ABUNDANCE PATTERNS IN THE DRACO, SEXTANS, AND URSA MINOR DWARF SPHEROIDAL GALAXIES

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ABSTRACT

The Keck I telescope and the High Resolution Echelle Spectrometer (HIRES) have been used to obtain spectra for red giant stars belonging to the Draco, Sextans, and Ursa Minor dwarf spheroidal (dSph) galaxies. An analysis of these spectra is presented, along with abundance ratios for more than 20 elements. The resulting database of element abundances for 17 dSph stars is the most extensive yet assembled for stars in such environments. Our principal findings are summarized as follows. (1) There is unambiguous evidence for a large internal dispersion in metallicity in all three galaxies: our program stars span a range of $\Delta[\text{Fe/H}]=1.53$, 1.40, and 0.73 dex in Draco, Sextans, and Ursa Minor, respectively. (2) The abundance patterns among the dSph stars are remarkably uniform, suggesting that three galaxies have similar nucleosynthetic histories and, presumably, similar initial mass functions. (3) A comparison of the measured element abundance ratios for our sample of dSph stars with published values for Galactic halo and disk field stars suggests that the dSph galaxies have $0.02 \lesssim \frac{\alpha}{\text{Fe}} \lesssim 0.13$ dex, whereas the halo field star sample has $\frac{\alpha}{\text{Fe}} = 0.28$ dex over the same range in metallicity. (4) The most metal-rich dSph stars in our sample have $\frac{[\text{Y/Fe}]}{[\text{Fe/H}]}=0.28$ dex over the same range in metallicity. (4) The most metal-rich dSph stars in our sample have $\frac{[\text{Y/Fe}]}{[\text{Fe/H}]}=0.28$ dex over the same range in metallicity.

The first high-resolution abundance analysis for the distant Galactic globular cluster NGC 2419 is also presented. From a HIRES spectrum of a single red giant, we find a metallicity of $\frac{[\text{Fe/H}]}{[\text{Fe/H}]}=-2.32 \pm 0.11$ dex. This is slightly lower than, but still consistent with, published estimates based on low-resolution spectroscopy. With the possible exception of a slight enhancement in the abundances of some heavy elements such as Ce, Nd, Y, and Ba, the observed abundance pattern closely resembles those exhibited by red giants in M92: a nearby, well-studied globular cluster of nearly identical metallicity.

Subject headings: galaxies: abundances — galaxies: dwarf — galaxies: individual (Draco, Sextans, Ursa Minor) — quasars: absorption lines — stars: abundances

On-line material: machine-readable tables

1. INTRODUCTION

As isolated, low-mass systems, dwarf galaxies are probably the closest approximations in nature to idealized "closed" or "leaky box" models of chemical enrichment. The old, nearby dwarf satellites of the Milky Way thus offer a unique opportunity to study the formation and chemical evolution of galaxies in a level of detail that will never be possible with high-redshift systems.

The apparent dearth of gas and young stars in the Galactic dwarf spheroidal (dSph) galaxies, coupled with their low metallicities, led early researchers to regard them as similar to globular clusters in terms of their stellar populations (e.g., Hodge 1971), despite clear differences in their respective structural parameters. However, careful scrutiny has now revealed that these systems are far from simple. Mateo (1998) recently reviewed the now overwhelming observational evidence for complex and varied star formation histories in these faint systems. High-precision photometric studies and low-resolution spectroscopy of individual red giant branch (RGB) stars have firmly established that both Galactic and M31 dSph galaxies show evidence for large internal metallicity variations (e.g., Zinn 1978; Stetson 1984; Suntzeff et al. 1993; Côté, Oke, & Cohen 1999; Da Costa et al. 2000). Recently, Shetrone, Bolte, & Stetson (1998; hereafter SBS98) presented an abundance analysis for four RGB stars belonging to the Draco dSph galaxy, the first study of dSph stars to make use of high-resolution...
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**Fig. 1.** $BV$ color-magnitude diagrams for the three dSph galaxies in our program, Draco, Sextans, and Ursa Minor. The red giant branch stars for which we have HIRES spectra are indicated for Draco (circles), Sextans (triangles), and Ursa Minor (squares). The four Draco stars observed by Shetrone et al. (1998) are also shown in the first panel. Photometric data for Draco, Sextans, and Ursa Minor are from Stetson (2000), Suntzeff et al. (1993), and Cudworth et al. (2000), respectively. The lower right panel shows the location of our program stars in the $M_V$–($B - V$)$_0$ plane. Dashed lines show 13 Gyr isochrones from Bergbusch & Vandenberg (1992) having metallicities of $[\text{Fe/H}] = 2.26, 1.66, \text{and} 1.26$ dex. The symbols are the same as in the proceeding panels.

$(R = 34,000)$ spectroscopy. SBS98 measured abundance ratios for a variety of elements and, despite the limited sample size, found unmistakable evidence for a wide range in metallicity of $-3 \lesssim [\text{Fe/H}] \lesssim -1.5$ dex.

Elemental abundances represent a potentially powerful means of testing the suggestion that dwarf galaxies are the surviving “building blocks” from which larger galaxies formed (Larson 1988; Zinn 1993). Such tests are particularly topical in view of the emerging empirical and analytical evidence that galactic halos are assembled from chemically distinct, low-mass fragments (e.g., Searle & Zinn 1978; Zinn 1993; Ibata, Gilmore, & Irwin 1994; Klypin et al. 1999; Moore et al. 1999; Côté et al. 2000; Yanny et al. 2000). Some hydrodynamical simulations of galaxy formation also point to the assembly of large galaxies from low-mass, gas-rich, protogalactic fragments (i.e., Haehnelt, Steinmetz, & Rauch 1998, 2000). If these gaseous fragments are the high-redshift analogs of local dwarf galaxies, then a correspondence between the abundance patterns of the dSph stars and those of damped Ly$\alpha$ (DLA) absorbers might be expected; such a correspondence in the mean metallicities has been known for some time (see Pettini et al. 1997 and references therein), although the association of DLAs with spiral disks (Wolfe et al. 1995; Prochaska & Wolfe 1997) or dwarf galaxies (York et al. 1986; Tyson 1988; Pettini, Boksenberg, & Hunstead 1990) remains an open question. By examining the abundance patterns of dSph galaxies and comparing with those of DLAs and Galactic halo/disk field stars, it may be possible to discriminate between these different scenarios.

**TABLE 1**

| Run | Date       | Decker | Binning | $\lambda/\Delta\lambda$ | Program Objects          |
|-----|------------|--------|---------|--------------------------|--------------------------|
| 1... | 1999 Mar 13–15 | C5     | 1 $\times$ 2 | 34000 | Sextans, NGC 2419, M3, M92 |
| 2... | 1999 Jul 15–16 | C5     | 1 $\times$ 2 | 34000 | Ursa Minor, M3, M92       |
| 3... | 1999 Aug 14  | C5     | 1 $\times$ 2 | 34000 | Draco                     |
TABLE 2

Properties of Program Stars

| Star* | $V^b$ (mag) | $(B-V)^b$ (mag) | $E(B-V)^b$ (mag) | $T$ (s) | S/N | HJD (+2,450,000.0) | $v_r$ (km s$^{-1}$) |
|-------|-------------|-----------------|------------------|--------|-----|-----------------|-----------------|
| III-13 | 12.03       | 1.31            | 0.02             | 360    | 105 | 1253.10461     | −111.8 ± 0.7    |
| VII-18 | 12.19       | 1.28            | 0.02             | 240    | 93  | 1374.75736      | 114.1 ± 0.3     |
| V-106  | 12.47       | 1.12            | 0.02             | 300    | 81  | 1375.75659      | −117.7 ± 0.2    |
| III-65 | 12.49       | 1.17            | 0.02             | 360    | 83  | 1253.11160      | −119.7 ± 0.6    |

M92 = NGC 6341

| III-28  | 12.81      | 1.36            | 0.01             | 240    | 65  | 1253.16298      | −152.8 ± 0.2    |
| I-21    | 13.05      | 1.36            | 0.01             | 300    | 65  | 1374.74650      | −145.6 ± 0.3    |
| IV-101  | 13.26      | 1.29            | 0.01             | 480    | 77  | 1375.73520      | −144.8 ± 0.3    |

NGC 2419

| RH 10   | 17.61      | 1.17            | 0.06             | 3600   | 20  | 1250.77596      | −18.1 ± 0.4     |

Draco

| 11      | 17.60      | 1.12            | 0.03             | 3600   | 24  | 1404.82121      | −283.1 ± 0.7    |
| 343     | 17.62      | 1.12            | 0.03             | 3600   | 24  | 1404.86929      | −293.1 ± 0.8    |

Ursa Minor

| 177     | 16.90      | 1.29            | 0.03             | 3600   | 36  | 1374.79308      | −234.5 ± 0.3    |
| 297     | 16.91      | 1.57            | 0.03             | 3600   | 36  | 1374.88445      | −235.9 ± 0.3    |
| K       | 16.98      | 1.35            | 0.03             | 3600   | 34  | 1375.82789      | −246.1 ± 0.6    |
| O       | 17.03      | 1.31            | 0.03             | 3600   | 34  | 1375.87494      | −250.5 ± 1.1    |
| 199     | 17.15      | 1.38            | 0.03             | 3600   | 33  | 1374.83949      | −249.2 ± 0.3    |
| 168     | 17.88      | 0.95            | 0.03             | 3600   | 19  | 1375.78264      | −232.9 ± 0.5    |

Sextans

| S35     | 17.30      | 1.41            | 0.05             | 3600   | 27  | 1250.92386      | 218.2 ± 0.3     |
| S56     | 17.37      | 1.43            | 0.05             | 3600   | 26  | 1250.82948      | 226.9 ± 0.4     |
| S49     | 17.59      | 1.15            | 0.05             | 3600   | 17  | 1250.87628      | 230.9 ± 0.6     |
| S58     | 17.69      | 1.17            | 0.05             | 3600   | 21  | 1251.77326      | 219.8 ± 0.4     |
| S36     | 17.96      | 1.10            | 0.05             | 3600   | 13  | 1252.77161      | 222.9 ± 0.5     |

* Star ID References.—Draco: Baade & Swope 1961; Ursa Minor: van Agt 1967; Sextans: Suntzeff et al. 1993.

In this paper we build upon the initial study of SBS98 by analyzing high-resolution spectra for an expanded sample of RGB stars belonging to the Draco, Sextans, and Ursa Minor dSph galaxies, as well as for a single red giant in the distant globular cluster NGC 2419. We compare the element abundance ratios measured for our sample of RGB stars to those of Galactic halo/disk field stars and DLA absorbers having low levels of dust depletion.

2. OBSERVATIONS AND REDUCTIONS

2.1. Selection of Program Stars

RGB stars belonging to three Galactic dSph galaxies (i.e., Draco, Sextans, and Ursa Minor) were selected from a combination of published color-magnitude diagrams, new unpublished magnitudes (P. B. Stetson 2000, private communication; K. M. Cudworth 2000, private communication), and radial velocity catalogs (e.g., Da Costa et al. 1991; Suntzeff et al. 1993; Stetson 1979, 1984; Armandroff, Olszewski, & Pryor 1995). Published radial velocities were used to ensure that only bona fide members of their respective galaxies were targeted for observation with the High Resolution Echelle Spectrometer (HIRES) on the Keck I 10 m telescope (Vogt et al. 1994).

Color-magnitude diagrams for the three dSph galaxies studied here are shown in Figure 1. RGB stars for which we have HIRES spectra are indicated by the large symbols. These three galaxies contain little or no gas (Blitz & Robishaw 2000) and are comprised predominantly of old stars, although Mateo, Fischer, & Krzeminski (1995) report the presence of a modest intermediate-age population in Sextans. The four Draco red giants observed by SBS98 are also shown in Figure 1, as we have reanalyzed their spectra here (see § 4). The lower right panel of Figure 1 shows the distribution of our sample of RGB stars in the $M_V -(B-V)_0$ plane. The dashed lines in this panel show 13 Gyr isochrones from Bergbusch & Vandenberg (1992) having metallicities of [Fe/H] = −2.26, −1.66, and −1.26 dex.

2.2. HIRES Spectroscopy

HIRES spectra for 13 RGB stars belonging to the Draco, Ursa Minor, and Sextans dSph galaxies were acquired
during three observing runs at the Keck I telescope. During the 1999 March observing run, we also obtained a spectrum of a single red giant in the outer halo globular cluster NGC 2419. A number of bright RGB stars belonging to the nearby, well-studied globular clusters M92 and M3 were also observed during the 1999 March and July observing runs, in order to compare our measured abundances with those of previous high-resolution spectroscopic studies. An observing log for these observations is presented in Table 1. For each run, we used the C5 decker to produce a 1.15 × 7" slit and a spectral resolution of λ/Δλ = 34,000. In all cases, the detector was binned 1 × 2 in the spatial direction in order to reduce the read noise. Spectra obtained during the 1999 July and August observing runs span the wavelength region 4540 ≤ λλ ≤ 7020 Å; different echelle and cross disperser angles were used during the 1999 March observations, giving a wavelength coverage of 3850 ≤ λλ ≤ 6300 Å. The raw spectra were reduced using the MAKEE software package (T. Barlow 2000, private communication) and wavelength-calibrated within the IRAF2 environment.

Table 2 summarizes several properties of the program stars. From left to right, this table records the star name, V magnitude, (B − V) color, interstellar extinction, HIRES exposure time, signal-to-noise ratio (S/N) measured at the continuum near λ = 6100 Å, and heliocentric Julian date. The final column records the heliocentric radial velocity of each star, measured directly from the spectra with the velocity zero point established using telluric lines (see Shetrone 1994). References for the photometry are given in the footnotes to the table. For all objects, the adopted reddening is taken from the DIRBE reddening maps of Schlegel, Finkbeiner, & Davis (1998).

3. ANALYSIS

The lines chosen for the abundance analysis were adopted from several sources, including Blackwell et al. (1982, 1986), Bizzarri et al. (1993), Fuhrmann, Axer, & Gehren (1995), McWilliam et al. (1995), Kraft et al. (1995), Shetrone (1996), Sneden et al. (1996), Carretta & Gratton (1997), and the National Institute of Standards and Technology Atomic Spectra Database. In some cases, the line choices differ from those of SBS98, mainly in the addition of more and better lines for Ti i, Ti ii, Mg i, and several rare earth elements. Equivalent widths (EWs) were measured from Gaussian fits to individual spectra lines. Table 3 lists the measured EWs and adopted line parameters for each of the elements considered below.

Figure 2 shows a comparison of our EWs for the M92 and M3 RGB stars that we have in common with Sneden et al. (1991b) and Kraft et al. (1992). There is a essentially no offset, ΔEW = 1.6 ± 1.2 mÅ, between the two data sets, and the rms scatter of σ = 7.1 mÅ is consistent with the errors expected from uncertainties of the individual measure-

![Fig. 2](image_url) Comparison of equivalent widths for the globular cluster red giants presented in Table 3 with those previously reported by Sneden et al. (1991b) and Kraft et al. (1992).

ments. These results are consistent with those found in SBS98.

Initial temperature estimates were made using the colors and reddenings from Table 2, using the dereddened colors, (B − V), and our own (B − V) − T eff calibration for giants with metallicities in the range −3.0 ≤ [Fe/H] ≤ −1.0 dex. These initial estimates were based on rough approximations of the metallicities of the program stars based upon their location in the color-magnitude diagrams. This estimate was then fine-tuned in two ways. First, the metallicity from the first iteration was fed back into our color temperature estimate, and the entire process was repeated until we converged upon a best color temperature. Second, we adjusted the color temperature by (1) demanding a minimized slope, to within the errors, in the plots of Fe abundance (from Fe i) versus both excitation potential and equivalent width; and (2) requiring that the abundance of the ionized species equal that of the neutral species (based largely upon Fe i and Fe ii, and to a lesser extent, Ti i and Ti ii). In making this minimization, the microturbulent velocity, effective temperature, and surface gravity were adjusted iteratively.

Among the sample of reference stars in M92 and M3, the largest deviations between the initial and final adopted parameters were ΔT eff = 75 K and Δ log g = 0.10 dex for the effective temperature and surface gravity, respectively. Even in the case of the much lower S/N spectrum of the red giant RH 10 in NGC 2419, the deviations were only −25 K and 0.1 dex. For the sample of dSph stars, the largest deviation from the predicted temperature was 175 K for Ursa Minor K. This giant has obvious C2 bands, which reveal it to be a carbon star; it is not surprising that the color temperature based upon noncarbon stars would predict a significantly cooler temperature than the actual spectroscopic effective temperature. Excluding this star, the average differences between the predicted and adopted temperatures were 63 ± 18, 38 ± 25, and 22 ± 18 K in Ursa Minor, Draco,

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2 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.
and Sextans, respectively. The differences in the predicted versus adopted surface gravities are $-0.1 \pm 0.1$, $0.0 \pm 0.2$, and $-0.15 \pm 0.1$ dex. These slight differences in the stellar parameters could arise in several ways: a slight underestimation (0.02 mag) of the true reddenings, the use of a halo star $(B-V)_{0} - T_{\text{eff}}$ relation for the dSph giants (see § 5.1), systematic errors in the unpublished photometry, or a systematic error due to working with low-S/N spectra. We reject this last possibility because the predicted and adopted parameters for NGC 2419 RH 10, which has a lower S/N than the majority of the dSph spectra, are in excellent agreement, while the dSph giants having the highest S/N spectra (i.e., those in Ursa Minor) exhibit the largest deviations.

Model atmospheres were taken from the computations of the MARCS code (Gustafsson et al. 1975), and the abundance calculations were performed using the current version of Sneden's (1973) LTE line analysis and spectrum synthesis code. The procedures are nearly identical to those employed in SBS98, except for the modified line list. Since some important lines were added, we have reanalyzed the Draco giants from SBS98 and included the results in this paper. It is important to note that, as with most high-resolution spectroscopic analyses of metal-poor stars using the MARCS models, we have compensated for the increased electron contribution from the overabundant $\alpha$-elements by slightly increasing the overall metallicity (0.1 dex) of the model atmospheres. This compensation for $\alpha$-element enhancement will be discussed further in § 5.1. The best-fit model parameters for each star, along with the measured EWs, are recorded in Table 3.

Note that several of the elements in our analysis (e.g., V, Mn, Ba, Eu) are known to exhibit hyperfine splitting. We have not included this hyperfine splitting in our analysis because our goal is the measurement of overall abundance differences, not absolute abundances. The magnitude of the correction is small in comparison to the EW measurement errors, i.e., for $[\text{Ba/Fe}]$ the effect is only 0.02 dex.

4. ABUNDANCES

The first important result of this work is the overall abundance spread within the three dSph galaxies. In Figure 1, the $\alpha$-enhanced isochrones of Bergbusch & Vandenberg (1992) are overlaid on the color-magnitude diagrams, with our sample of dSph stars indicated. If the galaxies are comprised primarily of old and coeval stars, and if the photometric uncertainties are negligible, then a metallicity range of $-2.5 \leq [\text{Fe/H}] \leq -1.5$ dex can be expected in all three galaxies. As Table 4 shows, our measured abundances are roughly consistent with this expectation, i.e., we find metallicity ranges of $\Delta[\text{Fe/H}] \approx 1.53, 1.40$, and 0.73 dex for Draco, Sextans, and Ursa Minor, respectively. Moreover, the stars with the lowest abundances are found close to the blue edge of the color distribution, as expected. A more detailed isochrone-age analysis is beyond the scope of this paper since, as discussed in § 5.1, the current set of $\alpha$-enhanced isochrones may not be entirely appropriate for these galaxies.

The weighted mean metallicities of the three dSph samples are $[\text{Fe/H}] = -2.00 \pm 0.21$, $-1.90 \pm 0.11$, and $-2.07 \pm 0.21$ dex for Draco, Ursa Minor, and Sextans, respectively. Despite the small sample sizes and the presence of large internal metallicity spreads within all three galaxies, these mean values are in good agreement with previous determinations (see, e.g., Mateo 1998). The mean metallicity of the lone red giant in NGC 2419 is found to be $[\text{Fe/H}] = -2.32 \pm 0.11$ dex. This is slightly lower than, but still consistent with, the value of $[\text{Fe/H}] = -2.10 \pm 0.15$ dex found by Suntzeff, Kraft, & Kinman (1988) from low-resolution spectroscopy of six red giants.

4.1. Light Elements

Many of the light elements such as O, Na, Mg, and Al are known to exhibit significant star-to-star variations in globular clusters. For instance, Shetrone (1996), Kraft et al. (1997), and Sneden et al. (1997) find large ranges in the abundances of these light elements for red giants belonging to M3 and M92: $-0.7 < [\text{O/Fe}] < 0.45$ dex, $-0.3 < [\text{Na/Fe}] < 0.5$ dex, $-0.1 < [\text{Mg/Fe}] < 0.4$ dex, and $0.0 > [\text{Al/Fe}] > 1.1$ dex. By contrast, halo field stars do not exhibit these abundance variations. The observed variations in the globular cluster stars follow a specific pattern that is sometimes referred to as a “deep mixing abundance pattern,” with Al and Na being enhanced and O (and sometimes Mg) being depleted. Any comparison of the dSph abundance patterns for these elements with those of the globular cluster stars is complicated by these variations. In Figure 3, the light-element abundances for our program stars are shown along with a sample of Milky Way halo and disk stars. At least three of the M92 giants and one of the M3 giants exhibit the aforementioned “deep mixing abundance pattern.” Unfortunately, most of the O, Na, and Al abundances for the dSph stars are upper limits, making a detailed comparison with the field star sample impossible.

4.2. Even-Z Elements

The light elements with even numbers of protons (e.g., O, Mg, Si, Ca, Ti) are sometimes referred to as $\alpha$-elements or even-Z elements. Figure 4 shows our measured abundances for these even-Z elements, except for O and Mg, which are shown in Figure 3, plotted against the iron abundance. The abundances of the globular cluster stars, M3, M92, and NGC 2419, are consistent with those of the halo field stars. The Galactic halo field stars exhibit $\alpha$-enhancements between 0.1 and 0.5 dex (with the exception of $[\text{Si/Fe}]$, which shows a much broader distribution) over the metallicity range $-3.0 < [\text{Fe/H}] < -1.2$ dex. Because of the large intrinsic spread among the Si abundances and because of our rather large errors and upper limits on the measured Si abundances, the $[\text{Si/Fe}]$ abundance pattern will be discussed no further. The bottom panel in Figure 4 gives average even-Z abundances, $[\alpha/\text{Fe}] = \frac{2}{3}([\text{Mg/Fe}] + [\text{Ca/Fe}] + [\text{Ti/Fe}])$, for both our program stars and for those stars taken from the literature. This definition excludes the contribution from $[\text{O/Fe}]$ since many of the stars (both in our sample and in the literature) do not have detected O lines.

A first impression from Figure 4 is that the stars belonging to the three different dSph galaxies occupy the same portion of the figures, i.e., they have roughly the same abundance patterns. In addition, their abundance pattern appears to differ from that of the Galactic halo field star sample, with the dSph stars falling below the Milky Way sample at a given metallicity. Considering the dSph samples separately, the average even-Z abundances, $[\alpha/\text{Fe}]$, are $0.09 \pm 0.02$ dex for Draco, $0.13 \pm 0.04$ dex for Ursa Minor, and $0.02 \pm 0.07$ dex for Sextans. Over the same range in metallicity, the halo field star sample has a mean value of $[\alpha/\text{Fe}] = 0.28 \pm 0.02$ dex. Thus, all three dSph samples...
TABLE 4A
ELEMENT ABUNDANCES FOR PROGRAM STARS

| Star     | $T_{eff}$ (K) | log $g$ (dex) | $v_t$ (km s$^{-1}$) | [Fe/H] (dex) | [O/Fe] (dex) | [Na/Fe] (dex) | [Mg/Fe] (dex) | [Al/Fe] (dex) | [Si/Fe] (dex) | [Ca/Fe] (dex) | [Ti/Fe] (dex) |
|----------|---------------|--------------|---------------------|--------------|-------------|--------------|--------------|--------------|--------------|--------------|--------------|
| M92 = NGC 6341 |
| III-13    | 4175          | 0.20         | 2.10                | -2.28±0.11  | 0.13±0.15   | 0.48±0.10    | 0.64±0.16    | 0.90±0.15    | 0.47±0.15    | 0.30±0.08    | 0.39±0.07    |
| VII-18    | 4225          | 0.00         | 2.15                | -2.27±0.11  | <0.15       | 0.38±0.15    | 0.37±0.15    | 1.25±0.15    | 0.75±0.18    | 0.29±0.08    | 0.32±0.07    |
| V-106     | 4375          | 0.70         | 2.00                | -2.33±0.11  | <0.36       | -0.21±0.15   | 0.48±0.15    | <0.90        | 0.47±0.15    | 0.26±0.08    | 0.24±0.07    |
| III-65    | 4325          | 0.50         | 2.10                | -2.30±0.11  | 0.23±0.15   | 0.31±0.14    | 0.38±0.18    | 1.01±0.18    | 0.62±0.20    | 0.27±0.07    | 0.15±0.06    |
| M3 = NGC 5272 |
| III-28    | 4175          | 0.70         | 1.90                | -1.70±0.11  | 0.37±0.14   | -0.23±0.09   | 0.41±0.15    | -0.06±0.20   | 0.31±0.12    | 0.28±0.08    | 0.37±0.07    |
| I-21      | 4200          | 0.70         | 1.70                | -1.44±0.11  | 0.21±0.14   | -0.26±0.09   | 0.30±0.15    | 0.24±0.14    | 0.15±0.14    | 0.27±0.07    | 0.32±0.06    |
| IV-101    | 4225          | 0.80         | 1.70                | -1.44±0.11  | 0.02±0.14   | 0.20±0.09    | 0.24±0.13    | 0.85±0.12    | 0.09±0.15    | 0.28±0.08    | 0.32±0.07    |
| NGC 2419 |
| RH10      | 4275          | 0.70         | 2.10                | -2.32±0.11  | ...         | <0.26        | 0.30±0.18    | ...          | <0.72        | 0.11±0.12    | 0.22±0.11    |
| Draco     |
| 11        | 4475          | 0.80         | 1.80                | -1.72±0.11  | <0.38       | <0.34        | 0.07±0.15    | <0.71        | <0.30        | 0.16±0.08    | 0.09±0.07    |
| 343       | 4475          | 0.90         | 1.80                | -1.86±0.11  | 0.42±0.22   | -0.15±0.00   | 0.06±0.20    | <0.34        | <0.50        | 0.03±0.11    | -0.03±0.11   |
| 473       | 4400          | 0.90         | 1.75                | -1.44±0.07  | -0.32±0.18  | -0.04±0.09   | -0.19±0.17   | ...          | <0.14        | 0.18±0.08    | -0.18±0.25   |
| 267       | 4180          | 0.60         | 1.95                | -1.67±0.13  | -0.59±0.17  | -0.04±0.21   | ...          | <0.29        | 0.19±0.08    | 0.02±0.31    |
| 24        | 4290          | 0.80         | 2.00                | -2.36±0.09  | 0.38±0.18   | -0.33±0.18   | 0.26±0.16    | ...          | ...          | 0.07±0.06    | -0.04±0.18   |
| 119       | 4370          | 0.15         | 2.80                | -2.97±0.15  | ...         | -0.09±0.17   | 0.20±0.17    | ...          | ...          | 0.11±0.07    | -0.17±0.31   |
| Ursa Minor |
| 177       | 4300          | 0.40         | 1.90                | -2.01±0.11  | <0.33       | -0.37±0.18   | 0.32±0.17    | <0.68        | 0.51±0.30    | 0.18±0.08    | 0.15±0.08    |
| 297       | 4075          | 0.40         | 2.30                | -1.66±0.11  | 0.18±0.22   | 0.15±0.12    | 0.24±0.22    | <0.21        | 0.30±0.20    | 0.02±0.08    | 0.12±0.07    |
| K         | 4325          | 0.10         | 2.00                | -2.17±0.12  | <0.38       | <0.20        | 0.69±0.25    | <0.90        | <0.88        | 0.43±0.11    | 0.04±0.10    |
| O         | 4325          | 0.30         | 1.80                | -1.91±0.11  | <0.22       | <0.24        | 0.43±0.20    | <0.51        | 0.32±0.30    | 0.09±0.08    | 0.20±0.07    |
| 199       | 4325          | 0.30         | 1.95                | -1.45±0.11  | <0.05       | <0.66        | 0.02±0.17    | <0.01        | 0.00±0.20    | -0.01±0.09   | -0.08±0.09   |
| 168       | 4625          | 1.30         | 1.70                | -2.18±0.12  | ...         | <0.30        | 0.23±0.17    | <0.49        | 0.11±0.30    | 0.01±0.14    |
| Sextans |
| S35       | 4425          | 0.10         | 2.00                | -1.93±0.11  | ...         | -0.24±0.18   | 0.27±0.19    | ...          | 0.45±0.30    | 0.11±0.10    | 0.07±0.10    |
| S56       | 4175          | 0.30         | 1.90                | -1.93±0.11  | ...         | -0.27±0.18   | 0.23±0.19    | ...          | 0.45±0.30    | 0.08±0.10    | 0.13±0.10    |
| S49       | 4325          | 0.10         | 2.50                | -2.85±0.13  | ...         | -0.41±0.20   | 0.27±0.19    | ...          | 0.30±0.08    | -0.29±0.15   |
| S58       | 4525          | 1.00         | 1.90                | -1.45±0.12  | ...         | <0.43        | -0.46±0.19   | <0.30        | -0.12±0.10   | -0.35±0.10   |
| S36       | 4425          | 1.10         | 2.10                | -2.19±0.12  | ...         | <0.15        | -0.07±0.20   | ...          | ...          | 0.34±0.11    | -0.10±0.11   |

Note—This table is also available in machine-readable form in the electronic edition of the Journal.
| Star     | [Fe/H] | [V/Fe] | [Cr/Fe] | [Mn/Fe] | [Co/Fe] | [Ni/Fe] | [Cu/Fe] | [Zn/Fe] | [Cr/Co] |
|----------|--------|--------|---------|---------|---------|---------|---------|---------|---------|
|          | (dex)  | (dex)  | (dex)   | (dex)   | (dex)   | (dex)   | (dex)   | (dex)   | (dex)   |
| III-13   | -2.28 ± 0.11 | 0.04 ± 0.10 | -0.15 ± 0.12 | -0.27 ± 0.08 | 0.18 ± 0.10 | 0.04 ± 0.12 | -0.64 ± 0.15 | 0.17 ± 0.14 | 0.33 ± 0.16 |
| VII-18   | -2.27 ± 0.11 | -0.02 ± 0.12 | -0.10 ± 0.12 | -0.37 ± 0.09 | 0.08 ± 0.10 | 0.02 ± 0.12 | -0.65 ± 0.15 | 0.30 ± 0.16 | 0.18 ± 0.16 |
| V-106    | -2.33 ± 0.11 | 0.43 ± 0.20 | -0.23 ± 0.14 | -0.28 ± 0.14 | 0.05 ± 0.11 | 0.13 ± 0.13 | -0.76 ± 0.15 | 0.14 ± 0.12 | 0.28 ± 0.18 |
| III-65   | -2.30 ± 0.11 | 0.17 ± 0.10 | -0.27 ± 0.11 | -0.42 ± 0.14 | 0.15 ± 0.15 | 0.10 ± 0.12 | -0.78 ± 0.15 | 0.07 ± 0.12 | 0.42 ± 0.19 |
| M92 = NGC 6341 |
| III-28   | -1.70 ± 0.11 | 0.12 ± 0.09 | -0.01 ± 0.13 | -0.26 ± 0.08 | -0.04 ± 0.20 | 0.11 ± 0.13 | -0.37 ± 0.13 | 0.09 ± 0.14 | -0.03 ± 0.24 |
| I-21     | -1.44 ± 0.11 | 0.08 ± 0.09 | 0.08 ± 0.12 | -0.14 ± 0.10 | -0.08 ± 0.16 | -0.04 ± 0.12 | -0.17 ± 0.13 | -0.02 ± 0.15 | -0.16 ± 0.20 |
| IV-101   | -1.44 ± 0.11 | 0.08 ± 0.09 | 0.12 ± 0.13 | -0.19 ± 0.10 | 0.07 ± 0.14 | -0.07 ± 0.16 | -0.28 ± 0.13 | 0.05 ± 0.10 | -0.05 ± 0.19 |
| M3 = NGC 5272 |
| NGC 2419 |
| RH 10    | -2.32 ± 0.11 | ...     | -0.32 ± 0.17 | -0.31 ± 0.12 | <0.00     | 0.00 ± 0.19 | < -0.43   | <0.15     | ...     |
| Draco    |
| 11       | -1.72 ± 0.11 | ...     | -0.01 ± 0.17 | -0.50 ± 0.10 | -0.19 ± 0.18 | 0.00 ± 0.15 | < -0.35   | -0.21 ± 0.15 | -0.18 ± 0.25 |
| 343      | -1.86 ± 0.11 | -0.02 ± 0.18 | -0.49 ± 0.18 | -0.56 ± 0.10 | -0.20 ± 0.18 | -0.06 ± 0.21 | < -0.43   | -0.28 ± 0.30 | 0.29 ± 0.25 |
| 473      | -1.44 ± 0.07 | -0.68 ± 0.18 | -0.05 ± 0.12 | -0.32 ± 0.15 | 0.12 ± 0.14 | 0.19 ± 0.13 | < -0.10   | 0.12 ± 0.20 | 0.17 ± 0.18 |
| 267      | -1.67 ± 0.13 | -0.20 ± 0.18 | -0.05 ± 0.13 | -0.28 ± 0.16 | <0.05     | 0.36 ± 0.14 | < -0.39   | < -0.46   | ...     |
| 24       | -2.36 ± 0.09 | ...     | 0.04 ± 0.11 | <0.05     | -0.07 ± 0.20 | 0.31 ± 0.16 | < -0.15   | 0.10 ± 0.20 | -0.11 ± 0.23 |
| 119      | -2.97 ± 0.15 | ...     | -0.54 ± 0.08 | <0.80     | <1.27     | -0.42 ± 0.11 | <0.92     | <1.06     | ...     |
| Ursa Minor |
| 177      | -2.01 ± 0.11 | ...     | -0.23 ± 0.17 | -0.37 ± 0.10 | 0.26 ± 0.13 | 0.08 ± 0.17 | < -0.50   | -0.01 ± 0.15 | 0.49 ± 0.21 |
| 297      | -1.68 ± 0.11 | -0.13 ± 0.10 | 0.14 ± 0.18 | -0.35 ± 0.10 | 0.06 ± 0.20 | -0.12 ± 0.15 | < -0.52   | -0.20 ± 0.30 | -0.08 ± 0.27 |
| K        | -2.17 ± 0.12 | ...     | -0.01 ± 0.22 | -0.32 ± 0.18 | <0.10     | -0.02 ± 0.22 | < -0.26   | 0.06 ± 0.20 | ...     |
| O        | -1.91 ± 0.11 | -0.01 ± 0.21 | -0.26 ± 0.17 | -0.33 ± 0.12 | -0.15 ± 0.18 | 0.00 ± 0.17 | < -0.61   | 0.50 ± 0.20 | 0.11 ± 0.25 |
| 199      | -1.45 ± 0.11 | -0.17 ± 0.11 | 0.07 ± 0.16 | -0.36 ± 0.08 | -0.27 ± 0.15 | -0.18 ± 0.25 | < -0.80   | -0.26 ± 0.25 | -0.34 ± 0.22 |
| 168      | -2.18 ± 0.12 | ...     | -0.64 ± 0.23 | < -0.10   | <0.17     | 0.03 ± 0.22 | <0.10     | 0.03 ± 0.15 | ...     |
| Sextans |
| S35      | -1.93 ± 0.11 | -0.26 ± 0.18 | -0.27 ± 0.20 | -0.46 ± 0.10 | -0.20 ± 0.20 | 0.01 ± 0.20 | < -0.74   | -0.15 ± 0.30 | 0.07 ± 0.28 |
| S36      | -1.93 ± 0.11 | -0.22 ± 0.15 | -0.18 ± 0.19 | -0.66 ± 0.12 | -0.14 ± 0.20 | -0.08 ± 0.19 | < -0.78   | -0.10 ± 0.20 | 0.04 ± 0.28 |
| S49      | -2.85 ± 0.13 | ...     | -0.46 ± 0.23 | ...     | ...     | 0.26 ± 0.23 | ...     | <0.47     | ...     |
| S58      | -1.45 ± 0.12 | ...     | -0.29 ± 0.24 | -0.49 ± 0.10 | -0.64 ± 0.30 | -0.33 ± 0.24 | < -0.58   | -0.56 ± 0.30 | -0.35 ± 0.38 |
| S36      | -2.19 ± 0.12 | ...     | -0.38 ± 0.23 | < -0.14   | <0.10     | -0.24 ± 0.23 | <0.10     | -0.02 ± 0.25 | ...     |

**Note:** This table is also available in machine-readable form in the electronic edition of the Journal.
| Star       | [Fe/H] | [Y/Fe] | [Ba/Fe] | [Ce/Fe] | [Nd/Fe] | [Sm/Fe] | [Eu/Fe] | [Ba/Eu] | [Ba/Y] |
|------------|--------|--------|---------|---------|---------|---------|---------|---------|--------|
|            | (dex)  | (dex)  | (dex)   | (dex)   | (dex)   | (dex)   | (dex)   | (dex)   | (dex)  |
| III-13     | −2.28±0.11 | −0.25±0.07 | −0.50±0.07 | −0.57±0.10 | −0.37±0.10 | 0.08±0.14 | −0.04±0.14 | −0.46±0.16 | −0.25±0.10 |
| VII-18     | −2.27±0.11 | −0.35±0.07 | −0.50±0.07 | −0.51±0.10 | −0.28±0.10 | 0.02±0.14 | −0.03±0.14 | −0.47±0.16 | −0.15±0.10 |
| V-106      | −2.33±0.11 | −0.33±0.07 | −0.40±0.07 | −0.50±0.10 | −0.14±0.10 | 0.12±0.14 | 0.27±0.14 | 0.67±0.16 | −0.07±0.10 |
| III-65     | −2.30±0.11 | −0.41±0.07 | −0.43±0.07 | −0.47±0.10 | −0.16±0.10 | 0.27±0.14 | 0.16±0.14 | −0.59±0.16 | −0.02±0.10 |
| M92 = NGC 6341 |        |        |         |         |         |         |         |         |        |
| III-28     | −1.70±0.11 | 0.08±0.07 | 0.08±0.07 | −0.15±0.10 | 0.28±0.10 | 0.63±0.14 | 0.48±0.14 | −0.40±0.16 | 0.00±0.10 |
| I-21       | −1.44±0.11 | −0.16±0.07 | 0.05±0.07 | −0.19±0.10 | 0.17±0.10 | 0.29±0.14 | 0.38±0.14 | −0.33±0.16 | 0.21±0.10 |
| IV-101     | −1.44±0.11 | −0.08±0.07 | 0.14±0.07 | 0.06±0.10 | 0.29±0.10 | 0.47±0.14 | 0.40±0.14 | −0.26±0.16 | 0.22±0.10 |
| M3 = NGC 5272 |        |        |         |         |         |         |         |         |        |
| RH 10      | −2.32±0.11 | 0.03±0.10 | −0.15±0.10 | −0.05±0.14 | 0.19±0.14 | <0.80   | ...     | ...     | −0.18±0.14 |
| NGC 2419   |        |        |         |         |         |         |         |         |        |
| Draco      |        |        |         |         |         |         |         |         |        |
| 11         | −1.72±0.11 | −0.68±0.10 | 0.11±0.10 | −0.13±0.14 | 0.23±0.14 | 0.36±0.20 | 0.55±0.20 | −0.44±0.22 | 0.79±0.14 |
| 343        | −1.86±0.11 | −0.45±0.10 | 0.09±0.10 | −0.53±0.14 | −0.19±0.14 | 0.18±0.20 | 0.51±0.20 | −0.42±0.22 | 0.54±0.14 |
| 473        | −1.44±0.07 | −0.74±0.16 | −0.01±0.16 | 0.03±0.35 | 0.50±0.35 | ...     | ...     | 0.73±0.23 | ...     |
| 267        | −1.67±0.13 | −0.73±0.16 | 0.41±0.16 | 0.19±0.35 | 0.11±0.18 | ...     | ...     | 1.14±0.23 | ...     |
| 24         | −2.36±0.09 | <−0.65    | −1.19±0.25 | <0.00     | <−0.04   | ...     | ...     | ...     | ...     |
| 119        | −2.97±0.15 | <−0.39    | <−1.17    | <0.41     | <0.37    | ...     | ...     | ...     | ...     |
| Ursa Minor |        |        |         |         |         |         |         |         |        |
| 177        | −2.01±0.11 | −0.52±0.10 | −0.22±0.10 | −0.51±0.14 | −0.09±0.14 | 0.48±0.20 | 0.26±0.20 | −0.48±0.22 | 0.30±0.14 |
| 297        | −1.68±0.11 | −0.04±0.09 | 0.15±0.09 | −0.23±0.11 | 0.45±0.11 | 1.06±0.18 | 0.74±0.18 | −0.59±0.20 | 0.19±0.13 |
| K          | −2.17±0.12 | 0.06±0.09 | 1.37±0.09 | 1.36±0.11 | 1.28±0.11 | 1.73±0.18 | 1.04±0.18 | 0.33±0.20 | 1.31±0.13 |
| O          | −1.91±0.11 | −0.67±0.10 | −0.39±0.10 | −1.02±0.14 | −0.27±0.14 | 0.28±0.20 | 0.15±0.20 | −0.54±0.22 | 0.28±0.14 |
| 199        | −1.45±0.11 | 0.34±0.09 | 0.77±0.09 | 1.03±0.11 | 1.13±0.11 | 1.75±0.18 | 1.49±0.18 | −0.72±0.20 | 0.43±0.13 |
| 168        | −2.18±0.12 | −0.34±0.10 | 0.18±0.09 | −0.18±0.14 | 0.23±0.14 | <0.65   | <1.30   | ...     | 0.52±0.13 |
| Sextans    |        |        |         |         |         |         |         |         |        |
| S35        | −1.93±0.11 | −0.07±0.10 | 0.70±0.10 | 0.89±0.11 | 0.79±0.11 | 1.58±0.18 | ...     | ...     | 0.77±0.14 |
| S36        | −1.93±0.11 | −0.37±0.13 | 0.23±0.14 | −0.25±0.14 | 0.22±0.14 | 0.86±0.20 | ...     | ...     | 0.60±0.19 |
| S49        | −2.85±0.13 | <−0.35    | −1.05±0.15 | <0.45     | <0.50    | <0.94   | ...     | ...     | ...     |
| S58        | −1.45±0.12 | −0.77±0.13 | 0.11±0.14 | −0.54±0.14 | 0.00±0.14 | 0.52±0.20 | ...     | ...     | 0.88±0.19 |
| S36        | −2.19±0.12 | 0.25±0.13 | 0.39±0.14 | <0.46     | 0.52±0.14 | <1.34   | ...     | ...     | 0.14±0.19 |

**Note:** This table is also available in machine-readable form in the electronic edition of the Journal.
have a statistically significant underabundance of Mg, Ca, and Ti in comparison to the Galactic halo. By contrast, we find \([\alpha/Fe] \approx 0.21 \pm 0.10\) dex for the lone red giant in NGC 2419, which is slightly lower than, but nevertheless consistent with, the mean value of \(0.34 \pm 0.04\) dex for the red giants in M92.

There is also some evidence for a trend of decreasing \([\alpha/Fe]\) abundance with increasing metallicity in the Sextans and Ursa Minor samples. The Ursa Minor sample is linearly correlated with a slope of \(d[\alpha/Fe]/d[Fe/H] = -0.26 \pm 0.11\). The trend is less obvious among the sample of Sextans stars, which have a slope of \(-0.12 \pm 0.08\). Nonetheless, it is certainly true that the most metal-rich star in the Sextans sample has a significantly lower even-Z abundance than the rest of the Sextans sample. Similarly, the most metal-rich star in the Draco sample has the lowest \([O/Fe]\) and \([Mg/Fe]\) abundance ratios for this galaxy.
Fig. 4.—Abundance ratios for additional $\alpha$-elements (Si, Ca, Ti) plotted against $[\text{Fe/H}]$. The lower panel shows the mean $\alpha$-element abundance ratio, taken here as $[\alpha/\text{Fe}] = \frac{1}{4}([\text{Mg/Fe}] + [\text{Ca/Fe}] + [\text{Ti/Fe}])$. The symbols are the same as in Fig. 3.

4.3. Iron Peak Elements

Figures 5 and 6 show the iron peak element abundance ratios plotted against metallicity. The $[\text{V/Fe}]$ abundances are undersampled as a result of the temperature-sensitive nature of these lines, i.e., the more metal-poor stars are hotter and hence the V lines are weaker as a result of both the lower abundances and the cooler temperatures. All of the dSph giants with measured V abundances exhibit the same abundance pattern as that of the halo field stars, with the exception of Draco 473. This may be a further indication of chemical peculiarity of this metal-rich star, or it could indicate a problem with our adopted temperature.

Among the halo field stars more metal rich than $[\text{Fe/H}] \approx -1.9$ dex, Co and Cr are found in their solar ratios; at lower metallicities, the abundances of Co and Cr diverge, with the $[\text{Co/Fe}]$ ratios increasing and the $[\text{Cr/Fe}]$ ratios decreasing. This same abundance pattern is seen in each of
the three dSph samples. Like [Cr/Fe], the [Cu/Fe] and
[Mn/Fe] abundances exhibit a decline with decreasing iron
abundance, although the onset occurs at higher metallicity.
All three dSph samples exhibit subsolar [Cu/Fe] and
[Mn/Fe] abundance ratios, consistent with that found in
the Milky Way sample. In addition, both [Ni/Fe] and
[Zn/Fe] are found in their solar ratios in the halo and dSph
samples over the metallicity range of interest.

For NGC 2419, the measured [Cr/Fe], [Mn/Fe], [Co/
Fe], [Ni/Fe], and [Cu/Fe] abundances are similar to those
found for the red giants in M92.

4.4. Heavy Metals

We define the heavy metals as those elements with
Z > 30. This broad definition includes many subcategories
including the first s-process elements, the second s-process
elements, and the r-process elements. The s-process ele-
ments are those produced mainly by slow neutron addition,
while the r-process elements are created largely through the
rapid addition of neutrons. Table 4 of Burris et al. (2000)
gives the relative contributions of the s- and r-processes for
all of the heavy elements in the Sun. Of the heavy metals for
which we have measured abundances, we have one first
Fig. 6.—Abundance ratios for additional iron peak elements (Ni, Cu, Zn) plotted against [Fe/H]. The lower panel shows the dependence of [Co/Cr] on metallicity. The symbols are the same as in Fig. 3.

$s$-process peak element ($Y$), three second $s$-process peak elements ($Ba$, $Ce$, $Sm$), one $r$-process element ($Eu$), and one element that is nearly an even mix of the $s$- and $r$-processes ($Nd$). Figures 7 and 8 show the heavy-metal abundances for the dSph, halo, and globular cluster samples.

While the concept of $s$-process elements and $r$-process elements is a traditional one, it can lead to possible misconceptions. In most Population II stars, the $r$-process dominates and the $s$-process contributes little to the abundance of the "second $s$-process peak elements." A notable exception to this trend is found among carbon stars. These asymptotic giant branch (AGB) stars have contaminated atmospheres, with anomalously high fractions of carbon and $s$-process elements on their surfaces. As a result, their spectra are rich in $C_2$ bands and the lines of $s$-process elements. One star in our sample, Ursa Minor K, has a spectrum with strong $C_2$ bands, as noted previously from lower resolution spectroscopy (Cantera & Schommer 1978; Aaronson, Hodge, & Olszewski 1983; Armandroff et al. 1995). Our analysis reveals an abundance pattern for this
star that is dominated by the $s$-process and confirms the classification of Ursa Minor K as a carbon star.

The abundance ratio $[\text{Ba}/\text{Eu}]$ is most often used to access the relative contribution of the $r$- and $s$-processes to the heavy-metal abundance pattern. Figure 8 shows the measured $[\text{Ba}/\text{Eu}]$ ratios plotted against metallicity for our program stars. For the halo field star sample, the $[\text{Ba}/\text{Eu}]$ abundances range from solar-like ratios in the most metal-rich stars to $[\text{Ba}/\text{Eu}] \approx -0.5$ for $[\text{Fe/H}] \lesssim -1$ dex. This trend can be understood as an evolution from old metal-poor stars having abundance patterns dominated by the $r$-process to younger solar metallicity stars with a mix of $r$-process and $s$-process patterns. Unfortunately, the spectrograph setup used during the observation of stars in Sextans did not include the lone Eu line that was included in the Draco and Ursa Minor spectra. For this reason, we have no $[\text{Ba}/\text{Eu}]$ ratio for the Sextans stars and hence no information about the relative $r$-process and $s$-process contributions. However, the Draco and Ursa Minor stars (Ursa Minor K excluded) exhibit the same $r$-process-dominated abundance pattern as does the Milky Way sample.

Inspection of Table 4 and Figures 7 and 8 reveals three stars whose heavy-element abundance ratios are enhanced relative to those typical for other dSph and halo field stars:
Ursa Minor K, Ursa Minor 199, and Sextans 35. As mentioned above, Ursa Minor K is an obvious carbon star with an enhanced $s$-process–dominated abundance pattern, while the heavy-element abundance pattern for Ursa Minor 199 is dominated by the $r$-process. Unfortunately, we do not know what process dominates the heavy-element abundance pattern for Sextans 35, since we lack a measured Eu abundance for this star. The enhancement of the heavy-element abundances for these stars does have a precedent among halo field stars: a small percentage of Population II stars that show $r$-process–dominated heavy-element abundance patterns have large overabundances of the heavy elements with respect to iron (e.g., Westin et al. 2000; Norris, Ryan, & Beers 1997; Cowan et al. 1995).

Excluding the three dSph stars with large overabundances of the heavy elements, the abundances of the second $s$-process elements (Ce, Sm, and Ba) are consistent with those of the halo field stars. This is also true for the abundances of the $r$-process peak element Eu. However, the abundances of $Y$ (a first $s$-process peak element) are much lower in the more metal-rich dSph giants than in the halo field stars of similar metallicity. In the bottom panel of
Figure 8, we have plotted the \([\text{Ba}/\text{Y}]\) abundance ratio against the metallicity. It is clear that the dSph sample has a significantly higher \([\text{Ba}/\text{Y}]\) abundance ratio than the halo field star sample over the entire range of dSph metallicities.

For NGC 2419, the measured ratios of \([\text{Ce}/\text{Fe}], [\text{Nd}/\text{Fe}], [\text{Y}/\text{Fe}], \text{and } [\text{Ba}/\text{Fe}]\) appear to be slightly enhanced over their respective ratios in the M92 giants. Interestingly, the inferred ratio of \([\text{Ba}/\text{Y}] = -0.13 \pm 0.14\) is in good agreement with the corresponding values measured for red giants in M92.

5. DISCUSSION

The abundance patterns of the three dSph stars sampled here are remarkably uniform. This suggests that the galaxies share fairly similar nucleosynthetic histories and thus similar initial mass functions. Because dwarf galaxies (and DLA systems) have been invoked in numerous models for the formation of large galaxies, we now address the issue of how Sextans, Draco, and Ursa Minor as a group fit into these scenarios.

5.1. Milky Way Comparison

As mentioned above, there are some significant differences between the abundance patterns in the Milky Way and those in the dSph samples. Probably the most important of these is the lower even-Z abundances found among the dSph stars. Since the production of even-Z elements is thought to be dominated by massive Type II supernovae (e.g., Tsujimoto et al. 1995), lower \([\alpha/\text{Fe}]\) abundance ratios would require either that the most massive Type II supernovae were absent in the young dSph stars or that the ejecta from these massive supernovae were lost from the galaxy and not incorporated in the subsequent generations of stars. Alternatively, it is possible that the chemical evolution of the dSph galaxies included a relatively large contribution from Type Ia supernovae (which are expected to produce large quantities of iron peak elements compared to the \(\alpha\)-elements).

The importance of the low \([\alpha/\text{Fe}]\) abundance ratios should not be understated. The even-Z elements are abundant electron donors and hence important sources of atmospheric opacity in K giants; thus, the abundances of even-Z elements influence age estimates based upon isochrone fitting (e.g., Bergbusch & Vandenberg 1992). As mentioned in § 3, the analysis of halo stars includes the extra electron contribution to the opacities due to the even-Z elements, which is offset by artificially inflating the metallicity of the model atmosphere. We have followed this same procedure for the dSph stars; if this compensation were not included, the abundances of the neutral species would increase by 0.03 dex, while the abundance of the ionized species would decrease by 0.03 dex. Since our metallicities are based mainly upon the large number of Fe I lines, we may have underestimated the dSph abundances systematically by 0.03 dex. The abundance ratios for the neutral species should not change, but the abundance ratios reported in Table 4 for the ionized species may be systematically too large by 0.06 dex for stars that do not have enhanced abundances of even-Z elements.

Although the Galactic halo does contain stars with low even-Z abundance patterns (e.g., Ivans et al. 2000), such stars are rare. The observed differences in the respective even-Z element abundance patterns may therefore put some interesting limitations on the suggestion that the Milky way was assembled from “building blocks,” or proto-Galactic fragments, similar to the dSph galaxies sampled here (e.g., Searle & Zinn 1978; Larson 1988; Zinn 1993; Mateo 1996; Côté et al. 2000). If these suggestions are correct, then perhaps the actual proto-Galactic fragments were larger and could better retain gas from massive Type II supernovae than the present sample of low-luminosity dSph galaxies. In the Monte Carlo simulations of Côté et al. (2000), the initial population of proto-Galactic fragments spans a wide range in luminosities, including a small number of large systems with present-day luminosities of \(L_V \sim 2 \times 10^8 L_{V,\odot}\) as well as numerous small objects with luminosities similar to those of Draco, Sextans, and Ursa Minor: \(<L_V> \sim 3 \times 10^7 L_{V,\odot}\). If the chemical enrichment of the proto-Galactic fragments can be roughly approximated by a closed box model (e.g., Telbott & Arnett 1971; Searle & Sargent 1972), then those proto-Galactic fragments that are similar in luminosity to the Fornax dSph \((L_V = 1.5 \times 10^7 L_{V,\odot})\) galaxy are expected to have contributed roughly half of the number of halo field stars with \([\text{Fe}/\text{H}] \sim -2\) dex that originated in smaller fragments such as Draco, Sextans, and Ursa Minor. Clearly, the measurement of even-Z abundances for stars belonging to the more massive Galactic satellites (such as Fornax, Sagittarius, and Leo I) are urgently needed to test these models.

Alternatively, it may be that the nucleosynthetic history of the proto-Galactic fragments was affected by the building process in such a way as to make them different from the dSph galaxies that survive today. Still another possibility is that the old, gas-poor dSph galaxies sampled here comprised only a small fraction of the actual proto-Galactic fragments and that the dSph galaxies with younger populations (i.e., those that had more gas for subsequent star formation) show even-Z abundance patterns that more closely resemble those of Galactic halo field stars. Again, element abundances for stars belonging to an expanded sample of dwarf galaxies are required to test these possibilities.

SBS98 reported that one of their giants, Draco 473, exhibits the deep mixing abundance pattern seen in many globular clusters, with Na enhanced and O and Mg depleted (see Kraft 1994 and Pinsonneault 1997 for recent reviews). With the expanded dSph sample presented here we now reinterpret the abundance pattern of Draco 473 as having its even-Z elements (including O and Mg) not enhanced in comparison to Milky Way halo field stars and probably not due to a deep mixing pattern as originally suggested.

Majewski et al. (2000) have proposed that \(\omega\) Cen may be the nucleus of a dwarf galaxy that has been tidally stripped by the Milky Way. If true, a comparison of the abundances in this dwarf galaxy core to the abundances found in the low-luminosity dwarf galaxies sampled here might reveal more clues to the formation of the halo. The dSph galaxies studied here exhibit heavy-element abundance patterns that are quite different from those of \(\omega\) Cen: Smith et al. (2000) find a large enhancement of s-process elements relative to \(r\)-process elements with increasing metallicity. They attribute this \(s\)-process domination to AGB nucleosynthesis enrichment by \(1.5–3 M_\odot\) stars. None of the dSph galaxies in our sample show evidence for such AGB nucleosynthesis enrichment. Thus, if \(\omega\) Cen is indeed the remains of a disrupted dwarf galaxy, then it must have been one different from Draco, Sextans, or Ursa Minor. Such a situ-
ation would not be entirely surprising given the relative luminosities of the dSph galaxies and ω Cen, i.e., the latter has roughly the same luminosity as the three dSph galaxies combined. If ω Cen is truly the surviving nucleus of a dwarf galaxy that has been tidally stripped by the Milky Way, then more massive systems such as Fornax or Sagittarius may be better analogs for the putative galaxy. Once again, high-resolution abundance analyses for stars belonging to the more massive Galactic satellites are needed to test this possibility.

As noted previously, two of the stars in our sample show large overabundances of the heavy elements with respect to iron and an r-process heavy-element abundance pattern. Such stars are known in the Milky Way halo (see Westin et al. 2000; Norris et al. 1997; Cowan et al. 1995), but they are fairly rare. To find two such stars in our small sample suggests that these stars are much more common in dSph environments.

The underabundance of Y in our dSph sample is not easily understood, mainly because Y abundances in the Milky Way nucleosynthesis are themselves poorly understood. We offer two possible solutions and suggest that higher S/N spectra with wider wavelength coverage are required to understand further the first s-process peak. The [Ba/Eu] abundances in Figure 8 suggest that the dSph sample is r-process dominated, at least among the second s-process peak elements. If the first s-process peak were created in a separate site from the second s-process peak, then we might expect to find variations between the various nucleosynthetic sites. Wasserburg, Busso, & Gallino (1996) suggest that different r-process sites might exist for low- and high-Z heavy elements, a hypothesis that has some observational support (e.g., Sneden et al. 2000). In an attempt to explain the deep mixing abundance profile found in globular cluster stars, Cavalo & Nagar (2000) suggested that intermediate-mass AGB stars (M > 4 M_{⊙}) could produce _27^Al from magnesium. These AGB stars will produce first s-process peak elements but no second s-process peak elements (Denissenkov et al. 1998; Boothroyd & Sackmann 1999). If either of the above processes contributes to the Galactic halo [Y/Fe] abundance pattern but not to that of dSph stars (or did not contribute to the gas that made up subsequent generations of stars), then the two samples could show different [Y/Fe] ratios. In principal, the contribution of AGB stars could be tested carefully by searching for age spreads within these galaxies.

5.2. DLA Comparison

In addition to the samples of dSph and halo stars, Figures 3–8 show element abundances for a sample of DLA systems with low dust contents. Given the complexities of deriving the intrinsic (i.e., undepleted) element abundances in such systems (see, e.g., Vladilo 1998), we show only the observed abundances in these systems, all of which show relatively low levels of dust depletion. For the elements Si, Cr, Mn, and Ni there is agreement among the abundances of the dSph, Milky Way, and DLA samples. As is well known, the Zn abundances of the DLA systems are systematically larger than those of the sample of Galactic halo and disk stars; the measured Zn abundances for the dSph stars are smaller still, at least for the more metal-rich dSph stars. The Zn overabundance in DLA systems has sometimes been attributed to depletion of Fe by dust grains (e.g., Pettini et al. 1994, 1999; Kulkarni, Fall, & Truran 1997), although others contend that the usual Zn abundances of the DLA systems may be intrinsic to their stellar nucleosynthesis (Lu et al. 1996).

Obviously, grain depletion is not an issue for our measured dSph abundances. We find significantly different [Zn/Fe] ratios than in the Galactic halo, suggesting that the mechanism responsible for the production of the Zn in these galaxies either was missing or was somehow kept from contributing to the enrichment of subsequent generations of stars. The former possibility would suggest that old, low-mass dSph galaxies such as Draco, Ursa Minor, and Sextans are not the surviving end products of high-redshift DLA systems. Alternatively, the latter possibility would indicate that the Zn-rich gas present in these galaxies would have to be removed during a quiescent star formation period or expelled by an energetic source.

Unfortunately, little is known about the nucleosynthetic site of Zn. Classified as an iron peak element, it is largely ignored in analyses of neutron capture processes. An exception is Burris et al. (2000), who report a solar system r-process fraction of 0.66 for Zn. In light of suggestions that different r-process sites might exist for low- and high-Z heavy elements, a more extensive study of Zn in relation to the first s-process peak elements might provide some useful insights.

6. SUMMARY

High-resolution spectra for red giant stars belonging to the Draco, Sextans, and Ursa Minor dSph galaxies, as well as the distant Galactic globular cluster NGC 2419, have been obtained with HIRES on the Keck I telescope. Using these spectra, we have measured element abundance ratios for more than 20 elements. This is the first investigation of the abundance patterns of stars belonging to Sextans, Ursa Minor, and NGC 2419 and constitutes a factor of 4 increase in the number of dSph stars having abundances measured from high-resolution spectra.

From a single red giant in NGC 2419, we find a metallicity of [Fe/H] = −2.32 ± 0.11 dex, slightly lower than, but in acceptable agreement with, previous estimates from low-resolution spectroscopy (Suntzeff et al. 1988). With the possible exception of slight enhancements in a number of heavy elements, the measured abundances ratios closely resemble those of red giant stars in M92: a nearby, well-studied globular cluster of similar metallicity.

We find a remarkably uniform abundance pattern for our sample of 17 dSph stars. This suggests that the three dSph galaxies have fairly similar nucleosynthetic histories and, presumably, similar initial mass functions. All three galaxies show unmistakable evidence for a large range in metallicity: Δ[Fe/H] = 1.53, 0.73, and 1.40 dex for Draco, Ursa Minor, and Sextans, respectively. We find that the dSph stars have [α/Fe] abundances that are ≈0.2 dex lower than those of halo field stars in the same metallicity range, i.e., [α/Fe] ∼ 0.1 dex, compared to [α/Fe] ∼ 0.3 dex for halo stars. The measured [Eu/Fe] and [Ba/Fe] abundances for the dSph stars suggest that the chemical evolution in the dSph environments has been dominated by the r-process. In addition, the dSph stars show significantly larger [Ba/Y] abundance ratios than do halo field stars over the full range in metallicity. These observations provide some evidence against the notion that the Galactic halo has been assembled entirely through the disruption of very low luminosity dSph galaxies like the three galaxies studied here. A
more detailed assessment of the role played by the disruption of dwarf galaxies in the formation of the Galactic halo must await the measurement of element abundances for stars belonging to an expanded sample of Galactic satellites, particularly more luminous systems such as Sagittarius, Fornax, and Leo I.

A comparison of the measured abundance ratios for the dSph stars with those reported for DLA systems having low levels of dust depletion reveals [Zn/Fe] abundance ratios that are nearly an order of magnitude lower than those in the high-redshift absorbers, indicating that old, gas-poor dSph galaxies like those studied here are probably not the low-redshift analogs of the DLA systems.

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