by adopting the relation $BC(EW)$ from Alonso et al. (1999). Finally, microturbulence velocity (ξ) was obtained from the relation of Marino et al. (2008). Atmospheric models were calculated using the ATLAS9 code (Kurucz 1970), assuming our estimations of $T_{\text{eff}}$, log(g), ξ, and assuming [Fe/H] = −1.5.

Then $T_{\text{eff}}$, log(g), and ξ were readjusted and new atmospheric models were calculated in an interactive way in order to remove trends in excitation potential and reduced equivalent width (EW) versus abundance for $T_{\text{eff}}$ and ξ, respectively, and to satisfy the ionization equilibrium for log(g). The [Fe/H] value of the model was changed at each iteration according to the output of the abundance analysis. The Local Thermodynamic Equilibrium (LTE) program MOOG (Sneden 1973, version 2014) was used for the abundance analysis. The final stellar parameters can be found in Table 2 and we adopt uncertainties on $T_{\text{eff}}$/log(g)/[Fe/H]/ξ of 50 K/0.2 dex/0.2 dex/0.1 km s$^{-1}$.

### 4. Abundance Analysis

Elemental abundances have been derived for C, Ca, Co, Sr, Ba, La, Ce, Nd, Eu, Dy, Pb, and Th. The details will be discussed below, and the line lists are provided in the online Table 6. All the stellar abundances have been derived using MOOG (Sneden 1973, version 2014) and the 1D ATLAS models with new opacity distribution functions (Castelli & Kurucz 2003) were interpolated to the stellar parameters determined as explained above (Section 3). The solar abundances are from Asplund et al. (2009). Because most of the lines we employ for deriving heavy element abundances are located in the blue part of the spectrum, the absorption features are often blended and in some cases saturated. In these cases, we include the lines in the final weighted mean, but with a lower weight. If the line is saturated and blended, a weight of 0 or 0.3 is assigned, if the line is only blended or slightly saturated a weight of 0.5 is used, if the line is not saturated but slightly blended a weight of 0.7–0.8 is assigned. When the line

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**Table 1**

| Star (ID)          | R.A.     | Decl.  | $T_{\text{hel}}$ (s) | $d$ (arcmin) | RV$_{\text{helio}}$ (km s$^{-1}$) |
|-------------------|----------|--------|----------------------|--------------|-----------------------------------|
| Sgr J184323.07−290337.64 | 18 43 23.074 | −29 03 37.650 | 9015 | 175.1 | 136.1 |
| Sgr J184828.45−294929.70 | 18 48 28.460 | −29 49 29.700 | 6010 | 94.2 | 127.6 |
| Sgr J185211.31−311907.51 | 18 52 11.317 | −31 19 07.510 | 6010 | 62.3 | 127.4 |
| Sgr J185259.59−312135.11 | 18 52 59.590 | −31 21 35.110 | 6010 | 59.0 | 154.9 |
| Sgr J185533.85−300521.20 | 18 55 33.858 | −30 05 21.200 | 6010 | 24.4 | 157.0 |
| Sgr J185549.44−300349.30 | 18 55 49.444 | −30 03 49.300 | 3005 | 26.9 | 135.7 |
| Sgr J190039.06−310720.53 | 19 00 39.069 | −31 07 20.540 | 6010 | 81.5 | 131.9 |
| Sgr J190043.03−311704.33 | 19 00 43.035 | −31 17 04.340 | 6010 | 87.2 | 153.9 |
| Sgr J190638.43−315135.94 | 19 06 38.436 | −31 51 35.950 | 2410 | 169.2 | 134.1 |
| Sgr J190651.47−320147.23 | 19 06 51.471 | −32 01 47.240 | 6010 | 176.6 | 165.5 |
| Sgr 3600436 | 18 53 35.657 | −30 26 36.380 | 6010 | 19.0 | 138.7 |
| Sgr 2300225 | 18 55 49.704 | −30 33 09.690 | 12685 | 10.9 | 167.2 |
| Sgr 2300275 | 18 55 38.608 | −30 27 04.130 | 9915 | 7.8 | 137.0 |

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**Table 2**

| Star (ID)          | $T_{\text{eff}}$ (K) | log(g) (dex) | [Fe/H] (dex) | ξ (km s$^{-1}$) |
|-------------------|----------------------|--------------|--------------|-----------------|
| Sgr J184323.07−290337.64 | 4490 | 0.49 | −1.81 | 1.79 |
| Sgr J184828.45−294929.70 | 4480 | 1.10 | −1.44 | 1.54 |
| Sgr J185211.31−311907.51 | 4825 | 2.00 | −1.07 | 1.34 |
| Sgr J185259.59−312135.11 | 4595 | 1.10 | −1.67 | 1.60 |
| Sgr J185533.85−300521.20 | 4610 | 1.13 | −1.46 | 1.56 |
| Sgr J185549.44−300349.30 | 4320 | 0.03 | −1.43 | 1.68 |
| Sgr J190039.06−310720.53 | 4660 | 1.03 | −2.02 | 2.06 |
| Sgr J190043.03−311704.33 | 4540 | 0.36 | −1.99 | 2.49 |
| Sgr J190638.43−315135.94 | 4250 | 0.65 | −1.47 | 1.72 |
| Sgr J190651.47−320147.23 | 4500 | 0.81 | −1.63 | 1.67 |
| Sgr 3600436 | 4660 | 0.54 | −1.63 | 1.98 |
| Sgr 2300225 | 4510 | 0.77 | −2.56 | 1.56 |
| Sgr 2300275 | 4975 | 1.90 | −2.96 | 1.50 |
is clean and can easily be modeled (or even allows for equivalent width measurements) a weight of 1.0 is used. Below, the weight we used to calculate the mean is listed in parenthesis after each line. In general, the final average is not very different (0.0–0.1 dex but mostly 0.02–0.03 dex) if we use a straight or a weighted mean, except for when we are dealing with upper or lower limits in the mean value. Hence, the weighted versus the straight mean value may differ significantly if we only have two measurements and one of them is a limit; however, this is the case for only 8 out of the 159 abundance values presented here.

As a test of our weighting scheme, we calculate the difference between the straight mean and the weighted mean, to explore the impact on the calculated abundances. For all elements, the average differences are <0.01 dex, which are below the standard deviation (scatter). The best case is La, where the average difference amounts to only 0.003 dex and the standard deviation 0.01 dex. There are two exceptions, namely Sr, where the two lower limits have been included resulting in an averaged difference for the 13 stars of 0.04 ± 0.06 dex, and Ca where the weighted mean and standard deviation are 0.29 and 0.17 dex while the straight mean is 0.27 and its standard deviation 0.16 dex. Within the uncertainty and standard deviation, these numbers are the same, which confirms that our weights are acceptable.

4.1. Carbon (Z = 6)

The carbon abundances were derived by fitting synthetic spectra to the CH G-band at 4300 Å. We focused on the region 4280–4290 Å (w = 1.0), as this region is mainly sensitive to C and there are only a few atomic lines in this region (if the star is metal-poor—see Figure 2). For most of the stars, a very low C abundance around [C/Fe] ~ −0.71 dex is derived, except for Sgr J190651.47–320147.23, where we find [C/Fe] = 0 (for more details, see Section 6.3). Our average carbon abundance is in good agreement with the [C/Fe] from the more metal-rich ([Fe/H] > −1.2) study by Hasselquist et al. (2017). We note that the C abundances have been derived assuming molecular equilibrium (and solar scaling all other elements like N and O), yet for these relatively cool (and likely mixed) stars the CH abundance from the G-band could still be slightly off compared to what we would derive from other molecular C-bands like, e.g., CN, and we assign the [C/Fe] values a slightly larger uncertainty (0.25 dex) for that reason, as we cannot derive N abundances from our spectra. All the abundances are listed in Table 3.

4.2. Calcium (Z = 20)

Calcium is the only α-element for which we present abundances here. A complete analysis of all lighter elements can be found in L. Monaco et al. (2018, in preparation). Here we only present Ca abundances derived from two Ca lines located close to the Ba lines. For getting a rough estimate of the α-abundance in these metal-poor stars, Ca was derived from the 5857.5 Å and 6493.8 Å lines (w = 1.0 and 0.7, respectively). The reason for this is to trace the formation site of the heavy elements, where α-elements provide insight into the nature (mass) of, e.g., the supernovae progenitor (Kobayashi et al. 2006). The average and standard deviation for the 13 stars studied here is ⟨[Ca/Fe]⟩ = 0.29, which is much higher than reported in previous studies (Monaco et al. 2005; Sbordone et al. 2007; McWilliam et al. 2013) and in agreement with enhancements seen in more massive galaxies like the MW at similarly low metallicities ([Fe/H] ≲ −2). This is in agreement with the medium-resolution study by Mucciarelli et al. (2017).

4.3. Cobalt (Z = 27)

This is the only Fe-peak element we studied (again we refer to L. Monaco et al. 2018, in preparation, for a detailed study of the lighter (Z < 30) elements). The reason for studying Co is the fact that it blends with our blue Th lines. In order to derive the Co abundances, we used the 4121.3 Å line (w = 1.0) combined with the wide Co line at 4020.9 Å (w = 0.5), since this line is located just redward of the 4019 Å Th line. However, the blue Co line is wide and complex, hence we assigned it the lower weight. For both lines, hyperfine structure (HFS) was included in the line list.9 The atomic data can be found in the online Table 6. We generally derive low (under abundant) Co abundances, and obtain an average of −0.18 dex. This is in agreement with previous studies, like Sbordone et al. (2007) and McWilliam et al. (2003, 2013), where they likewise find subsolar Co and Mn values, although at a higher metallicity.

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9 http://kurucz.harvard.edu/linelists.html
### 4.4. Strontium (Z = 38)

We perform a spectrum synthesis of two Sr II lines (4077.7, 4215.5 Å) in order to gain information about a light s-process element (for more details on, e.g., loggf, see Bergemann et al. 2012; Hansen et al. 2013). The 4077 Å line is at the highest metallicities saturated resulting in lower limits, and we assign the values from this line a lower weight (0.5—see Figure 3), while the 4215.5 Å is assigned full weight (1.0). The Sr abundances listed in Table 3 are thus weighted means. Due to the strong (sometimes saturated lines resulting in lower limits), the largest difference between the straight and weighted means is found for Sr (0.04 dex). The sample average and standard deviation of the Sr abundances are 0.21 and 0.22, respectively, i.e., slightly above solar.

### 4.5. Barium (Z = 56)

For barium, we use two of the red lines 5853.7 and 6496.9 Å (w = 0.8/1.0 and 1.0—see Figure 3) in order to avoid the strong (easily saturating 4554.0 Å line as well as the heavily NLTE affected 6141.7 Å line; Korotin et al. 2015). However, the difference between assigning w = 0.8 and w = 1.0 is so small (<0.01 dex except for one case where it reaches 0.02 dex) so we present a straight mean for Ba. Generally, a small line-to-line Ba abundance variation is found using these two Ba lines. We conduct spectrum synthesis using the HFS from Gallagher et al. (2012), and we measure EW to make sure that the Ba lines are not saturated (as reported in many other studies focusing on metal-rich, [Fe/H] > −1 stars.

### Table 3

| Element | Sgr J184323 | Sgr J184828 | Sgr J185211 | Sgr J185259 | Sgr J1885533 |
|---------|-------------|-------------|-------------|-------------|-------------|
| [Fe/H]  | −1.81       | 0.20        | −1.44       | 0.20        | −1.07       |
| [C/Fe]  | −1.00       | 0.25        | −0.75       | 0.25        | −0.55       |
| [Ca/Fe] | 0.31        | 0.27        | 0.38        | 0.25        | 0.49        |
| [Co/Fe] | −0.03       | 0.04        | −0.27       | 0.35        | −0.30       |
| [Sr/Fe] | >−0.20      | ...         | >−0.10      | ...         | 0.14        |
| [Ba/Fe] | −0.07       | 0.08        | 0.43        | 0.09        | 0.22        |
| [La/Fe] | 0.13        | 0.11        | 0.27        | 0.23        | 0.43        |
| [Ce/Fe] | −0.12       | 0.06        | 0.14        | 0.13        | 0.00        |
| [Nd/Fe] | 0.15        | 0.13        | 0.49        | 0.24        | 0.53        |
| [Eu/Fe] | 0.24        | 0.19        | 0.27        | 0.23        | 0.29        |
| [Dy/Fe] | 0.35        | ...         | 0.80        | ...         | 0.70        |
| [Pb/Fe] | <0.50       | ...         | <0.10       | ...         | <0.60       |
| [Th/Fe] | 0.10        | ...         | ...         | ...         | 0.40        |

However, for our most metal-poor star ([Fe/H] ~ −3; Sgr 2300275), we find a super solar Co abundance, [Co/Fe] = 0.29.

### Table 3 (Continued)

| Element | Sgr J185549 | Sgr J190039 | Sgr J190043 | Sgr J190638 | Sgr J190651 |
|---------|-------------|-------------|-------------|-------------|-------------|
| [Fe/H]  | −1.43       | 0.20        | −2.02       | 0.20        | −1.99       |
| [C/Fe]  | −0.80       | 0.25        | −0.90       | 0.25        | −0.90       |
| [Ca/Fe] | 0.54        | 0.35        | 0.15        | 0.08        | 0.23        |
| [Co/Fe] | −0.23       | 0.25        | −0.40       | 0.28        | −0.08       |
| [Sr/Fe] | 0.11        | 0.03        | 0.10        | ...         | 0.42        |
| [Ba/Fe] | 0.13        | 0.05        | −0.32       | 0.01        | −0.09       |
| [La/Fe] | 0.27        | 0.06        | −0.04       | 0.07        | 0.00        |
| [Ce/Fe] | 0.02        | 0.16        | 0.11        | 0.11        | 0.09        |
| [Nd/Fe] | 0.55        | 0.13        | 0.15        | 0.16        | 0.09        |
| [Eu/Fe] | 0.47        | 0.05        | 0.28        | 0.11        | 0.30        |
| [Dy/Fe] | 1.10        | ...         | 0.50        | ...         | 0.25        |
| [Pb/Fe] | 0.60        | 1.05        | ...         | <1.10       | ...         |
| [Th/Fe] | 0.65        | ...         | <−0.50      | ...         | 0.50        |

### Table 3 (Continued)

| Element | Sgr 3600436 | Sgr 2300225 | Sgr 2300275 |
|---------|-------------|-------------|-------------|
| [Fe/H]  | −1.63       | 0.20        | −2.56       |
| [C/Fe]  | −0.80       | 0.25        | −0.35       |
| [Ca/Fe] | 0.28        | 0.23        | 0.48        |
| [Co/Fe] | −0.28       | 0.30        | −0.15       |
| [Sr/Fe] | 0.10        | 0.05        | 0.20        |
| [Ba/Fe] | −0.19       | 0.10        | −0.70       |
| [La/Fe] | −0.20       | 0.03        | 0.00        |
| [Ce/Fe] | −0.04       | 0.06        | 0.01        |
| [Nd/Fe] | 0.10        | 0.08        | 0.20        |
| [Eu/Fe] | 0.24        | 0.20        | −0.12       |
| [Dy/Fe] | 0.50        | ...         | <0.00       |
| [Pb/Fe] | <0.80       | ...         | <1.25       |
| [Th/Fe] | 0.65        | ...         | ...         |
e.g., McWilliam et al. 2013). The average Ba abundance is lower than what we measure for La and is just below solar \(
abla (\text{Ba}/\text{Fe}) = -0.06\) with a standard deviation of 0.42 dex (in part, due to Sgr 2300275), indicating a fairly large star-to-star scatter for this \(s\)-process element (~85% in the solar \(s\)-process distribution according to Bisterzo et al. 2014).

### 4.6. Lanthanum (\(Z = 57\))

Lanthanum is another main \(s\)-process element (75% in the solar system; Bisterzo et al. 2014) for which we derive abundances from two lines 4086.7 and 4123.2 Å, where the blue-most one has Th as a blue wing blend. We therefore need to model the 4086-La line well, to make sure we separate the La contribution from the Th line. The difference between using equal weights or \(w = 0.8\) and 1.0, respectively, is very small (&lt;0.01 dex, on average 0.003 dex). Spectrum syntheses of both La lines (including HFS—Lawler et al. 2001) result in an average La value of 0.17 dex (standard deviation 0.43 dex), which is similar to the average we obtain for Sr. Lanthanum shows a slightly larger star-to-star abundance spread than Ba (somewhat driven by Sgr J190651.47–320147.23). With such a star-to-star abundance scatter, it is clear that the resulting heavy/light \(s\)-process ratio (HS/LS) must be discussed on a star-to-star basis to explore the formation site (see Section 5).

### 4.7. Cerium (\(Z = 58\))

Five Ce lines were used with different weights \((w = 1.0, 0.3, 0.8, 1.0, 0.5)\) owing to blends. The lines are: 4118.1, 4119.8, 4120.8, 4127.4, 4133.8 Å (\(\log gf\) from Lawler et al. 2009). For this element, we reinforce the weighted average since the lines are of varying quality. The abundance derived from synthesis varies as a consequence of a few unresolved blends as well as other heavy blends (e.g., from Nd). The weighted average and standard deviation are 0.03 and 0.29 dex. From this value, we see that Ce behaves a lot like Ba, and we note that Ce, like Ba, is an even \(s\)-process element (84% \(s\)). Further details will be discussed in the sections below.

### 4.8. Neodymium (\(Z = 60\))

The Nd abundances listed in Table 3 are based on seven lines: 4061.1, 4069.3, 4075.1, 4075.3, 4109.4, 4133.4, and 4135.3 Å with \(w = 1.0, 1.0, 0.8, 0.8, 0.5, 0.7\), where 4075.1 and 4075.3 lines blend together, and the 4133 Å line is a blended line resulting in this line often yielding upper limits. The weighted mean is 0.34 dex (standard deviation 0.33 dex), which is the highest average so far. Chronologically speaking, this is the first element where the \(r\)-process contributes by more than 20%, and according to Bisterzo et al. (2014) the \(s\)-/\(r\)-distribution is 57/43%.

### 4.9. Europium (\(Z = 63\))

For Eu, we used the two strongest lines, 4129.7 and 4205.1 Å, where the blue-most line is shown in Figure 3. As seen from the spectra, several lines nearby or blending into the 4129 Å line have atomic data (oscillator strengths) that are poorly known. In Koch & Edvardsson (2002), fake Fe lines were introduced to obtain a better fit. In order to correctly reproduce the blending Fe line in the red Eu wing, the Fe \(\log gf\) had to be increased by 1 dex for all stars (despite knowing the Fe-abundance to within 0.1–0.2 dex accuracy). Despite the poorly constrained oscillator strengths of the surrounding Fe lines, the Eu abundance is not affected by either of the 4129.2 or 4130.0 Å lines and their \(\log gf\) values, so we decided to assign both Eu lines full weight. Moreover, the Co line at 4130.5 Å can also not be reproduced with the Co value derived from the two Co lines mentioned above even though we take HFS into account. Therefore, we did not use this Co line in our study (see Figure 3), and we note that it has no influence on the derived Eu abundances. However, this highlights the need for improved atomic data for a large number of lines in the blue (4100–4150 Å) region.

Europium is our best \(r\)-process tracer (94% \(r\)-process in the solar system; Bisterzo et al. 2014), which makes it the best \(r\)-process element for which we can derive stable abundances for a nuclear cosmochronometer (see Section 6.4). The average
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Table 4
Average and Standard Deviation for the 12 Elements Studied

| Abundance | Mean  | St.dev. |
|-----------|-------|---------|
| [C/Fe]    | −0.71 | 0.28    |
| [Ca/Fe]   | 0.29  | 0.17    |
| [Co/Fe]   | −0.18 | 0.17    |
| [Sr/Fe]   | 0.21  | 0.22    |
| [Ba/Fe]   | −0.06 | 0.42    |
| [La/Fe]   | 0.17  | 0.43    |
| [Ce/Fe]   | 0.03  | 0.29    |
| [Nd/Fe]   | 0.34  | 0.33    |
| [Eu/Fe]   | 0.25  | 0.25    |
| [Dy/Fe]   | 0.52  | 0.32    |
| [Pb/Fe]   | 0.76  | (1.23)  |
| [Th/Fe]   | 0.33  | (0.38)  |

Note. Values in parenthesis exclude upper limits.

The Eu abundance is 0.25 dex and the standard deviation is 0.25 dex.

4.10. Dysprosium (Z = 66)

We use one Dy line, namely 4073.1 (\(w = 1.0\)), since we find 4077.9 and 4103.3 Å to be too blended and we decided not to include them. The 4103.3 Å line blends with H, La, and Sr. We have intentionally avoided the Dy line at 4077.9 Å, which blends severely with Sr but also Nd. The average Dy abundance is 0.52 dex. Dy is the next best r-process tracer after Eu with 85% r-process material in the solar system (Bisterzo et al. 2014).

4.11. Lead (Z = 82)

Lead is the heaviest s-process element we have studied here and we rely on the abundance synthesized from the 4057.8 Å line. We derived abundances for three stars and upper limits for seven stars. The rough average (treating limits and detections evenly in this estimate) is super solar at 0.76 dex, which is somewhat biased by the high upper limits we derive. For comparison, the average abundance from the three Pb detections amounts to 1.23 dex (see Table 4), which is even higher and the values spread owing to Sgr J190651.47–320147.23 having a [Pb/Fe] = 2.05 (see Section 6.3). However, since lead has not been investigated in Sgr dSph before, we choose to present these and lend the limits slightly more value.

4.12. Thorium (Z = 90)

Two Th lines were analyzed, namely 4019.1 and 4086.5 Å. The 4086 line is very weak and yielded only upper limits, while the 4019 line provided us with detections of Th in five stars and limits in two. The values listed in Table 3 are therefore only based on the 4019-Th line.

This is a transition blended with not only atomic contaminants, but also CH lines. The first step is to establish the elements that blend. On the left hand/blue side, the line is blended with Nd II at 4018.82 Å and Ni I at 4019.19 Å, while, on the right/red side, Th is blended with a CH line at 4019.13 Å and Co I at 4019.12 Å. In addition, Fe I and V II lines are blending into the Th line as pointed out by Caffau et al. (2008). With Fe set by the metallicity and solar-scaled V and Ni, the first step in the analysis was to determine the abundance of Nd, Co, and CH, respectively. The analysis of C, Co, and Nd was explained previously. The abundances of CH, Co, and Nd were added to the spectral synthesis, including their uncertainties (see Figure 4). Very few stars have had Th detected in their spectra, and we stress that deriving Th in these stars is very demanding owing to the heavy line blending. In order to produce satisfactory synthetic spectra, we had to update line lists both from VALD\(^\text{10}\) and the recent compilation from Sneden et al. (2014), which includes molecular C lines. The final line list is appended in the online material (Table 6) and the average Th abundance and its standard deviation is 0.33 and 0.49 dex, respectively (see Table 4).

5. Results

The chemical imprint of Sgr is known to be a mixture of high, heavy s-process, low \(\alpha\), and low Fe-peak (McWilliam et al. 2003, 2013; Hasselquist et al. 2017). Our sample has revealed the first abundance enhancements with respect to solar at very low metallicity in Sgr dSph. We find enhancements of both \(\alpha\)- and s-process elements, and the most metal-poor star shows a (possible) pure r-process trace atypical for dwarf galaxies, in particular, for Sgr. Below we describe the results with increasing atomic numbers of the 12 elements studied.

Starting with our lightest studied element, carbon, we find a remarkably low [C/Fe] \(-0.71\) in all but one star (Sgr J190651.47–320147.23, which is solar). So far, carbon has not been studied in Sgr at high resolution and low metallicity ([Fe/H] \(< -1.2\)—see Figure 5). The low C abundances were also shown by Hasselquist et al. (2017), albeit at higher metallicities. Our carbon abundances at low [Fe/H] are in good agreement with [C/Fe] in Hasselquist et al. (2017), which at their lowest [Fe/H] \(-1.2\) span a [C/Fe] from \(-0.8\) to \(-0.5\).

It should be borne in mind that our sample of stars, like those of Hasselquist et al. (2017) are very luminous, and therefore have very likely already undergone internal mixing. In the material that has been nuclearily processed and is mixed in the atmosphere, the C and the O have been partly destroyed to create N. The approximate amount of reprocessed C can be estimated using the predictions from Placco et al. (2014) and reading off the C-corrections from their Figure 15. This requires that we know the luminosity, which we can calculate using the distance modulus, the luminosity—absolute magnitude relation (\(\log(L/L_\odot) = 4 \log(M/10^{-3} M_\odot) - 4\)) and assuming the distance to Sgr of 26.3 kpc and \(M_\odot = 4.83\). This results in \(\log(L/L_\odot)\) values between 2 and 2.6, which for the lowest gravity stars indicates a correction in [C/Fe] of \(-0.2\) to \(-0.4\) dex and up to 0.6 dex in one case (Sgr J190309.06–310720.53). Despite these fairly large corrections, all our stars remain C-poor except for Sgr J190651.47–320147.23 (see Section 6.3). Hasselquist et al. (2017) have the abundances of also C and N, and can conclude that the ratio \([C+N+O]/Fe\) is subsolar for the majority of their sample. They advocate a top-light initial mass function to explain this. We note that in their data there is a hint that this ratio increases at lower metallicity, although this is represented by very few stars. Our sample is ideal to check this trend at even lower metallicity, but we need to complement our C abundances with N abundances, at least. This is, unfortunately, not possible with the spectra that are currently available.

\(^{10}\) Vienna Atomic Line Database—http://vald.astro.uu.se.
Our only α-element, Ca, is generally found to be overabundant with respect to solar, except for the most metal-poor star (Sgr 2300275), which has a remarkably low [Ca/Fe] = −0.1. The general Ca overabundance is in good agreement with Mucciarelli et al. (2017), who find down to [Fe/H] ∼ −2 find Ca to be enhanced and match the Ca level of the MW. For comparison to other α-elements, we draw parallels to the sample of Hasselquist et al. (2017). Their O and Mg abundances are deficient by ∼0.1 dex compared to MW disk stars, and Si slightly less so (see their Figure 5). Their O and Ca trends in the same figure are seen to agree, and their Mg/Ca-ratio cluster around 0 (±0.2 dex) as seen from their Figure 9. With this in mind, our trends and results from Ca should be representative of the α-element behavior in Sgr, even if Ca is slightly less mass dependent than Mg and O.

Except from Sgr 2300275, Figure 6 shows subsolar values of [Co/Fe] of ∼−0.6 at solar metallicity, which increases with decreasing [Fe/H] to around or just below [Co/Fe] = 0.0. This is also in agreement with the Sgr APOGEE data from Hasselquist et al. (2017) and the UVES/VLT data from Sbordone et al. (2007) that showed low Co values (−0.4 down to −0.8) for their more metal-rich samples. Previous studies have drawn parallels between the formation and evolution of Sgr and the LMC (Monaco et al. 2005; McWilliam et al. 2013) in that they both seem to have a top-light IMF and have lost gas early in their history. Therefore, we compare our results to other studies of both Sgr and LMC to comment on this.

Our resulting 1D, LTE abundances for Co agree well with the LMC (Pompéia et al. 2008) and Sgr trends as well as some of the metal-poor, MW halo stars, which also exhibit low Co values. Some of the LMC stars are even solar or slightly above
the [Co/Fe] solar-scaled value. Since we rely on giant stars in this study, which may lower the Co abundances by \( \sim 0.2 \) dex compared to dwarfs (as noted in Bonifacio et al. 2009), the Co values are expected to be a bit lower than what dwarf stars in Sgr may exhibit. The 1D, LTE analysis may also be one of the reasons why we derive low Co abundances, as a 1D, NLTE analysis could increase the value by up 0.7 dex in metal-poor dwarfs (Bergemann et al. 2010). However, the final 3D, NLTE abundances would need to be calculated with our adopted stellar parameters to get the complete picture (which is beyond this paper’s scope). For this analysis, we have used the recent Co I HFS logf values from Lawler et al. (2015), which for Co I yields values in good agreement with Co II (Snedden et al. 2016), thereby reducing the need for the strong NLTE corrections. In summary, only slightly higher values would indeed be expected.

From a Galactic chemical evolution point of view, a large amount of Fe-peak elements is generally associated with supernovae type Ia. In Sgr, these are expected to explode 1–3 Gyr after formation, and an increase in Fe-peak elements as a function of time. When SN Ia become more frequent and dilute the previous generation of SN II (\( \alpha \)-rich) material, higher Fe-peak abundances and a decreasing \( \alpha/Fe \) are expected. Such a metallicity-dependent trend was clearly seen in McWilliam et al. (2003) for Mn. This is not the trend we find for our more metal-poor Sgr sample studying Co, and a metal-poor type Ia progenitor generation does not seem to be able to explain our results. Our average \( ([\text{Co}/\text{Fe}]) = -0.18 \pm 0.05 \) (see Table 4), combined with the average \( \alpha/\text{Fe} \)-ratio obtained from Ca \( (0.29 \pm 0.05) \)—see Table 4—results in an average \( [\text{Ca}/\text{Co}] \sim 0.47 \pm 0.07 \). These are clearly higher values than the subsolar ones reported in previous, more metal-rich studies (e.g., Monaco et al. 2005; Sbordone et al. 2007; McWilliam et al. 2013).

As the mass of the supernova tends to correlate with the amount of \( \alpha \)-elements ejected (Kobayashi et al. 2006), our results indicate that more massive supernovae were indeed present and enriched the early composition of Sgr before it got accreted into the Milky Way and/or lost its gas (for more details on \( \alpha \)- and lighter elements, we refer to L. Monaco et al. 2018, in preparation). To get an estimate of the SN mass, we compare our Ca/Co-ratio with yields from a supernova with \([\text{Fe}/\text{H}] \sim -2.4\). A good match (to within 0.16 dex) for half the sample is found with the SN yields from a 20 \( M_{\odot} \) star (Kobayashi et al. 2006). For comparison, a 13 \( M_{\odot} \) SN of the same metallicity would produce a subsolar Ca/Co-ratio. This is in contrast with the results and interpretation of McWilliam et al. (2003, 2013) that imply the lack of such massive SN \( (>20 M_{\odot}) \). Note that here we use the nomenclature “massive” for SNe heavier than 15 \( M_{\odot} \), as these have clear differences in their explosion mechanism and physics related to compactness, \( \nu \)-mechanism, and possible magnetic fields compared to the SN with masses below 12 \( M_{\odot} \) collapsing onto a O–Ne–Mg core. A cut at 30 \( M_{\odot} \) makes less physical sense and we furthermore note that the \( \alpha \)-elements are already enhanced in 15–20 \( M_{\odot} \) SN compared to the lower mass ones (Janka 2017, and references therein).

In the following, we split the heavy neutron-capture elements into two groups—those that are predominantly formed by the \( s \)-process in the solar system (Sr (weak s), Ba, La, Ce, Pb (main s)), while the \( r \)-process forms Eu, Dy, and Th, and finally Nd is formed in almost equal amounts by either of the two processes (Bisterzo et al. 2014). Figure 7 shows our 1D, LTE derived abundances compared to literature studies of Sgr, LMC, and the MW halo (as our stars are more metal-poor than the average MW disk stars and seem to show a chemical composition resembling the MW halo rather than that of its disk).

Starting with the lightest n-capture element, Sr, we see a sparse trend of data clustered around \([\text{Sr}/\text{Fe}] = 0.18 \) (see Table 4), making this the first sample probing the nature of Sr in Sgr. The stellar abundances of our giant sample agree well with those of the old, metal-poor RR lyrae stars from the LMC (Haschke et al. 2012) as well as Sr from the MW halo (Hansen et al. 2012; Roederer 2013).

Both Ba and La show increasing trends as a function of \([\text{Fe}/\text{H}]\) with La abundances slightly higher than the Ba ones. This is in good agreement with Sbordone et al. (2007) and McWilliam et al. (2013). The \([\text{La}/\text{Fe}]\) trend is remarkably clean and consistently growing in both Sgr and the LMC, whereas Ba shows a slightly larger scatter (considering all samples or when excluding Sgr J190651.47–320147.23). Part of the explanation might be related to the Ba lines being stronger and possibly close to or saturated in the more metal-rich samples at \([\text{Fe}/\text{H}] = -1.0\). The \([\text{Ba}/\text{Fe}]\) star-to-star scatter in Sgr and the LMC is slightly larger than what is found at that metallicity in the MW. This could indicate a large degree of inhomogeneity in the smaller dwarf galaxies (Venn et al. 2012; Koch et al. 2013). A difference in timescale and evolution might play a deciding factor here where the increased \( s \)-process level and mass loss of the dwarf galaxies could explain such trends. However, a large star-to-star abundance scatter is expected for n-capture elements (e.g., François et al. 2007; Hansen et al. 2012; Roederer 2013).

Despite Ce mainly being formed by the \( s \)-process, it shows a flat trend around 0 similar to that of Eu albeit \([\text{Eu}/\text{Fe}] = 0.25 \) is predominantly formed by the \( r \)-process. This is puzzling and could indicate that our Ce abundances are low or that the rare Earth elements share formation processes at some level. While Ce shows a small star-to-star scatter, Eu is widely spread in the abundance diagnostics figure. The Nd abundances are slightly increasing as a function of \([\text{Fe}/\text{H}]\) (in agreement with Sbordone et al. 2007) but grow more slowly than the \( s \)-process elements Ba and La. Part of the explanation could be that Nd is produced in equal amounts by the \( r \)-process (creating Eu) and by the \( s \)-process forming Ba and La (see Section 6).

Another oddball is Dy, which should be formed mainly by the \( r \)-process. However, Dy exhibits a clean growing trend as a function of \([\text{Fe}/\text{H}]\) just like a boosted La (\( s \)-process) trend. We note that the Dy lines were blended and that the abundances therefore may be slightly high (despite conducting de-blending and spectrum synthesis).

The two heaviest elements, Pb and Th, are presented here for the first time in Sgr. Most of the Pb abundances are only upper limits (owing to severe blends, see Figure 4), but they support the high level of \( s \)-process enrichment both from the detections and the limits. The slowly decaying Th is found at two levels—one around solar and one just above 0.5 dex. This might indicate that we are looking at two different populations or groups with different ages (see Section 6.4). This would make sense considering the large \([\text{Fe}/\text{H}]\) span of our sample.

6. Discussion

The chemical composition of the very metal-poor stars of Sgr dSph provided surprising new results from which we constrain the formation processes and objects that enriched this
accreted, disrupted dwarf galaxy early on. From Figure 7, the anticipated behavior of a few elements seemed at odds with what we expect from their classical \( s \)- or \( r \)-production channels, and we explore their trends in more detail using absolute abundances. We fit trends (lines) using “ladfit” in IDL, which is a least absolute deviation method to obtain linear fits that are robust against outliers. Compared to a straight line fit (using, e.g., a minimum \( \chi^2 \) the changes are negligible (about 0.04, i.e., changes on the second digit). Here we also note that changes in the fitted lines/trends originating from using our weighted means or straight means are small (changes on the second or third digit on the slope and intersect with the \( y \)-axis — see also Section 4). These are insignificant compared to the uncertainty in stellar abundances (~0.15 dex).

As expected, two \( s \)-process elements, like La and Ba, show an almost perfect 1:1 correlation on an absolute abundance scale (see Figures 8 and 9 within the standard deviation around the line), and La (\( s \)) versus Eu (\( r \)) show a linear trend clearly deviating from 1:1 with a slightly larger star-to-star scatter and a poorer Pearson’s correlation coefficient (see Figures 8 and 9). Deviation from 1:1 and abundance scatter are clear indications of differing formation processes/origin as shown in Hansen et al. (2012, 2014). In this regard, it is puzzling that a typical \( s \)-process element like Ce does not correlate 1:1 with La, but good that the Pearson’s \( r \) is 0.97 and the spread around the line is low (0.07). Neodymium (~50/50% \( s/r \)) shows clear and almost equally good correlations with both Eu and La with high Pearson’s \( r \) values, which is encouraging. This could indicate that equal amounts of \( s \)– and \( r \)-process materials have been mixed into these metal-poor stars (see also Figure 10). Moreover, the light element Sr shows a very different origin compared to La, as does the heavy \( s \) element Pb compared to La. This indicates that different \( s \)-process formation sites are at work in Sgr, forming different amounts of Sr, La, and Pb (see Figure 7. Our Sr, Ba, La, Ce, Nd, Eu, Dy, Pb, and Th abundances for Sgr compared to literature studies of Sgr: Sbordone et al. (2007), McWilliam et al. (2013); LMC: Hill et al. (1994), Pompeia et al. (2008), Haschke et al. (2012); and the MW halo: Hansen et al. (2012), Roederer (2013). The enhanced outlier is Sgr J190651.47–320147.23, where [La/Fe] = 1.48 and [Pb/Fe] = 2.05 are outside the plotting range (as indicated by the black arrows). The symbols are explained in the legend box.
Figure 8. Absolute stellar abundances of La (x-axis) vs. Sr, Ba, Eu, Ce, Nd, Pb (y-axis), and Eu vs. Nd, Pb (listed from the top to the bottom panels). Lines fitted to the data are indicated in the figures. In parenthesis, the Pearson’s r-value and the standard deviation on the distance to the line is provided.
Figure 9. Slopes fitted to Sr, Ba, Ce, Nd, Eu, Dy, and Pb with respect to La is shown alongside the fraction of main $s$-process material (according to Bisterzo et al. 2014). The lower right corner shows selected linear trends between Eu and Ba, Nd, Dy, and Pb and their $r$-process fraction in percent.

Figure 10. $[\text{Ba/Fe}]$ vs. $[\text{Fe/H}]$ for the sample stars. Pure $r$- and $s$-process content (Arlandini et al. 1999) is indicated by dashed lines.

Figure 9). Alternatively, it could be an expression of different (evolving) physics in the same environment/object, e.g., different neutron density as a function of time. The poor Pearson’s $r$ and large scatter (standard deviation around the line) in lower panels of Figure 8 show that neither detections nor upper limits of Pb can be explained by the same formation channel creating Eu (which is reassuring and illustrates that the “trends method” works).

Figure 9 shows how the abundances and elements studied here correlate with the $s$-process element La, and in the inserted lower right corner trends versus the $r$-process element Eu is shown for comparison. Indicated in the figure are the relative fractions of $r$- and $s$-processes taken from the main $s$ contribution from Bisterzo et al. (2014). As indicated above, a few surprises were found, the main one being La correlating more strongly with Nd than Ce, despite La and Ce being closer in atomic number than La and Nd. Moreover, there is only a 10% difference in main $s$-process contribution between La (75%) and Ce (84%), while Nd is only 57% created by the $s$-process. This is hard to explain. We tested if there were differences in the weighted versus straight means but both resulted in very similar linear fits (a slight change on the second digit—see also Section 4). The poorer agreement between La and Sr (a large scatter and a slope clearly different from 1) indicated that a larger fraction of Sr could be formed by the weak $s$-process than was accounted for in the models. A similar observational indication of the weak $s$-process making a larger contribution to the production of Sr was also found in Hansen et al. (2012, 2014).

To find the origin of the elements, we compare the observationally derived abundances to model predictions from AGB stars (from the F.R.U.I.T.Y. database; Cristallo et al. 2011) and magnetohydrodynamic-driven supernovae of 15 $M_{\odot}$ exploding with jets (Heger et al. 2005; Winteler et al. 2008).
This kind of SN might host an r-process. Based on previous studies (e.g., Letarte et al. 2010; McWilliam et al. 2013) the very metal-poor, low-mass AGB stars were predicted to enrich the more metal-rich Sgr stars, and we therefore select AGB model predictions with $Z = 0.00002 Z_\odot$, 0.0002 $Z_\odot$, 0.0003 $Z_\odot$, and 0.001 $Z_\odot$, which corresponds to [Fe/H] = −2.8, −1.8, −1.6, and −1.2 to test this. The former is the most metal-poor model available in the database and the latter is the highest value the AGB star could have had if its material should be incorporated into any star from our sample. The top panel of Figure 11 shows the abundance pattern for our sample stars with [Fe/H] > −1.5, where both supernovae of type Ia and II can, in principle, have enriched the ISM. This panel shows a much lower star-to-star scatter than the bottom one, illustrating more metal-poor stars. It hints that the ISM of Sgr was likely to be homogeneous at metallicities above −1.5, and inhomogeneous below this value. Surprisingly, both the metal-poor and the more metal-rich stars in our sample show a better agreement with the intermediate massive 3−5 $M_\odot$ AGB stars than the lower mass AGB, except for Sgr J190651.47−320147.23, which agrees well with both of the 1.3−3 $M_\odot$ AGB models (this is investigated further below and in Figure 12). None of the stars provide a good fit to the most metal-poor, low-mass AGB star. Again, in stark contrast, to McWilliam et al. (2013) and Letarte et al. (2010). Moreover, some of the metal-poor stars (−2.5 < [Fe/H] < −1.5) show some agreement with the MHD jet SN (except for the Dy abundances), indicating supernova or mild r-process enrichment but not to the extent of the well studied r-rich star, CS22892-052 (Sneden et al. 2003). A mixture of (r+s) formation sites is clearly needed to explain the chemistry of metal-poor as well as metal-rich Sgr stars (see also Figure 10).

6.1. More Massive Progenitor Stars

As indicated by the higher $\alpha$-abundances and stellar abundance patterns, the enrichment in Sgr seems to have been of a more massive stellar progenitor population than previously believed. This includes both supernovae and AGB stars. The level of s-process enrichment depends on the mass of the AGB star, which we explore here using a standard $^{12}$C-pocket, no rotation, and the final yield composition of 1.3, 2, and 5 $M_\odot$ AGB stars from the F.R.U.I.T.Y. database. We combine our Ba, La, and Nd into a heavy s-process (HS) tracer (in line with the approach of the database and literature) and use Sr to represent the light s-process (LS). We compare to the final elemental abundances from their model predictions using different metallicities ($Z = 0.00002 Z_\odot$, 0.001 $Z_\odot$, $\sim$ [Fe/H] = −2.8 to −1.2). In addition, we include the yields from massive (25 $M_\odot$, not rotating) stars with a standard $^{17}$O reaction rate (Frischknecht et al. 2012). This means that fewer neutrons are available than if the $^{17}$O-rate is reduced, since these reactions work as neutron poisons in reducing the number of neutrons available for creating s-process material. Moreover, Frischknecht et al. (2012) also showed that an increased rotation would produce and burn slightly more $^{22}$Ne at the end of the convective He-core burning. Since the massive stars are hot enough to activate $^{22}$Ne$(\alpha,n)^{25}$Mg reactions, this would lead to a larger production of s-process material than a nonrotation case. We select a nonrotating model with a normal (high) $^{17}$O reaction rate to get the lowest level of s-process enrichment.
As illustrated by Figure 12, only one star falls above the high heavy to light s-process (HS/LS) enrichment from a 2\,M_\odot, 0.001\,Z_\odot AGB star. This is Sgr J190651.47–320147.23, which is discussed in more detail below (Section 6.3). Four stars (two detections, two limits) agree with the low-mass 1.3\,M_\odot AGB stars of different metallicities, while the remaining part of the sample lies between the bottom floor set by the massive (25\,M_\odot) nonrotating star and the intermediate mass (5\,M_\odot) AGB star. This shows that more massive (intermediate-mass) AGB stars and short-lived 15–25\,M_\odot stars or even jet-driven SN are needed to explain the chemical composition of the (very) metal-poor stars in our sample. Previous studies were limited to more metal-rich stars and could therefore, based on smaller (limited) samples, have drawn other conclusions (e.g., McWilliam et al. 2013).

Even though we mainly determine upper limits for Pb, we compare our abundances to the same AGB predictions, and similarly find that only one star is in the vicinity of the prediction from a 1.3\,M_\odot AGB star, while the same four stars as those shown in Figure 13 come closer to the Pb predictions from the 5\,M_\odot AGB stars. Here we note that the metallicity of the AGB star might play a secondary role compared to its mass, as all the 5\,M_\odot AGB stars regardless of their metallicity match (within the uncertainty) these four stars. In contrast to Letarte et al. (2010) and McWilliam et al. (2013) who found high [Ba/Y] or [La/Y] (0–1 dex), we calculate [Ba/Sr] values in the range −1.4 to 0.3 dex (or −0.7 < [HS/LS] < 0.5, see Figure 12). For a few of the stars, we find values above solar, which is also in agreement with some degree of metal-poor AGB enrichment (with fewer seeds leading to more HS than LS). However, more than half of our sample show subsolar HS/LS values and therefore seem to need more seeds in a metal-rich AGB environment (or a more massive AGB star).

This is in agreement with Figures 11–13.

The [Ba/Eu]-ratio we derive (typically below 0—see Figure 10) deviates from previous findings in both Sgr and
abundances. Therefore, we single out this star and compare it to AGB yields of varying mass and metallicity (see Figure 14). With our abundances spanning a broad range of atomic numbers, we have different ways of chemical tagging Sgr J190651.47–320147.23, either using single elements, or the stellar pattern. Starting from the lightest element, carbon, we find at [Fe/H] = −1.63 this star is a clear outlier in a [C/Fe] diagnostics diagram. It is not enhanced with respect to the Sun, but it is the most C-rich star in Sgr below [Fe/H] = −1.0 known to date. We have argued before that probably all of our stars have undergone some amount of internal mixing, resulting in the destruction of carbon. It seems very difficult to admit that this particular star has not undergone the same process as the other stars of similar luminosity. To estimate the original C-composition of this evolved giant, we adopt an approximate correction from Figure 15 in Placco et al. (2014) in which computations for a [Fe/H] = −1.3 star is presented. We assume the distance to Sgr (as outlined in Section 5) and use the apparent V magnitude (16.5) to estimate the log(L/L⊙) = 2.2, resulting in a correction of +0.4 dex. This would bring the current [C/Fe] from 0 to 0.4. However, this is still not sufficiently high to classify this star as a carbon enhanced metal-poor (CEMP) star. For the star to be a CEMP it must be metal-poor ([Fe/H] < −2) and C-rich ([C/Fe] > 0.7, see, e.g., Hansen et al. 2016). However, the star could belong to the more metal-rich counterparts, namely CH stars, but even for this class the C abundance is a bit low. Interestingly, the largest sources of C are AGB and Wolf Rayet stars through stellar winds (Kobayashi et al. 2006). Hasselquist et al. (2017) state that the C yield from supernovae are mass sensitive, which would argue against a massive progenitor generation. However, Sgr is strongly polluted by AGB stars and only metal-rich, massive (∼6 M⊙) AGB would produce some of the lowest C yields, which are still slightly above solar in [C/Fe] (in agreement with Kobayashi et al. 2006). This confirms a massive, metal-rich AGB progenitor for Sgr J190651.47–320147.23 in agreement with our results drawn from the other elements. We note that despite having derived C from the G-band using molecular equilibrium, the final [C/Fe] might still be uncertain and we therefore weigh results from other (heavy) elements higher in our conclusions.

Figure 14 shows only the yields from a mass and metallicity combination that come close to the derived stellar abundances of Sgr J190651.47–320147.23. We see that all heavy elements, except Ba and Ce, fit the 3 M⊙ AGB model with a metallicity of [Fe/H] = −1.7, which is very close to the metallicity of Sgr J190651.47–320147.23 (−1.63). The close match in [Fe/H] does not allow for much delay time to incorporate the AGB ejecta into the following generation of low-mass stars (here Sgr J190651.47–320147.23). However, it indicates that this star was not enriched by very metal-poor AGB stars as only one of the other stars in our sample might be. Since Ce shows an odd behavior most likely due to blends, which we have not been able to remove completely, neither in the synthesis nor in our weighting scheme, it is not surprising that Ce is not well described by any of the yields for Sgr J190651.47–320147.23. However, the low Ba abundance is closer to the 5 M⊙ AGB model (Z = 0.0001 Z⊙ ∼ [Fe/H] = −2.15). For Sr and Pb, the more metal-rich 3 M⊙ AGB model provides a perfect fit to these two elements. This is, however, very unlikely, as the AGB metallicity (−0.63) exceeds that of the low-mass, observed star. In any case, the best fit to Sgr J190651.47–

Figure 14. Abundances of Sgr J190651.47–320147.23 compared to AGB yields (Cristallo et al. 2011) of various mass and metallicity (see the legend for values in M⊙ and Z⊙).
320147.23 remains the $3M_{\odot}$ AGB model at $[\text{Fe/H}] = -1.7$ as confirmed by the smallest $\chi^2$. The large Pb abundance of 2.05 dex (an actual detection) is slightly overproduced by the preferred AGB model, which is a common problem (Bisterzo et al. 2014; Cristallo et al. 2015). The combination of mass and metallicity of the most likely progenitor AGB star, might have contributed to the special (enriched) $s$-process pattern of Sgr J190651.47–320147.23. Combining this with the radial velocities, we cannot reject that Sgr J190651.47–320147.23 could have resided in a binary system, and more follow-up observations would be needed to test this. For this star, we also have upper limits for Th and we were therefore able to determine an approximate age for this star (see Section 6.4 below).

### 6.4. Thorium and Ages

Nuclear cosmochemistry has been conducted to derive stellar ages using a variety of elements for the past three decades (e.g., Butcher 1987; Cowan et al. 1991; Sneden et al. 1996; Cowan et al. 1999; Cayrel et al. 2001; Truran et al. 2001; Hill et al. 2002; Aoki et al. 2007; Kratz et al. 2007). We derive Th in five stars and upper limits in two stars belonging to the main body of Sgr. We focus on Th and ages from Th/Eu, as we expect the stars to be old, and comment on the uncertainties associated with the abundances and ages derived from the 4019.1 Å line. We consider this line better suited for determining ages than the 4086 Å line. Details on the blends and line list can be found in Section 4 and in Table 6. Owing to the blends and difficulty in placing continuum at $\sim$4000 Å, uncertainties of 0.05–0.1 dex in Th II are derived for all of our stars. This translates into $\pm$2 Gyr, which is in agreement with the findings of Ludwig et al. (2010). However, in addition to the uncertainties from observations and model atmospheres, uncertainties in the nuclear prediction of the formation of the radioactive $^{232}$Th isotope with a half-life of $\tau_{1/2} = 1.405 \times 10^{10}$ years (Cowan et al. 1991; Kratz et al. 2007) arise. These nuclear uncertainties relate, e.g., to the $\beta$- and $\alpha$-decay rates and $\beta$-delayed fission and cause an uncertainty of $\sim$2 Gyr (Cowan et al. 1991, 1999; Schatz et al. 2002; Otsuki et al. 2003).

Earlier studies of 3D effects and corrections to Th II (Caffau et al. 2008) found average values (corrections) for the Sun to be of the order of $\sim 0.1$ dex. Mashonkina et al. (2012) calculated NLTE corrections of $\sim 0.1$ dex for the same line but for giant stars with parameters closer to our stars. This could indicate that the corrections to the 1D, LTE abundances might cancel out for 3D, NLTE, but full calculations using the adequate stellar parameters would need to be carried out to test this (which is beyond the scope of this paper). Hence, we continue using our 1D, LTE values to derive ages, which we consider accurate to within 2.5–2.8 Gyr (with the observational and nuclear uncertainties added in quadrature).

### Table 5

| Star          | [Fe/H] | Age (Gyr)  |
|---------------|--------|------------|
| Sgr J184323.07–290337.64 | $-1.81$ | $9.6 \pm 2.8$ |
| Sgr J190043.03–311704.33   | $-1.99$ | $7.2 \pm 2.3$ |
| Sgr J190651.47–320147.23   | $-1.63$ | $>8.2$     |

To calculate the ages ($\Delta t$), we start out with $Y_r(\Delta t) = Y_r(0) \cdot \exp(-\Delta t/\tau_r)$, where $Y_r$ is the yields/abundances, and we use the formula

$$\Delta t = 46.7(\log(\text{Th/Eu})_0 - \log(\text{Th/Eu})_{\text{obs}}),$$

where 46.7 is ln(10) times the mean lifetime (20.3 Gyr) in Gyr ($\tau_{1/2}/\ln(2)$), and (Th/Eu)$_0$ is the initial produced Th ratio, where we adopt the predicted value of 0.507 from Table 4 in Cowan et al. (2002), resulting in a log(Th/Eu)$_0 = -0.295$. The last term in Equation (1) is the absolute abundance derived from the present-day, observed abundance. For three of the stars, we derive “realistic” ages ($\Delta T < 14$ Gyr), and these are listed in Table 5. These stars are the more metal-poor ones where the blends are less severe than in the more metal-rich stars in our sample. By adopting a different value for (Th/Eu)$_0$ using the meteoritic values as representation of the initial solar system $r$-process fraction from Anders & Grevesse (1989), the ages would be $\sim 1.6$ Gyr lower, which is within the adopted uncertainty.

We note that the ages listed in Table 5 are likely to be lower (the stars are most likely older) owing to uncertainties from observations and nuclear physics. However, within the uncertainties, these values are in agreement with de Boer et al. (2015), predicting that the faint old stream stripped about 9 Gyr ago from Sgr main body consists of stars with $[\text{Fe/H}] \leq -1.3$, coinciding with the $\alpha$-knee. It would therefore make sense if our sample stars from the main body, from which the stripped stars originate, with their slightly lower metallicities, would at least be around 9 Gyr. Moreover, the ages we derive are slightly lower (i.e., the stars are younger) than the predictions by Siegel et al. (2007), who found ages of 9–13 Gyr for the metal-poor population of Sgr centered around $[\text{Fe/H}] = -1.3$. This agrees with our assessment that, since our stars are more metal-poor, we should likely have found slightly higher ages (i.e., the stars might be older than predicted). We note that we could not derive U from the spectra and, since most Pb abundances are merely upper limits, we constrain our age determinations to the Th/Eu estimates despite the large gap in atomic number between Th and Eu, leading to its slightly poorer value as a stellar clock.

### Table 6

| Wavelength (Å) | Atom.Ion | Ex.pot. (eV) | loggf (dex) | $E_{\text{diss}}$ (eV) |
|----------------|----------|-------------|-------------|-----------------|
| 4018.605       |          | 4.301       | -3.877      |                 |
| 4018.737       |          | 3.349       | -3.250      |                 |
| 4018.789       |          | 0.287       | -6.805      |                 |
| 4018.789       |          | 4.440       | -2.822      |                 |
| 4018.812       |          | 3.648       | -2.629      |                 |

(This table is available in its entirety in machine-readable form.)
Moreover, the smaller dwarf galaxies are often thought to be simpler as a poorer gas reservoir and gas loss place constraints on the mass of the objects that facilitated the chemical evolution of such dwarf galaxies (Hyde et al. 2012). Here we have analyzed one of the best case studies for chemical evolution and galaxy formation by studying Sagittarius, which has merged with the MW, and is thought to carry a unique chemical imprint based on previous studies. However, our study of the most metal-poor stars associated with Sgr dSph has shown a chemical composition somewhat more similar to that of the MW halo and not lending support to a top-light IMF. We find a high level of s-process enrichment as found in earlier studies, however, our Co values, despite (mainly) being sub-solar, are at the metal-poor end higher than previously found, but most notably we find a clear α-enrichment and a strong contribution from a main r-process (with Sgr 2300275 at [Fe/H] ~ −3, indicating a pure r-process origin). This is the first time in a metal-poor sample that clear abundance enhancements are found in Sgr stars. However, still no extreme r-rich star like CS22982-052 has been discovered in Sgr.

The [Ba/Eu] ratio as a function of [Fe/H] shows that the r-process contributed more than 50% of the heavy elements to the most metal-poor stars of our sample. Combining this with the average Ca/Ce-ratio and SN yield predictions, a clear presence of massive stars (15–25\(M_\odot\) SN) has been shown using two different abundance ratios and they can explain both Ca (α) and Eu (r-process).

Sgr seems to host stars with a broad range of s-process enhancements spanning from the s-rich star Sgr J190651.47–320147.23 to s-normal very metal-poor stars (such as Sgr 2300275). Sgr J190651.47–320147.23 could have been polluted by a 3\(M_\odot\) with [Fe/H] ~ −1.7; more observations are needed to probe the binary nature of this star. Also stars with a much lower s-process content are found at metallicities below [Fe/H] = −1.5 pointing toward an inhomogeneous early ISM of Sgr. Most of our sample stars are best mimicked by AGB stars of intermediate mass (5–15\(M_\odot\)), while the metallicity seems to be a secondary factor, yet with a tendency toward the higher metallicity variety. We find a few stars with high [Ba/Sr] or high [HS/LS] (> 0), yet more than half of our sample stars have [Ba/Sr] < 0 down to a record low −1.4. This shows that a range of AGB stars (with high and low metallicity combined with masses of 3–5\(M_\odot\)) are needed to explain both the HS/LS-ratios as well as the abundance patterns (see Figures 10–14). Stars stripped from Sgr and similar dwarf galaxies could indeed be building blocks of the MW halo and possibly offer an explanation for s-rich stars in the Galactic halo.

We also calculated ages for three of the stars and found realistic, consistent values around 9 ± 2.5 Gyr for those three. This is in agreement with previous predictions of the first stripping from the main body taking place around 9 Gyr ago (Fellhauer et al. 2006; Belokurov et al. 2014; de Boer et al. 2015; Hyde et al. 2015; Koposov et al. 2015), and our calculated ages are therefore to be taken as lower limits.

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