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ABUNDANCES FOR GIANT STARS IN THE DRACO DWARF GALAXY

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ABSTRACT

We have determined the abundances of 14 giant stars with $+0.2 > M_V > -2.5$ $(19.6 > V > 16.9)$ in the Draco dwarf galaxy, using a synthetic spectral analysis of the calcium infrared triplet and the strongest line (5183 Å) of the magnesium *b* triplet. The average abundance of the galaxy is $\sim -1.9 \pm 0.4$ (all quoted uncertainties are 1 σ), with a range from ~ -1.4 to -2.4. As previously noted by Zinn and Kinman et al., the abundances seem to fall into two groups, one with an average [Ca, Mg/H] near -1.6 ± 0.2 and the other -2.3 ± 0.2. These results confirm and, in two significant ways, extend other claims for an abundance spread. First, our study extends to stars about 1.5 mag fainter than previous spectroscopic studies and is thus less sensitive to uncertainties arising from rapid evolutionary or mixing processes near the peak luminosity of the red giant branch and asymptotic giant branch, or from modeling quite extended atmospheres. Second, our study is one of the few to use model atmosphere techniques to match absorption features. A discussion of the origin of the color range among Draco giants and other problems of understanding dwarf spheroidal galaxy formation and evolution is presented.

Subject headings: galaxies: individual (Draco) — Local Group — stars: abundances — stars: evolution — stars: giants — stars: Population II

1. INTRODUCTION

With their relatively low masses and low surface brightnesses, dwarf spheroidal galaxies (dSphs) are hardly impressive objects. However, for good reason, they have been the subject of many studies. Besides being the most numerous type of galaxy in the Local Group, they provide the possibility of studying how chemical evolution and star formation proceeded in "simple," relatively compact, isolated environments. Indeed, according to one picture (Searle & Zinn 1978), the halo of our Galaxy may have been formed by the merger and disruption of objects with dimensions and masses comparable to those of the dSphs (see, e.g., Da Costa 1988 for a review).

Certainly the most studied of the local dSphs is Draco. With modern detectors it is possible to obtain low-resolution spectra of its brighter giants, as well as to obtain reasonably accurate photometry near its main-sequence turnoff. Both types of data are necessary to determine Draco's chemical evolution and star formation history.

A range of heavy element abundance among the brighter Draco giant stars has been found by many authors (e.g., Zinn 1978; Kinman, Kraft, & Suntzeff 1981; Smith 1984; Stetson 1984; Carney & Seitzer 1986). However, Bell (1985) examined the evidence critically and raised the concern that much of the inferred range might arise from underestimation of observational errors. Before Suntzeff's (1988) subsequent reanalysis of the older data largely allayed those fears, we had already undertaken a major new observational effort designed to address the conflict by determining the chemical abundance of Draco's giant branch through a spectral synthesis analysis of the Ca II infrared and the Mg I *b* triplets. Our program included considerably fainter giants than had been previously studied spectroscopically, which we hoped would contribute to resolving the conflict then in the literature. The ultimate goal is to answer such questions as how Draco evolved chemically and how its star formation proceeded.

2. OBSERVATIONAL MATERIAL

The observations consisted of multislit TI 800 × 800 CCD frames taken using the double-spectrograph (Oke & Gunn 1982) on the Hale 5 m telescope. Each of the eight slitlets was $\sim 15''$ long; typically we could place about six of them on suitable Draco giants, which were selected from the studies of Stetson (1979a, b, 1980a, b). It should be borne in mind that our sample of only 14 stars was selected at random from Stetson (1979a) according to the availability of uncrowded stars within the field of view of the multislit device (approximately $2'$).

An initial observing run occurred on the nights of 1984 July 6–8, in which a 600 grooves mm^{-1} grating was used. While badly affected by clouds, the run demonstrated that our hope of achieving with CCDs significantly fainter limiting magnitudes at resolutions comparable to those of Stetson's (1984) "2D-Frutti" studies in the region ~3700–4800 Å was somewhat optimistic. On the 1984 run the red channel sampled the region ~4600–7000 Å (the exact range depends upon the

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grating angle and the position of each slitlet). In 1985 (July 9–11, also affected by clouds) and 1986 (June 12–14) we used a 300 grooves mm^{-1} grating in the green channel and a 316 grooves mm^{-1} one in the red channel. Consequently, the green and red channels sampled the spectral regions ∼3800–5400 Å and ∼6400–8600 Å, respectively, resulting in the reddest Ca II triplet line often being lost for the Draco giants. Typically we secured two or three observations of 4000 s per field per run. In 1985 2".0 slit widths were used, and flat-fielding relied on incandescent lamps within the spectrograph turret; during the 1986 run, 1".0 wide slitlets were used, and the flat-fielding was based upon quartz lamp dome flats.

The data were reduced using standard Palomar software in Pasadena by J. B. O. and J. E. H. Since care was taken during instrument setup to align the spectra with respect to the CCD, no tilt corrections were required. For the exposure times used, typically less than one cosmic ray was encountered per spectrum; in the rare case that one landed near a spectral feature, that feature was not measured. Following flat-fielding, the spectra were extracted interactively with care to associate each slitlet correctly with the proper star. Sky subtraction was performed using all available information from a particular slitlet; since the stars were generally well centered along the slitlets, this typically meant that the average of 3"–4" on each side of each star was used. Observations of Oke & Gunn (1983) standard stars were used to flux-calibrate the spectra.

The final spectra were the result of co-adding individual spectra from the 1985 and 1986 runs; total integration times from 11,000 to 20,000 s were common. Each individual spectrum was carefully checked for consistency with the others before addition. The resulting spectra have a resolution of ∼6 Å for the green spectra and ∼8 Å for the red spectra (∼3 pixels for both) and a signal-to-noise ratio, as measured directly from the completely reduced spectra and within about 20 Å on each side of the Ca triplet and Mg line, ranging from about 10 to 80, with about 40 being typical. While the signal-to-noise ratios (S/N) are not identical for the red and the green spectra in each observation, the range of S/N over the ensembles of red and green spectra is similar. Sample green and red spectra for several stars are shown in Figure 1.

TABLE 1

MAGNITUDES, COLORS, T_{eff}, log g, AND MEMBERSHIP PROBABILITIES FOR THE DRACO DWARF GALAXY GIANTS

Star[a]	M_V	$(B-V)_0$	T_{eff}	log g	P_{mem}
45–22	−1.36	1.04	4500	1.30	0.92
45–24	−2.39	1.27	4250	0.75	0.92
75–45	−1.84	1.10	4400	1.10	0.96
165–106	−0.03	0.89	4650	1.95	0.87
165–114	−0.76	0.90	4650	1.70	0.94
165–115	−0.31	0.82	4800	1.95	0.93
165–116	−0.38	0.95	4550	1.80	0.97
195–119	−1.99	1.09	4450	1.00	0.92
165–335	−1.40	1.07	4450	1.30	0.96
222–536	−2.54	1.56	3850	0.50	0.94
225–539	+0.20	0.78	4950	2.20	0.55
225–544	−0.55	0.87	4700	1.80	0.88
345-N	−0.57	0.86	4700	1.80	0.97
15-Q	+0.02	0.83	4750	2.20	0.89

[a] Designations from Baade & Swope 1961.

NOTE.—$B-V$ photographic photometry from Stetson 1979a. P_{mem} is the probability of membership from Stetson 1979b.

The color excess $[E(B-V)=0.03]$ and distance modulus $(V_0-M_V=19.4)$ were taken from Stetson (1979a), whose photographic photometry we used. We chose not to use CCD photometry from Stetson, VandenBerg, & McClure (1985) or Carney & Seitzer (1986) because their data do not include many of the stars studied here. From Stetson's photographic photometry, the temperatures and gravities given in Table 1 were derived from a grid of model atmospheres (in M_V and $B-V$) from Bell et al. (1976), assuming a mass for each star of 0.75 $M_{\odot}$ and metal abundance, $[\mathrm{M/H}]=-2.0$. Our temperatures were compared with Bell & Gustafsson's (1989) theoretical calibration of $V-K$ as a function of T_{eff} using the $V-K$ colors of Aaronson & Mould (1985) for stars 45–22, 45–24, 75–45, and 195–119. The temperatures derived from $B-V$ and $V-K$ agree very well, with the measured uncertainty being ∼ ±100 K with no systematic trend over the 0.23 mag $B-V$ range of these four stars.

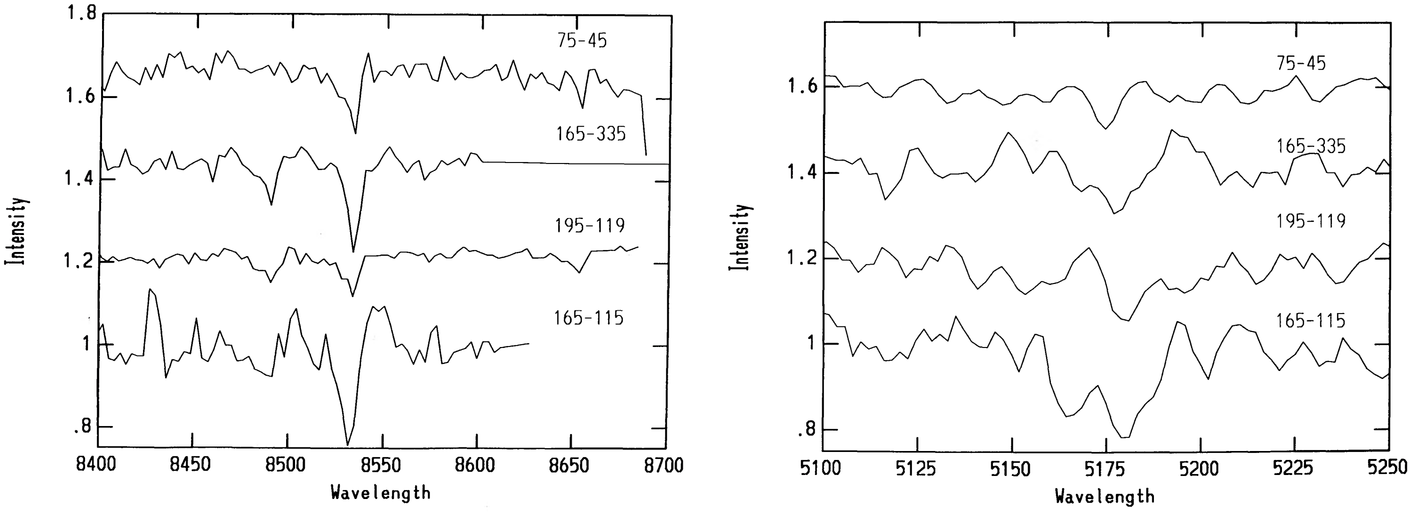

FIG. 1.—Examples of the red and green spectra for four Draco giants. Each of the spectra is normalized to one. As is evident from the relative line strengths, 75–45 and 195–119 represent the low abundance group, while 165–335 and 165–115 represent the high abundance group. Also, due to the positions of the slitlets relative to the chip, 165–335 and 165–115 do not extend far enough into the red for 8662 Å to be measured.

Stetson (1979b) gives proper-motion membership probabilities for Draco stars. His results indicate that all save one of the stars used in this study have membership probabilities ≥87% (see Table 1). Star 275–539 has a membership probability of 55%, which casts its membership in greater doubt. Fortunately, removal of any one (or several) of the stars from our sample would not affect our conclusions.

3. REDUCTION AND ANALYSIS

3.1. *Model Atmosphere Calculations*

Owing to the faint apparent magnitudes and great metal deficiencies of Draco giants, only strong lines are suitable for abundance analyses at low spectral resolution. For this reason the Ca II IR triplet and 5183 Å line of the Mg I triplet were chosen. Only the 5183 Å line was used because it was felt that the other triplet lines were much too weak to get consistent and reliable results, especially in the spectra with low S/N. The oscillator strengths of the Ca triplet were determined by the procedure described in Lehnert, Bell, & Cohen (1991). Table 2 documents the atomic data used.

Model atmospheres were constructed using the MARCS code (Gustafsson et al. 1975). From them synthetic spectra were generated using the SSG code (Bell & Gustafsson 1978). The model atmospheres are parameterized by temperature, gravity, and metal abundance ($T_{\rm eff}/\log g/[{\rm M/H}]$), and the microturbulent velocity. For the latter we chose 1.7 km s^{-1} to be a representative figure (Gustafsson, Kjærgaard, & Andersen 1974; Frisk 1984).

3.2. *Method of Analysis*

The equivalent widths, W_λ, were measured by fitting a Gaussian to the line profiles. The continuum level was chosen immediately adjacent to the feature (within 10–20 Å) and the line automatically fit using a χ^2 minimizing routine. Using a graphics engine, each fit was overlaid on the spectrum and checked visually for goodness of fit as well as displaying the measured χ^2 value. This procedure was repeated several times to check for consistency and it was found that the measurements were repeatable to within 10%.

For each line, we adjusted the elemental abundance of the model by 0.1 or 0.2 dex until the calculated equivalent widths spanned the measured equivalent width. We then fitted the calculated equivalent width–abundance relation with a cubic spline and interpolated to find the abundance which gave the observed equivalent width. This value of [Ca/H] or [Mg/H] was then taken as the abundance for that line and the final abundance for the star was the average of the abundances of the individual lines for each element. Even though the lines of the calcium triplet are not of equal strength (the 8542 Å line is the strongest) and, in the stars with lowest abundance, the 8498 Å line (the weakest) was difficult to measure (sometimes at $\approx 2\ \sigma$ level, see Fig. 1), the typical scatter in [Ca/H] from the three Ca lines was only ~0.1 dex.

TABLE 2

ATOMIC DATA

Element	Wavelength (Å)	χ (eV)	$\log gf\lambda$
Ca II	8498.02	1.69	2.49[a]
Ca II	8542.09	1.70	3.28[a]
Ca II	8662.14	1.69	3.17[a]
Mg I	5183.61	2.72	3.56[b]

[a] Lehnert et al. 1991.

[b] Wiese et al. 1969.

3.3. *Error Analysis*

Apart from observational uncertainties in the W_λ values, the obvious sources of error in abundance analyses are those associated with the oscillator strengths, broadening constants, effective temperatures, gravities, and microturbulence. To estimate these accurately is impossible, and sometimes even to give reasonable estimates is difficult. Nevertheless, in Table 3 we give our best estimates based upon tests made by adjusting the parameters in a controlled manner for the model 4650/1.70/ − 2.0 used to obtain abundances for star 165–114, which has M_V, $B-V$ values fairly representative of our sample. While some of these errors are probably not random, such as the uncertainty in W_λ values, we have assumed that all of them are uncorrelated and random. We stated earlier (§ 3.2) that we could measure the equivalent widths at the 10% consistency level, but in Table 3, we list the estimated uncertainty in equivalent width as ±20%. Thus somewhat arbitrary increase is meant to compensate partially for any undetected residual errors in the sky subtraction. (In the spectral region of the calcium triplet the night sky is very bright, about 18th mag, and has many strong night sky lines, a few of which lie near or on the calcium lines.) Note that although the three lines of the calcium triplet are not of equal strength, we have simply averaged the abundances derived from each line. Taking the above factors into account, our analysis suggests a *total* uncertainty for [Ca/H] and [Mg/H] of ~ ±0.2–0.3 dex and it appears to be dominated by ΔW_λ. While this estimated uncertainty is larger than we would like, it must be remembered that the stars have $16 < V < 20$ mag.

If lines used in an abundance analysis are gravity sensitive, then some errors might arise in Draco, whose giant branch exhibits a large color spread (Stetson 1979a; Carnet & Seitzer 1986). The giants may thus represent a range of masses (ages) and/or evolutionary states (a mixture of red and asymptotic giant branch [RGB, AGB] stars), or some combination thereof. Fortunately, the strong lines of the Ca triplet are relatively insensitive to log *g* at low abundances (see Lehnert et al. 1991 and Diaz, Terlevich, & Terlevich 1989 for discussion). Using the VandenBerg & Bell (1985) isochrones, we see that *if*

TABLE 3

ESTIMATION OF UNCERTAINTIES

Uncertainty	Effect
$\Delta \log gf\lambda = \pm 0.1$	$\Delta[{\rm Ca/H}] = \pm 0.1$ $\Delta[{\rm Mg/H}] = \pm 0.1$
$\Delta T_{\rm eff} = \pm 100$ K	$\Delta[{\rm Ca/H}] = \pm 0.03$ $\Delta[{\rm Mg/H}] = \pm 0.01$
$\Delta \log g = \pm 0.1$	$\Delta[{\rm Ca/H}] = \pm 0.06$ $\Delta[{\rm Mg/H}] = \pm 0.09$
$\Delta W_\lambda = \pm 20\%$	$\Delta[{\rm M/H}] = \pm 0.2$
$\Delta V_\xi = \pm 1$ km s^{-1}	$\Delta[{\rm Ca/H}] = \pm 0.02$ $\Delta[{\rm Mg/H}] = \pm 0.15$
Quadrature sum	$\Delta[{\rm Ca/H}] \sim 0.23$ $\Delta[{\rm Mg/H}] \sim 0.28$

Draco giants have an age range from 10 to 18 Gyr (as suggested by Carney & Seitzer 1986, but see Da Costa 1988), the turn-off mass varies only by $\sim 0.2\ M_\odot$. This implies a range in log *g* of ∼0.2 dex and an uncertainty in [Ca/H] of ∼0.1 dex. Similarly, if some of the stars are on the AGB and, for illustrative purposes, we assume that (*a*) their masses are $0.2\ M_\odot$ less than RGB stars, and, (*b*) take conservatively (that is, overestimate, in order to maximize the resulting uncertainty) the vertical spread of the giant branch to be 1.0 mag at constant color (i.e., approximately constant temperature), then this implies a log *g* difference of ∼0.3 dex, which converts to an uncertainty of ∼0.2 dex in [Ca/H]. This would have the sense that mistaking an AGB star for a RGB star would lead to an overestimate of the true abundance of the star since an AGB star has a lower gravity than a RGB star at the same temperature and the equivalent width of the calcium triplet increases with decreasing gravity. Mg I also seems to be relatively insensitive to uncertainties in log *g*, such that for every ±0.1 dex uncertainty in log *g*, there is roughly a ±0.1 dex uncertainty in [Mg/H]. We believe that these estimates represent the maximum possible uncertainty, as a result of using conservatively large estimates of the mass difference and vertical spread at constant color of Draco's giant branch.

While the main thrust of this study concerns the reality of a range of abundances, the zero point of the abundance scale is of interest. One line of reasoning suggests that our [Ca/H] results may be systematically too high by ∼0.2 dex, since Lehnert et al. (1991) noted such a systematic difference between [Ca/H] derived from the Ca triplet and that derived from six other weak calcium lines for M22 and M13 giants.

4. RESULTS

The results, shown in Table 4, suggest that $\langle[\mathrm{Ca/H}]\rangle \approx \langle[\mathrm{Mg/H}]\rangle \sim -1.9$ dex, with each showing an abundance spread of ∼1 dex, in agreement with Suntzeff (1988). That the correlation between [Ca/H] and [Mg/H] is good can be seen in Figure 2. From a physical point of view this is not surprising since both are even-*Z* α-elements, but existence of a strong correlation builds confidence in our data and methodology for these faint stars.

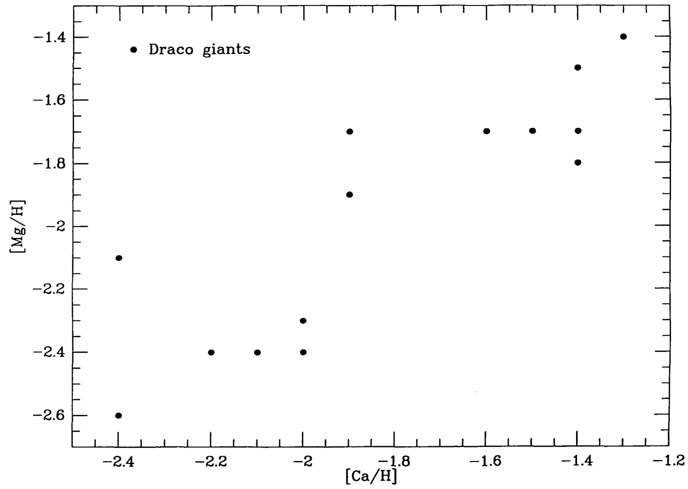

FIG. 2.—A plot of [Ca/H] vs. [Mg/H] showing that the calcium and magnesium abundances are well correlated (correlation coefficient = 0.86); there is a suggestion that the stars may fall into two groups, one centered around ∼ −2.3 and the other near ∼ −1.6.

Considering the variety of approaches that have been applied to abundance determinations on faint Draco giants, the agreement between our conclusion and those of other studies (summarized in Table 5) is satisfactory. Our sample consists of stars with $+0.2 < M_V < -2.5$, and hence extends to stars about 1.5 mag fainter than previous spectroscopic studies. Thus we should be less likely to infer a spurious range in [Ca, Mg/H] such as might arise from rapid evolutionary or mixing processes near the peak luminosity of the RGB and AGBs, or from modeling the quite extended atmospheres of such luminous stars. Also, our study is one of the few to use model atmosphere techniques to match the strength of absorption features. While it is difficult to prove that our data and techniques are inherently more accurate, at a minimum they

TABLE 4

ABUNDANCES AND EQUIVALENT WIDTHS OF DRACO GIANTS

			log *W*/λ				
STAR	[Ca/H]	[Mg/H]	8498 Å	8542 Å	8662 Å	5183 Å	GROUP
45-22	−2.0	−2.4	−3.97	−3.77	−3.76	−3.95	L
45-24	−2.4	−2.6	−4.15	−3.98	...	−4.03	L
75-45	−2.2	−2.4	−4.10	−3.66	−4.05	−3.95	L
165-106	−1.5	−1.7	−3.80	−3.61	...	−3.53	H
165-114	−1.3	−1.4	−3.71	−3.53	...	−3.41	H
165-115	−1.4	−1.5	−3.87	−3.55	...	−3.49	H
165-116	−1.9	−1.7	−3.99	−3.75	...	−3.46	H
195-119	−2.4	−2.1	−4.08	−3.93	−4.03	−3.82	L
165-335	−1.9	−1.9	−4.01	−3.68	...	−3.71	H
222-536	−1.6	−1.7	−3.80	−3.55	...	−3.51	H
225-539	−2.1	−2.4	−4.07	−3.94	−3.96	−3.99	L
225-544	−2.0	−2.3	−4.11	−3.81	−3.85	−3.88	L
345-N	−1.4	−1.7	−3.80	−3.54	...	−3.61	H
15-Q	−1.4	−1.8	−3.78	−3.55	...	−3.58	H
Mean:	−1.8 ± 0.4	−2.0 ± 0.4					

NOTE.—Average of high-abundance group (H): [Ca/H] = −1.6 ± 0.2 and [Mg/H] = −1.7 ± 0.2. Average of low-abundance group (L): [Ca/H] = −2.2 ± 0.2 and [Mg/H] = −2.4 ± 0.2. All uncertainties are 1 σ.

TABLE 5

COMPARISON WITH OTHER STUDIES

Study	Mean Abundance	Element[a]	Variation	Number of Stars	Type of Study
Aaronson & Mould 1985	−1.80[b]	[M/H]	Yes	8	Photometric ($V-K$)
Bell 1985	−2.1	[M/H]	No	10	Spectroscopic
Bell & Gustafsson 1983	−1.76	[M/H]	Yes (1 dex)	17	Spectrophotometric
Carney & Seitzer 1986	−2.0[c]	[M/H]	Yes (0.8 dex)	875	Photometric
Kinman & Kraft 1980..............	−2.2[d]	[M/H]	Yes (1 dex)	10	Spectrophotometric
Kinman et al. 1981	−2.27	[Fe/H]	Yes (1 dex)	9	Spectrophotometric
Nemec 1985.........................	...	[M/H]	Yes (∼0.5 dex)	10	RR Lyrae P-A
Smith 1984..........................	−2.2	[Fe/H]	Yes (0.7 dex)	5	Spectroscopic
Stetson 1980b.......................	...	...	No	17	Spectrophotometric
Stetson 1984	−2.3	[Fe/H]	Yes (1 dex)	12	Spectroscopic
Zinn 1978	−1.86	[Fe/H]	Yes (0.5 dex)	17	Spectrophotometric
This study	−1.9	[Ca/H], [Mg/H]	Yes (1 dex)	14	Spectroscopic
Mean	−2.0				

[a] [M/H] implies general metal abundance.

[b] Also found −2.15 from $J-K$ colors.

[c] From $(B-V)_{0,g}$.

[d] Original determination was relative to M92 for which we have assumed [Fe/H] = −2.2 from Sneden et al. 1991.

offer the benefit that they are probably affected by some rather different systematic errors than previous analyses, although (*a*) all spectroscopic studies to date, including ours, are probably dominated by uncertainties in the equivalent width measurements, and (*b*) almost all studies rely on Stetson's (1979a) photographic photometry.

There are additional reasons for having confidence in our results. A few of our stars have been measured by others and the agreement is on balance encouraging. We have three stars in common with Kinman et al. (1981) and three in common with Smith (1984), where in each case we find $[\mathrm{Ca/H}]_{\mathrm{LBHO}} - [\mathrm{M/H}]_{\mathrm{K,S}} = 0.0 \pm 0.3$ dex. On the other hand, a comparison with Zinn (1978) shows $[\mathrm{Ca/H}]_{\mathrm{LBHO}} - [\mathrm{Fe/H}]_{\mathrm{Z}} = +0.2$ dex for three stars in common; a similar disparity was noted previously by Kinman et al. (1981) and Suntzeff (1988). There is an average difference in the same sense of −0.5 dex for two stars in common with Bell (1985). Recalling again the faintness of the stars, the wide variety of techniques used (see Table 5) to estimate [M/H], and the small samples in common, it is perhaps not surprising that some differences have surfaced; however, note in reviewing Table 5, that [Ca, Mg/Fe] may well be enhanced by ∼0.3 dex relative to solar (see Wheeler, Sneden, & Truran 1989 for a review) and that we have not attempted to correct for zero-point differences.

Another powerful way of inspiring confidence in our results has recently presented itself. Armandroff & Da Costa (1991) have compiled the equivalent widths of the Ca triplet of several globular clusters with widely different abundances. Using a plot of the sum of the equivalent widths of the two strongest lines of the Ca triplet versus the V magnitude of the star minus the V magnitude of the horizontal branch, they find that the location of the stars is a strong function of globular cluster abundance with red giants of a single globular cluster lying roughly along the same line. Thus, if Draco had a uniform abundance we would expect that the stars would be collinear in such a plot. In Figure 3, we have reproduced the plot from Armandroff & Da Costa (1991) with the five Draco red giants for which we have equivalent widths of 8542 Å and 8662 Å superposed. Noting that $[\mathrm{M/H}]_{\mathrm{M15}} \sim -2.1$ and that the five stars are all in the low-abundance group (cf. Table 4), the placement of our Draco measurements in the Armandroff & Da Costa diagram is entirely consistent with the abundances we derived.

Figure 2 hints that the stars we measured clump around [Ca, Mg/H] ∼ −2.3 and [Ca, Mg/H] ∼ −1.6, an effect reported by others (e.g., Kinman et al. 1981; Aaronson & Mould 1985; Suntzeff 1988), which may be associated with Zinn's (1978) A and B branches. When viewed in the color-magnitude diagram (Fig. 4), the lower abundance stars tend to lie preferentially to the blue side of the giant branch, in accord

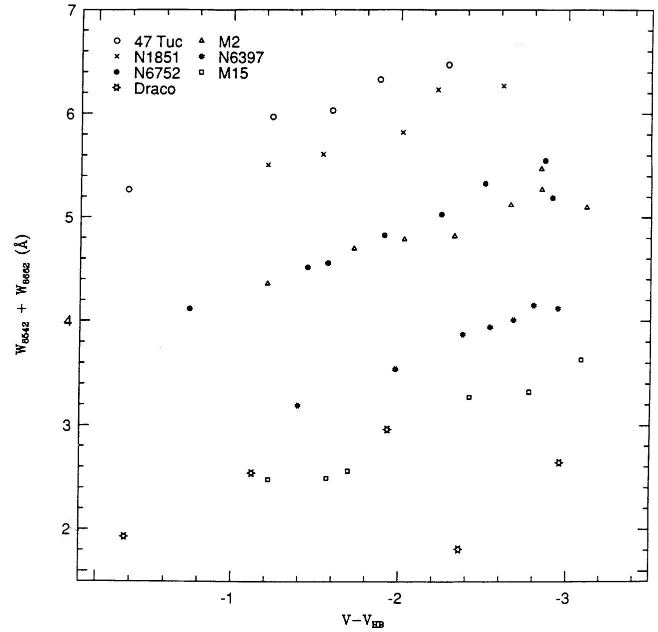

FIG. 3.—The five stars for which we have W_λ measurements of both 8542 Å and 8662 Å are plotted upon Armandroff & Da Costa's (1991) abundance sensitive plane. The placement of the Draco points corroborates our spectral synthesis analysis that suggested all five stars are quite metal deficient with some spread among them.

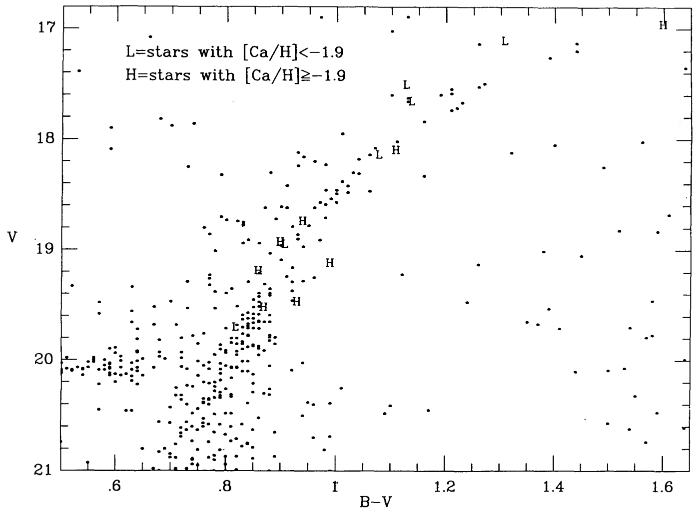

FIG. 4.—The $B-V$ vs. V color-magnitude diagram (from Stetson 1979a) uncorrected for reddening. Within the inevitable limitations of a small sample, stars of the low-abundance group (indicated by L in the figure and in Table 4) seem to lie preferentially to the "blue" side of the red giant branch as compared with the members of the high-abundance group (indicated by H).

with the usual progression of globular cluster giant branches as a function of heavy-element abundance. As discussed earlier, the apparent separation into two groups could be a result of evolutionary differences (AGB vs. RGB stars) or a significant range of masses among the Draco giants, rather than being entirely due to abundance (e.g., Stetson 1980b). Improved photometry and abundances would place this suggested bimodality, and its origins, on a sounder footing.

5. DISCUSSION

Draco's color-magnitude diagram morphology raises a number of interesting questions. The first and foremost is the cause of the color spread of the giant branch. Second, why does such a metal-deficient system have a red horizontal branch (HB)—i.e., what is the "second parameter" (see Zinn 1980)? Third, what has Draco's star formation history been? With the data now available, answers to these questions are emerging. In particular, the color spread of Draco's giants appears to be dominantly due to a ~ 1 dex range in metal abundance. The massive globular cluster ω Cen, which is sometimes compared to the dSphs, also exhibits a color range throughout its giant branch. Observations of faint subgiants by Hesser et al. (1985) demonstrated that it almost certainly arises from a range of abundances rather than of ages. Indeed, isochrones, for instance those recently presented by Chieffi & Straniero (1989), consistently suggest that an abundance spread of 0.5 dex at an average abundance $[M/H] \approx -2.0$ gives a $B-V$ color spread of about 0.07 mag all along the giant branch. This difference is easily encompassed by the color spread seen in Draco's giant branch (Carney & Seitzer 1986).

However, we cannot at present rule out a role for a range of ages in explaining Draco's color spread since, unfortunately, the available faint photometry appears incapable of addressing the age question definitively (Stetson et al. 1985; Carney & Seitzer 1986, but see Da Costa 1988). Nonetheless, recent globular cluster research may bear indirectly on the role of age as an explanation of Draco's "second-parameter" character, as follows. Bolte (1989) makes a careful differential comparison between precise CCD photometry of the globular clusters NGC 288, NGC 362, and NGC 1261. NGC 288 and NGC 362 have similar right ascensions, distances, reddenings, chemical abundances, including [CNO/H] (Dickens et al. 1991) and possibly helium (using the R method, Buonanno et al. 1984; Buzzoni et al. 1983), but NGC 288 has a blue HB, while NGC 362 has a red HB. Bolte finds an age difference between the clusters of about 3 Gyr, with NGC 288 being the older, and he attributes the differing HB morphologies to this age difference (see also Zinn 1980; Stetson et al. 1989; Green & Norris 1990; VandenBerg, Bolte, & Stetson 1990; and Sarajedini & Demarque 1990). Further, Lee, Demarque, & Zinn (1990) and Sarajedini & King (1989), in studies of globular cluster systematics, argue strongly that age is probably the dominant "second parameter" determining HB morphology (but see, e.g., Rood 1990a, b for cautionary remarks). Such direct evidence from "simpler" globular cluster systems for age as the "second parameter" places previous suggestions for explaining Draco's red HB and the spread in color of its giants on a much more plausible basis.

There is some evidence from deep CCD photometry of Draco to support the existence of an age range. Carney & Seitzer (1986) have fitted the main-sequence turnoff of Draco with VandenBerg & Bell (1985) isochrones. They find that Draco's main-sequence turnoff is best fitted by isochrones that range from about 10 to 18 Gyr, although the exact range is made uncertain by considerable uncertainties in the faint-star photometry (Da Costa 1988).

The picture for the evolution of Draco presented in Zinn (1978) and Smith (1984) appears to us to be qualitatively correct. From chemical evolution models, Smith argued that Draco must have lost a large fraction ($\sim 90\%$) of its mass while increasing its heavy element abundance tenfold, and that this loss must have taken place over many crossing times to prevent dissociation and to allow for the mixing of Ca, C, and N. This picture has important implications for the evolution of dwarf galaxies as a whole. If the other dSphs evolved in much the same way as Draco appears to have, then, following Kormendy (1985, 1987), dSphs evolved from objects that look much like dwarf irregulars (dIrrs).

Dwarf galaxy evolutionary models fall, crudely, into three broad categories based on whether the main driving force resides inside or outside of the galaxy: externally driven evolution (e.g., ram pressure stripping, Lin & Faber 1983; Kormendy 1988; ejection from larger galaxies, Gerola, Carnavali, & Salpeter 1983); internally driven evolution (e.g., supernova-driven winds, Saito 1979; Wyse & Silk 1985; Dekel & Silk 1986; Vader 1986; Hensler & Burkert 1990); and combinations of external and internal (e.g., infall of intergalactic medium and supernova-driven winds, Silk, Wyse, & Shields 1987; Davies & Phillips 1988). The list of authors or modes of evolution is not intended to be exhaustive or complete. All the above models forge a plausible link between dIrrs and dSphs that seems to be suggested by observation (e.g., Bothun & Caldwell 1984; Kormendy 1985; Bothun et al. 1986; Davies et al. 1988). We believe, however, that considering the low rotational speeds and escape velocities observed in dwarf galaxies (see Gallagher & Hunter 1984 for a review), supernova ejecta and stellar winds alone can probably provide enough momentum and energy to drive out considerable amounts of material from a dwarf galaxy's interstellar medium. Such stellar ejecta will also chemically enrich the interstellar medium, as seems required to produce a range of chemical abundances like that observed in Draco. Thus it seems reasonable to suggest, as it has to many authors before us, that supernova must have had a major effect on the structure and evolution of dwarf galaxies.

Recent galactic evolution models by Hensler & Burkett (1990) seem to put such speculation on a sounder theoretical footing. Their models, which incorporate stars, a multicomponent interstellar medium, and interactions between them, indicate that the evolutionary connection between dIrrs and dSphs is not only plausible but is a direct consequence of considering the interaction between gas dynamical processes and stellar evolution in low-mass systems. They envision the evolution of a 10^{10} $M_\odot$ dwarf galaxy as follows.

1. Initial star formation extends over the whole galaxy, whose low density prevents collapse.
2. After 2 Gyr star formation is concentrated in the central regions and occurs in bursts.
3. Subsequently the galaxy loses $\sim$50% of its initial mass due to galactic winds, but on time scales much greater than the crossing time, thereby preventing dissociation.

Features in their models seem to evolve from dIrrs to nucleated dIrrs or dSphs and then, finally, to dSphs.

As encouraging as they are, their models do not yet quantitatively address questions of chemical evolution, such as whether the metals ejected by supernovae and stellar winds escape from the gravitational potential, but other studies provide guidelines. For instance, De Young & Gallagher (1990) modeled a 1.4×10^9 $M_\odot$ galaxy with 0.1 $Z_\odot$ allowing for stellar evolution and gas dynamical processes. They find that approximately two-thirds of the supernova debris escapes. Quantitatively, they parameterize the fraction of the debris that escapes, $f_{\rm esc}$, as the fraction of supernovae within the "chimney," $f_{\rm SN}$, multiplied by the escape efficiency, $\epsilon_{\rm esc}$. Qualitatively, $\epsilon_{\rm esc}$ must increase as the escape velocity decreases with lower galactic masses, but $\epsilon_{\rm esc}$ will also depend on OB association richness (i.e., supernova frequency). Their model further suggests that concentrated star formation (perhaps one large OB association) will lead to more mass loss than star formation distributed among many smaller OB associations with the same combined total mass. Smaller galaxies will lose much more mass than initially larger systems, thereby further strengthening the link between mass loss and control of the chemical evolution of systems of the lowest masses (see also, e.g., Hartwick 1976; Da Costa 1988).

However, as reviewed by Kormendy (1987) and by Aaronson & Olszewski (1988), the Draco and Ursa Minor dSphs may be comprised of $\sim$98% dark matter (also see Pryor & Kormendy 1990; Lake 1990), while Fornax contains almost none (but see Mateo et al. 1991 who find $5 < M/L < 26$ for Fornax). Were Draco dark-matter rich, the efficiency of gas ejection in the aforementioned models would be *significantly* lower. Cuddeford & Miller (1990) argue that past analyses have made incorrect assumptions (e.g., using the tidal equation, Lin & Faber 1983) that lead to an erroneous range in the amount of dark matter inferred for local dSphs. They suggest that a more proper analysis is consistent with local dSphs having either little or no dark matter or roughly the same amounts, thereby removing the observed correlations between M/L_V and both distance and integrated visual luminosity. Also, Kuhn & Miller (1989) have argued that the velocity dispersions of the dSphs are inflated by their rapid passage through the tidal field of the Galaxy (orbital coupling). Were this the case, one would expect exaggerated mass estimates, well in excess of what is suggested by the amount of visible mass. The amount of exaggeration would be a function of Galactocentric distance, with dSphs nearer the Galaxy having the more exaggerated masses, in quantitative agreement with observations (see Kuhn & Miller). This, however, would imply that Draco and Ursa Minor are both being observed at a special time in which they are dissipating in something of the order of a few crossing times (the crossing time is about 10^8 yr for Draco and UMi).

Clearly, examination of correlations capable of elucidating the effects of dark matter in dSphs merits close attention. However, the above arguments aside, let us assume that the velocity dispersions and photometric properties of the local dSphs do indicate large amounts of dark matter. We can now ask how might dark matter influence the evolution of dwarf galaxies? Lake (1990) argues that M/L is anticorrelated with both luminosity and average metal abundance of the local system of dSphs, thereby possibly revealing a strong connection between dark matter and star formation. Also, he speculates that copious dark matter and low metallicity argue strongly for the formation of low-mass objects. It is obviously a difficult problem, and we wonder if the opposite might not be true. Perhaps a large amount of dark matter, with its associated increased gravitational potential, provides an environment conducive for collapse to high density with enhanced or relatively vigorous star formation. In the simulation of De Young & Gallagher, this might lead to a rich OB association (high $f_{\rm SN}$) and a strong supernova wind that efficiently drives out metals and large amounts of interstellar gas (high $f_{\rm esc}$). Relatively small differences in early development might account for the differences in chemical homogeneity seen in UMi and Draco (purportedly the dSphs with high dark matter central densities), while dSphs with lower dark matter densities may have experienced fairly quiescent star formation (low $f_{\rm SN}$) continuing to within the last few Gyr because the efficiency of removing their interstellar media might have been lower (low $f_{\rm esc}$). Were such speculations correct, dark matter–poor dSphs might have evolved into more chemically inhomogeneous galaxies than either UMi or Draco appears to be.

The fragmentary evidence available allows us to speculate that perhaps not only does a large amount of dark matter make for relatively vigorous star formation in dSphs like Draco and UMi, but that it might also hasten the onset of star formation (e.g., by fostering a more rapid collapse of the galaxy), so that such a dSph contains a significant population of old stars analogous to those in metal-poor globular clusters. There is some evidence for a range of stellar ages in the local dSph system (see Da Costa 1988). The available color-magnitude diagram for UMi appears very similar to that of the metal-poor Galactic globular cluster M92. For Draco, as discussed earlier, the available color-magnitude diagrams can be argued as providing some evidence of extended early star formation in this otherwise very old system. Mighell (1990) suggests that the Carina dSph has not only a $\sim$0.3 dex spread in metallicity, but seems to have experienced star formation that probably began $\sim$9 Gyr ago and ended $\sim$5 Gyr ago. Similarly, we might expect that the most metal rich dSphs, Fornax and Leo I, should have stars younger than, or as young as, 5 Gyr, for which there is some evidence. Aaronson & Mould (1985) indicated that five of the seven Galactic dSphs then known have extended giant branches (the exceptions being Draco and UMi) characteristic of an intermediate-age population, with the more metal-rich systems having a stronger intermediate-age population. This led them to speculate that the amount of gas retention in dSphs is dependent upon their visible mass.[4]

Available evidence suggests that rather puzzling trends exist between the distance of the local dSphs from our galaxy, R_{gc}, and [Fe/H], M/L (more specifically, the central density of dark matter, see Mateo et al. 1991), and luminosities of such systems. An explanation that has been advanced is that the dSphs must compete with the Galaxy for material with which to form stars—whether that material is stripped out of the dSph (see Lin & Faber 1983) or the dSph is not able to accrete as much gas during formation as it might otherwise have done due to its proximity to the Galaxy (see Silk et al. 1987). However, without some modification this competition limiting the reservoir of material for star formation does not explain a trend of dark matter central density with R_{gc}. It seems reasonable that dark matter may act as a seed for galaxy formation. At smaller R_{gc}, those seeds with higher central densities would have had a better chance of competing successfully with the Galaxy for material with which to form stars. If correct, then the trends of R_{gc} with [M/H] and M/L arise from processes described in the preceding paragraphs.

6. SUMMARY AND CONCLUSIONS

Multi object, low-resolution spectroscopy of Ca II and Mg I features for 14 giant stars ($+0.2 > M_V > -2.5$) in the Draco dSph galaxy analyzed with the aid of spectrum synthesis techniques reveal a range of [Ca, Mg/H] ~ 1 dex and $\langle[\mathrm{Ca/H}]\rangle \sim -1.9$. While our general findings are in substantial agreement with most previous work (see Suntzeff 1988), the spectral features analyzed, the use of detailed model atmosphere calculations, and the inclusion of stars nearly 1.5 mag fainter than earlier spectroscopic studies, distinguish our effort and improve the confidence in our observational understanding of chemical evolution in Draco. Metallicity estimates from Ca and Mg features correlate well, as expected for two even-Z, α elements. There is a suggestion that our randomly chosen sample may separate into two metallicity groups, one centered near [Ca, Mg/H] ~ -2.3 and the other near ~ -1.6. The lower metallicity stars exhibit a tendency to lie toward the blue side of the color-magnitude diagram, as also found by Kinman et al. (1981) and Suntzeff (1988), which may be related to Zinn's (1978) A and B branches.

It appears that the color spread on Draco's giant branch dominantly arises from the metal-abundance range we and others have demonstrated. However, a range of ages, such as that which might explain Draco's "second-parameter" phenomenon (a RHB in a very metal-poor system), may also be important in understanding the color spread (e.g., Stetson 1980b). Unfortunately, the present evidence for an age range from turnoff region photometry is open (Stetson et al. 1985; Carney & Seitzer 1986; Da Costa 1988). *If* star formation took place over a few Gyr, it would seem likely that there were a couple of early episodes of star formation separated by 0.3–0.4 dex in [M/H].

We use results from recent dwarf galaxy evolution models to speculate on the connection between the amount of material lost from a galaxy and its final average metallicity. If the local dwarf spheroidals contain significant dark matter and if the anticorrelation between M/L and luminosity, on the one hand, and M/L and average metallicity on the other, is real (see arguments in Lake 1990; Pryor & Kormendy 1990; Kuhn & Miller 1989; Cuddeford & Miller 1990), then dark matter may control the time of formation, the rate of star formation, the mass-loss rate through supernova-driven winds and, hence, the average metal abundance. As suggested by the possible correlation between central density of dark matter and R_{gc}, dark matter may indeed control how much baryonic matter the dwarf galaxies are able to accrete during formation in the tidal field of the Galaxy.

Clearly a much more thorough and systematic observational attack on the populations, abundances, ages, and dynamics of the Milky Way's family of dSphs, as well as more realistic modeling, will be needed to confirm or refute the above speculations. Such problems are a clear target for the new generation of 8–10 m class telescopes under development.

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[4] Note, however, two important distinctions between them and the classical, metal-poor, inner-halo globulars, which have been shown by VandenBerg et al. (1990) to be indistinguishable in age, and whose color-magnitude diagrams and various spectroscopic diagnostics indicate an extremely high degree of chemical homogeneity for elements heavier than CNO.

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