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INFRARED PHOTOMETRY AND THE COMPARATIVE STELLAR CONTENT OF DWARF SPHEROIDALS IN THE GALACTIC HALO

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ABSTRACT

We report infrared *JHK* photometry for carbon stars in the Ursa Minor, Draco, Leo I, and Leo II dwarf spheroidal galaxies, and for a number of oxygen-rich giants in these systems as well. In combination with previously published data, our results enable a detailed comparison to be made of the red stellar content in all seven nearby spheroidals.

While the Draco and Ursa Minor giant branches terminate near the first giant branch tip, the Leo I and II systems are found to possess extended giant branches, indicating the presence of an intermediate-age stellar population. Five of the seven Milky Way spheroidals appear now to contain stars younger than those found in galactic globulars. With the curious exception of Ursa Minor, the bolometrically most luminous stars in all the dwarfs are carbon stars. In the mean, the C stars become both redder and brighter as parent galaxy luminosity increases. This result is consistent with a systematic increase in metallicity, and furthermore implies that somehow the more massive dwarfs managed to retain gas the longest to form successive generations of stars. At least two mechanisms seem to be involved in the formation of the carbon stars discussed here, one related to thermal pulses during the asymptotic giant branch phase, and the second to binary mass transfer, although the relative importance of these two processes remains unclear. In any event, the carbon star luminosity function observed in the spheroidals does not appear easily to reconcile with dredge-up theory in its present stage of development.

Interpolation between globular cluster giant branches is employed to derive mean abundances for the Ursa Minor, Draco, and Leo systems from our measurements of the oxygen-rich giants. The results are in good agreement with available spectrophotometric measures when $J-K$ color is used, but not when $V-K$ color is employed. We demonstrate the existence of a well-defined abundance-absolute magnitude relation among the seven dwarfs, which when extended joins smoothly onto the abundance-magnitude relation for more luminous early-type systems. However, the fractional carbon star number is at best only weakly related to mean dwarf abundance.

Subject headings: galaxies: Local Group — galaxies: stellar content — infrared: sources — star: abundances — stars: carbon — stars: evolution

I. INTRODUCTION

The discovery of carbon stars in the early-type dwarf satellites of the Milky Way indicates a quite different stellar population in these galaxies from that traditionally associated with the galactic halo. Successful searches for these stars in all the dwarf spheroidals are documented by Aaronson, Olszewski, and Hodge (1983). The association of asymptotic giant branch (AGB) carbon stars with an intermediate-age stellar population was originally made for Fornax (Aaronson and Mould 1980). This link was proven in the case of the Carina dwarf (Mould and Aaronson 1983) by direct observation of a luminous main-sequence turnoff. Whether such an intermediate-age population exists in all the dwarf spheriodals, or whether some other mechanism is responsible for their carbon stars, is up to now unanswered, despite the important implications of this question for the history of the halo's collapse, and for the evolutionary nature of the carbon stars themselves.

In this paper we present infrared photometry of the reddest giants in the northern hemisphere dwarf spheroidals in order to determine the bolometric luminosities of these stars, and the extent of the AGB in the galaxies they belong to. Our sample includes all of the carbon stars known at the time of writing to be spectroscopically confirmed in the Draco, Ursa Minor, and Leo I and II dwarfs, which in combination with already published results on the Fornax, Sculptor, and Carina dwarfs allows us to undertake a comprehensive discussion of the AGB population in these seven halo systems. We have also measured a number of the noncarbon star giants, and we use these data to obtain mean metallicity estimates and to discuss the abundance-magnitude relation.

The organization of the paper is as follows: in § II we present the observations. In § III we discuss various color-color and color-magnitude diagrams and derive bolometric luminosities and temperatures. The main inferences of the paper are drawn in § IV, where we consider the systematic stellar content properties of the dwarf systems, and also the origin of their carbon stars. Our conclusions are summarized in § V. In the Appendix, we derive new transformations between Johnson's

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(1966) photometric system and the CIT system of Elias *et al.* (1982) used here, and present new mean near-IR color relations for galactic field giants which supersede those of Frogel *et al.* (1978).

II. PHOTOMETRY

a) Observation and Reduction

A program of infrared *JHK* photometry of red giants in dwarf spheroidals was initiated in 1981 May at the f/30 Cassegrain focus of the Mayall 4 m telescope on Kitt Peak. The "Blue Toad" InSb photometer was employed, generally with a 5″ or 7″ aperture. Program stars were chosen from the color-magnitude (*C-M*) diagrams of Baade and Swope (1961) in Draco and of van Agt (1967) in Ursa Minor, with emphasis on Draco objects being studied spectroscopically by Kinman, Kraft, and Suntzeff (1981). Poor weather extended the program into the following year, at which time the survey of Aaronson, Olszewski, and Hodge (1983) and *C-M* diagrams by Demers and Harris (1983) and by Olszewski, Suntzeff, and Hodge (1984) encouraged us to tackle the Leo galaxies as well. The bulk of the data, and the data of highest quality, comes from an observing run in 1983 April with the Palomar 5 m telescope. For this run we used the f/70 infrared photometer with a 6″ aperture, and the D-68 InSb detector. By this time, visual spectrophotometry of many Ursa Minor stars had also become available (Suntzeff *et al.* 1983).

At KPNO we observed standards on the Harvard College Observatory (HCO) photometric system (Aaronson 1977). The results were transformed to the CIT system (Elias *et al.* 1982) by means of the relation $(J-H)_{\rm CIT} = 0.92(J-H)_{\rm HCO}$; no other transformation appeared necessary.[3] At Palomar we observed Caltech standards, whose proper transformation from the instrumental to the CIT system required a color term at H given by

$$\begin{aligned} H &= H_{\rm instr} - 0.05(J-K)\,, \qquad J-K \le 1\,; \\ &= H_{\rm instr} - 0.05\,, \qquad J-K > 1. \end{aligned}$$

The same transformation, established both by the 1983 April run and an earlier 1982 December run, was employed for the program stars. With these precautions we are confident that the data are consistently reduced to the CIT system. A check on 12 Draco and Ursa Minor stars measured both at Palomar and at KPNO yielded $\langle \delta(J-K) \rangle = 0.003 \pm 0.015$, $\langle \delta(H-K) \rangle = -0.007 \pm 0.012$, and $\langle \delta(K) \rangle = 0.015 \pm 0.013$ (the sense being Palomar minus Kitt Peak).

The photometry is all collected in Table 1. Column (1) gives the identification from the references noted in the table, Column (2) gives the telescope(s) employed, and columns (3), (4), and (5) present the infrared colors and magnitudes, along with 1 σ error estimates, where these exceed 0.03 mag. Parentheses in column (3) indicates that the K magnitude was not measured (it is the most difficult because of sky noise), and was instead estimated from the mean $J-H$, $H-K$ two-color relation (see below). Column (6) gives the number of separate nights the star was observed. Note that multiple observations were averaged with weights inversely proportional to the minimum of the statistical error and 0.04 mag. Unfortunately, observations in the Leo galaxies made at KPNO were rejected altogether because of blind offsetting problems at that telescope. Available V magnitudes (as referenced in Table 1) and the resulting $V-K$ colors are given in columns (7) and (8), respectively.

b) Membership

Potential membership problems in our sample appear to be well under control. All of the Draco stars are proper-motion members (Stetson 1980), as is likewise true for the Ursa Minor stars (Schommer, Olszewski, and Cudworth 1981). In addition, spectra, radial velocities, or both are now available for a number of the stars, as noted in columns (9) and (10) of Table 1. This information can further serve to weed out interlopers, a case in point being the Ursa Minor star SOC 388, a foreground dwarf (Aaronson, Olszewski, and Hodge 1983) which we exclude from further discussion.

Membership of several additional stars in Draco and Ursa Minor may be open to question. Zinn (1978) has argued that Draco 285-194 is in the galactic foreground based on enhanced Mg at 5200 Å. However, as pointed out by Stetson (1980), the star has a proper-motion membership probability of 0.97, and lies in $B-V$ within 0.01 mag of its expected location on the Draco giant branch. We shall retain the star for the present. Another potential problem is with the Ursa Minor star vA 177, measured to have too low a radial velocity for membership by Hartwick and Sargent (1978). A more recent and accurate measurement by Stetson (1984), though, clearly places the star in Ursa Minor.

The IR photometry can itself be used to gauge luminosity class. In this regard, only star 135-324 in Draco has *JHK* colors which might suggest it were a nearby dwarf. However, in the $J-K$, $V-K$ diagram, this star lies far removed from both the mean field giant and field dwarf relations. Both 135-324 and Draco 165-513 have peculiar positions in the K, $J-K$ *C-M* diagram, but not the K, $V-K$ *C-M* diagram. These points, combined with the fact that 135-324 and 165-513 are the faintest Draco stars we observed, suggest that the $J-K$ colors are probably affected by photometric errors, and it seems premature to conclude either of the stars is a nonmember.

With regard to the Leo systems, there seems little doubt that the carbon stars are members, given their faint visual magnitudes. There is a greater danger of foreground contamination among the noncarbon stars, these being somewhat randomly selected for observation based on their location in the Leo II *C-M* diagram of Demers and Harris (1983), and the preliminary Leo I *C-M* diagram of Olszewski, Suntzeff, and Hodge (1984). However, the IR colors of the Leo stars all appear "normal," except for Leo I-A24, which like the aforementioned Draco stars has a peculiar position in the K, $J-K$ *C-M* diagram, but not the K, $V-K$ *C-M* diagram. We again attribute this effect to photometric errors and will assume that all of our Leo stars are true members.

III. COLORS, LUMINOSITIES, AND TEMPERATURES

a) The JHK Two-Color Diagram

The $J-H$, $H-K$ two-color diagram is shown in Figure 1 for the stars in Table 1 for which photometry in all three filters was actually obtained. Also shown in this diagram are the

[3] The relation of the Blue Toad instrumental system to other better established photometric systems remains poorly defined. However, use of the HCO values did give smaller nightly standard star residuals than what resulted from employing the CIT values. In any event, the photometric errors are larger than the uncertainty in the applied transformation (see the Appendix). The situation with regard to Kitt Peak standards should improve when the photometry program of Joyce, Probst, and Guetter (1984) reaches fruition.

TABLE 1

INFRARED PHOTOMETRY OF DWARF SPHEROIDAL GIANT STARS

Name[a] (1)	Telescope[b] (2)	K^c (3)	$J-H^c$ (4)	$H-K^c$ (5)	n^d (6)	V^e (7)	$V-K$ (8)	Spectra[f] (9)	Velocity Member[g] (10)	BC_K (11)	m_{bol} (12)	$-M_{bol}$ (13)	T_{V-K}[h] (14)	T_{J-K}[i] (15)	Notes
						Ursa Minor									
E	K, P	13.66	0.60	0.07	2	16.79	3.13	1	1, 2	2.35	16.00	3.30	4210	4475	
K = SOC 215	K, P	14.20	0.54	0.05	2	17.12	2.92	2, 3, 4	3, 4	2.05	16.25	3.05	4300	4470	1
M	K, P	13.05	0.59	0.10	3	16.75	3.70	3	2	2.55	15.55	3.75	3945	4420	
X = SOC 66	P	14.34	0.56 (4)	0.12	1	17.32	2.98	1		2.25	16.60	2.70	4300	4450	
vA 177 = SOC 26	P	13.82	0.61	0.09	1	17.01	3.19	1, 2, 4, 5	1, 3, 4, 5	2.35	16.15	3.15	4175	4390	
vA 199	P	13.95	0.62	0.10	1	17.28	3.33	2, 4	3, 4	2.40	16.35	2.95	4095	4335	
vA 202 = SOC 132	P	15.12	0.56	0.15 (4)	1	17.93	2.81			2.20	17.30	2.00	4410	4360	
vA 228 = SOC 102	P	(15.86)	0.51 (4)	(0.07)	1	18.39	(2.53)			2.05	17.90	1.40	4625	4835	2
vA 230 = SOC 96	P	14.59	0.58	0.03	1	17.48	2.89	1, 5	5	2.25	16.80	2.50	4360	4665	
vA 236 = SOC 267	P	(15.42)	0.58 (5)	(0.09)	1	18.09	(2.67)			2.10	17.55	1.75	4515	4475	3
vA 261 = SOC 366	P	14.91	0.55	0.12 (4)	1	17.73	2.82	1		2.20	17.10	2.20	4405	4475	
vA 291 = SOC 429	P	(15.75)	0.52 (4)	(0.08)	1	18.31	(2.56)			2.05	17.80	1.50	4600	4725	4
vA 297	P	13.60	0.67	0.06	1	17.02	3.42	4	2, 3	2.45	16.05	3.25	4055	4305	
vA 335	K, P	14.15	0.59	0.19	2	17.71	3.56	3	6	2.30	16.45	2.85	3800	3875	5
SOC 171	K	14.27	0.62 (4)	0.09 (4)	1	17.31	3.04	1	1, 4	2.30	16.55	2.75	4265	4360	
SOC 233	P	13.97	0.63 (4)	0.10 (4)	1	17.04	3.07	1	1, 4	2.30	16.25	3.05	4245	4305	
SOC 388	K	12.73	0.65 (6)	0.13 (5)	1	15.82	3.10	3		...	...	...	...	...	6
Reddening correction		−0.01	−0.01	0.00		−0.06	−0.05								
						Draco									
C1	K, P	13.54	0.63	0.21	2	17.07	3.53	6	6	2.40	15.95	3.45	3845	3740	5
C2 = J	K, P	13.99 (5)	0.58	0.21 (4)	2	17.35	3.36	4, 6, 7	3, 6	2.35	16.30	3.10	3945	3850	5
C3	K	14.44	0.58 (4)	0.14 (4)	1	17.5	3.06	6	6	2.25	16.65	2.75	4140	4050	5
45-22	P	15.47 (5)	0.54 (4)	0.09 (5)	1	18.14	2.67	8		2.10	17.55	1.85	4540	4555	
45-24	K, P	14.08 (4)	0.56 (4)	0.13 (5)	2	17.12	3.04	4, 5, 8, 9	3, 4, 5	2.30	16.35	3.05	4285	4420	
75-45	K	14.78 (5)	0.56 (5)	0.18 (6)	1	17.71	2.93	7, 8, 9		2.25	17.00	2.40	4355	4275	
105-72	P	(15.78)	0.57 (4)	(0.08)	1	18.38	(2.60)			2.05	17.85	1.55	4590	4530	7
195-119	K, P	14.79	0.55	0.13	2	17.55	2.76	7, 8, 9		2.15	16.95	2.45	4465	4450	
285-194	P	(15.75)	0.57 (5)	(0.08)	1	18.29	(2.54)	8		2.05	17.80	1.60	4645	4530	8, 9
15-249	P	14.05	0.66 (4)	0.11 (4)	1	17.28	3.23	8, 9	2	2.35	16.40	3.00	4170	4200	
75-267	K, P	13.87	0.65 (4)	0.10 (4)	2	17.14	3.27	4, 5, 8, 9	2, 3, 5	2.40	16.25	3.15	4150	4250	
105-286	K	14.84 (5)	0.63 (5)	0.09 (6)	1	17.77	2.93	8, 9		2.25	17.05	2.35	4355	4335	
135-324	P	16.11	0.57 (4)	0.22 (4)	1	18.62	2.51			2.05	18.15	1.25	4680	4145	
75-473	K, P	14.57	0.64	0.10	2	17.56	2.99	4, 8, 9	2, 3	2.25	16.80	2.60	4315	4275	
105-490	P	14.74	0.61 (4)	0.08 (4)	1	17.59	2.85	4, 7, 8	3	2.20	16.95	2.45	4405	4420	
135-506	P	15.41 (7)	0.53	0.07 (7)	1	17.97	2.56	8		2.05	17.45	1.95	4625	4725	
165-513	P	(16.46)	0.43 (5)	(0.04)	1	18.79	(2.33)			1.95	18.40	1.00	4890	5350:	10
285-562	K, P	13.88 (4)	0.70	0.12	2	17.24	3.36	4, 8, 9	3, 4	2.40	16.30	3.10	4095	4065	
315-576	K, P	13.91	0.62 (4)	0.10 (4)	3	17.03	3.12	8, 9	4	2.30	16.20	3.20	4235	4335	
315-581	K, P	14.73	0.63	0.05 (4)	2	17.66	2.93	7, 8		2.25	16.95	2.45	4355	4450	
Reddening correction		−0.01	−0.01	0.00		−0.09	−0.08								

TABLE 1—*Continued*

Name[a] (1)	Telescope[b] (2)	K^c (3)	$J-H^c$ (4)	$H-K^c$ (5)	n^d (6)	V^e (7)	$V-K$ (8)	Spectra[f] (9)	Velocity Member[g] (10)	BC_K (11)	m_{bol} (12)	$-M_{bol}$ (13)	T_{V-K}[h] (14)	T_{J-K}[i] (15)	Notes
Leo I															
A8	P	(15.90)	0.69(5)	(0.11)	1	19.52	(3.62)			2.55	18.45	3.25	3955	4095	11
A24	P	(15.60)	0.88	(0.23)	2	19.46	(3.86)			2.60	18.20	3.50	3870	3420	12
B76	P	15.49(4)	0.79(5)	0.08(4)	2	19.20	3.71	3		2.55	18.05	3.65	3925	3925	13
B81 = ALW 3	K, P	14.67	0.90(4)	0.45(4)	1	19.50	4.83			2.95	17.65	4.05	3070	2845	14
B86 = ALW 2	K, P	14.45(4)	0.83	0.32	4	19.04	4.59	3	7	2.80	17.25	4.45	3175	3110	5
B101	P	(15.99)	0.69(5)	(0.11)	1	19.38	(3.39)			2.45	18.45	3.25	4045	4095	15
B108 = ALW 5	P	14.47	0.77(4)	0.35(4)	1	19.17	4.70			2.75	17.25	4.45	3120	3150	14
B201	P	15.13(4)	0.82	0.13(5)	1	19.12	3.99	3		2.65	17.75	3.95	3825	3755	16
C55 = ALW 7	P	14.61(4)	0.79	0.31(4)	2	19.27	4.66			2.75	17.35	4.35	3140	3185	14
C108	P	14.92(4)	0.78(3)	0.35(5)	1	19.46	4.54			2.80	17.70	4.00	3195	3135	14
C116	P	15.26(4)	0.75	0.15(5)	1	19.23	3.97			2.65	17.90	3.80	3835	3870	
D108	P	15.13(5)	0.76	0.09(4)	2	19.17	4.04	3		2.65	17.80	3.90	3810	3960	13
D118	P	(16.11)	0.71(6)	(0.11)	1	19.59	(3.48)			2.50	18.60	3.10	4005	4035	17
D132	P	(15.68)	0.74(5)	(0.12)	1	19.54	(3.86)			2.60	18.30	3.40	3870	3940	18
Leo II															
DH 196	P	(15.97)	0.69(6)	(0.11)	1	19.34	(3.37)			2.45	18.40	3.30	4055	4095	19
DH 197	P	15.33(5)	0.75(4)	0.09(5)	1	18.99	3.66			2.55	17.85	3.85	3940	3980	
DH 253 = 1 = ALW 6	P	14.86	0.70	0.16(4)	1	19.04	4.18	3	7	2.45	17.30	4.40	3490	3655	5
DH 257 = 3 = ALW 7	P	15.48(6)	0.68	0.24(7)	2	19.52	4.04	3		2.55	18.00	3.70	3485	3535	5
DH 260 = 2	P	(16.58)	0.64(7)	(0.10)	1	19.61	(3.03)	3		2.30	18.90	2.80	4240	4250	20
4 = ALW 4	P	15.24	0.68	0.23(4)	2	19.44	4.20	3		2.50	17.75	3.95	3375	3555	5
5 = ALW 3	P	14.72(4)	0.79	0.37(5)	2	19.15	4.43	3	7	2.80	17.55	4.15	3245	3080	5
6 = ALW 1	P	14.96	0.83	0.46	2	19.27	4.31	10		2.90	17.90	3.80	3315	2910	5

NOTES.—(1) CH star; (2) $H = 15.93$ mag; (3) $H = 15.51$ mag; (4) $H = 15.83$ mag; (5) C star; (6) foreground dwarf; (7) $H = 15.86$ mag; (8) $H = 15.83$ mag; (9) possible foreground dwarf; (10) $H = 16.50$ mag; (11) $H = 16.01$ mag; (12) $H = 15.83$ mag; (13) star measured 3 times at J and H; (14) probable carbon star based on JHK colors and K luminosity; (15) $H = 16.10$ mag; (16) star measured twice at J and H; (17) $H = 16.22(4)$ mag; (18) $H = 15.80$ mag; (19) $H = 16.08(4)$ mag; (20) $H = 16.68(5)$ mag.

[a] Source identifications are as follows: Ursa Minor: letters and vA numbers from van Agt (1967), SOC numbers from Schommer, Olszewski, and Cudworth 1981. Draco: C numbers from Aaronson, Liebert, and Stocke 1982; letter and other numbers from Baade and Swope 1961. Leo I: quadrant numbers from Olszewski, Suntzeff, and Hodge 1984. Leo II: DH numbers from Demers and Harris 1983; single numbers from Aaronson, Olszewski, and Hodge 1983. ALW numbers for Leo I and II are from Azzopardi, Lequeux, and Westerlund 1984.

[b] P = Palomar 5 m telescope; K = Kitt Peak 4 m telescope.

[c] Photometric errors given in parantheses in hundredths of a magnitude when larger than 0.03 mag. K and $H - K$ values surrounded completely by parentheses are estimates obtained from $J - H$ data and the mean JHK two-color relation.

[d] Number of separate nights star observed.

[e] Sources for V photometry are as follows: Ursa Minor: Schommer, Olszewski, and Cudworth 1981. Draco: C stars from Aaronson 1983, and references therein; remaining stars from Kinman and Kraft 1980 and Stetson 1979*a*, with photoelectric observations given twice weight of photographic measurements. Leo I: Olszewski, Suntzeff, and Hodge 1984. Leo II: stars 4–6 from Demers and Harris 1984; remaining stars from Demers and Harris 1983.

[f] Spectrophotometry, spectroscopy, or both, reported by (1) Suntzeff *et al.* 1983. (2) Zinn 1981. (3) Aaronson, Olszewski, and Hodge 1983. (4) Stetson 1984. (5) Cowley, Hartwick, and Sargent 1978. (6) Aaronson, Liebert, and Stocke 1982. (7) Smith 1984. (8) Zinn 1978. (9) Kinman, Kraft, and Suntzeff 1981. (10) Unpublished observations by Aaronson and Olszewski.

[g] Velocity membership reported by (1) Suntzeff *et al.* 1983. (2) Aaronson and Cook 1983. (3) Stetson 1984. (4) Aaronson, unpublished. (5) Hartwick and Sargent 1978. (6) Aaronson 1983. (7) Aaronson, Olszewski, and Hodge 1983.

[h] Temperature derived from $V-K$ color.

[i] Temperature derived from $J-K$ color.

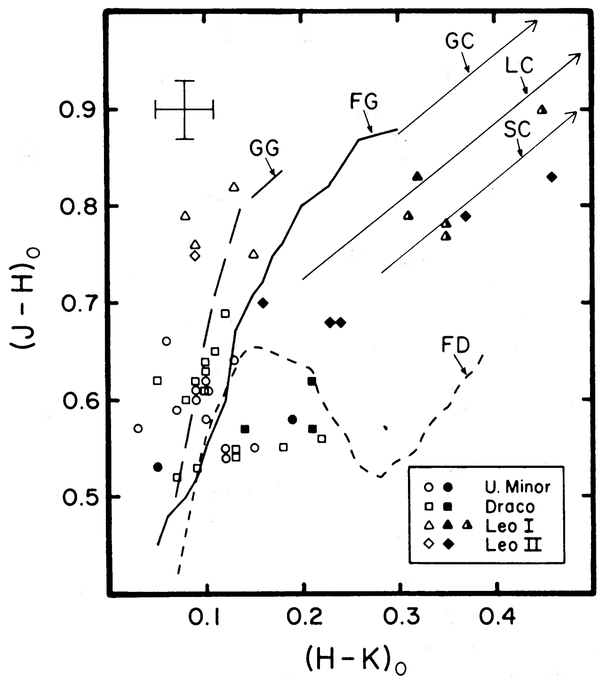

FIG. 1.—The $J-H$, $H-K$ two-color diagram. Open symbols are oxygen-rich stars; solid symbols are carbon stars. Half-solid triangles for Leo I are "photometric" C stars. The various labeled mean relations are FG, galactic field giants (Appendix); FD, field dwarfs (Frogel *et al.* 1978); GG, globular cluster giants (Frogel, Persson, and Cohen 1983). GC, LC, and SC are the loci for galactic, LMC, and SMC carbon stars, respectively, from Cohen *et al.* (1981). In this and succeeding figures, the error bar is the typical uncertainty of an individual spheroidal giant measurement.

mean relation for field giants discussed in the Appendix, the relation for field dwarfs from Frogel *et al.* (1978), the mean relation for globular cluster giants from Frogel, Cohen, and Persson (1983, hereafter FCP), and the mean relations for carbon stars in the Galaxy and the Magellanic Clouds (Cohen *et al.* 1981).

We first note that four new objects in Leo I appear to be carbon giants from their observed photometric colors. These are denoted by semifilled symbols to distinguish them from C stars confirmed with spectra, which are shown by filled symbols. The IR luminosities of the four stars are also consistent with their interpretation as carbon giants. Indeed, three of these stars (B81, B108, and C55) were selected as carbon star candidates in the new objective grating survey of Azzopardi, Lequeux, and Westerlund (1984, hereafter ALW); and the fourth star, C108, was picked out by these authors as an uncertain candidate. A recent spectrum obtained with the Multiple Mirror Telescope confirms B108 as a carbon star.

The Leo I and II carbon stars are seen in Figure 1 to scatter about the blue end of the mean LMC and SMC C star relations. Cohen *et al.* (1981) have interpreted the separation in mean C star loci shown in terms of blanketing effects consistent with the known present-day ranking by abundance of the Milky Way and the Clouds. Perhaps as expected, the location of the Leo I and II carbon stars does suggest the presence of a relatively metal poor stellar population. The Draco and Ursa Minor carbon stars are seen to lie well off the mean C star sequences in a location which probably reflects both the warm temperatures of these stars as compared with the sample from Cohen *et al.* (1981), as well as a low abundance.

Turning briefly to the noncarbon stars, and bearing in mind the photometric errors, we see a well-defined scatter about the mean relation for globular cluster giants. Opacity differences are again presumed to account for the displacement of metal-poor stars from the mean field giant relation, and the effect has indeed been noted by a number of earlier authors (e.g., Glass and Feast 1973; Cohen, Frogel, and Persson 1978). (Note that we have used the mean globular cluster giant relation to "predict" K magnitudes for stars in Table 1 having only J and H magnitudes.)

b) The $J-K$, $V-K$ Two-Color Diagram

Figure 2 shows the $J-K$, $V-K$ relation for noncarbon stars from Table 1 measured at both J and K. The Draco and Leo stars are seen to scatter nicely about the mean field giant relation, while curiously the Ursa Minor stars appear displaced to the right of the field giants. On the other hand, as first noted by Mould and Aaronson (1980), globular cluster giants are shifted to the left of the mean field relation in the $J-K$, $V-K$ diagram, the effect being more pronounced for stars in Magellanic Cloud clusters than for those in galactic globulars (Fig. 2).

Aaronson and Mould (1982) have attributed the displacement of the globular giants in Figure 2 primarily to the absence of blanketing at V, while Frogel, Persson, and Cohen (1981) emphasize instead blanketing differences in the IR as a source of the effect, at least for the warmer stars. This question is of some importance, as the cause of the problem has considerable bearing on the derivation of reliable effective temperatures for warm, metal-poor giants. In any event, it is perhaps surprising that the dwarf spheroidal stars do not show any displacement in Figure 2 or, in the case of Ursa Minor, show displacement opposite to that expected. The problem clearly requires further study.

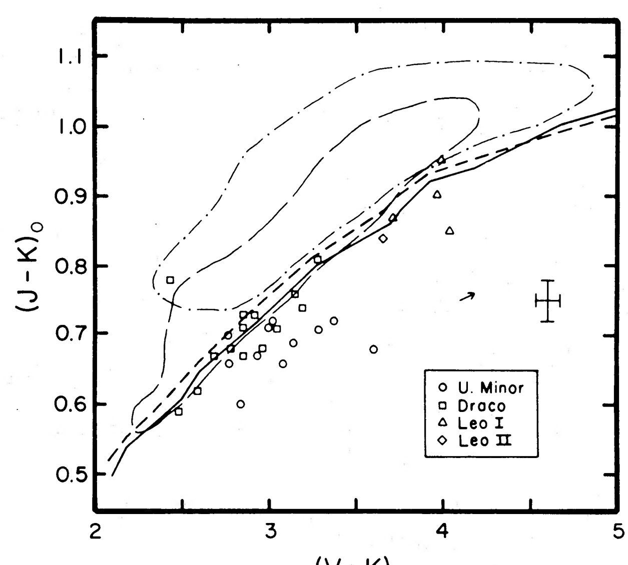

FIG. 2.—The $J-K$, $V-K$ two-color diagram for oxygen-rich stars. The solid line is the mean field star relation from Table 6 in the Appendix, while the short-dashed line is the mean field relation from Frogel *et al.* (1978). The long-dashed boundary encloses the majority of galactic globular cluster stars from Frogel, Persson, and Cohen (1983), while the dash-dot boundary encloses Magellanic Cloud intermediate-age cluster stars from Aaronson and Mould (1982).

c) *Temperatures and Bolometric Magnitudes*

Bolometric corrections BC_K, reddening-corrected apparent and absolute bolometric magnitudes, and temperatures derived from both $V-K$ and $J-K$ colors are given in columns (11)–(15) of Table 1. (Our adopted reddenings and distance moduli can be found in Table 3 below.) The distances of Draco and Ursa Minor should be fairly reliable, being based on assuming $M_V = +0.6$ mag for the horizontal branch; while for the Leo systems the moduli are based on visual luminosities of the brightest stars, and must be considered more uncertain. Fortunately, the deep *C-M* diagram for Leo II obtained by Olszewski, Suntzeff, and Hodge (1984) yields a preliminary hotizontal-branch luminosity roughly consistent with our assumed modulus.

The procedures followed for deriving carbon star luminosities and temperatures are similar to those used in our earlier work. Briefly, bolometric corrections to the K magnitudes are obtained from Figure 2 of Frogel, Persson, and Cohen (1980), which gives BC_K as a function of $J-K$ color. Temperatures were obtained from the color scale of Mendoza and Johnson (1965), after first transforming their $V-K$ and $J-K$ colors from the Johnson (1966) system to that of Elias *et al.* (1982), as discussed in the Appendix. The limiting angular measurements available for galactic carbon stars yield T_e values consistent with the Mendoza and Johnson scale (see Fig. 4, Aaronson and Mould 1982); however, the blanketing effects apparent in Figure 1 here suggest that the quoted temperatures should be treated with caution.

For the oxygen-rich stars, bolometric luminosities were found using Figure 10 of Frogel, Persson, and Cohen (1981), which gives BC_K as a function of $V-K$ color. We have confirmed these authors' results by integrating the energy distributions of a few selected stars using the methods of Carney and Aaronson (1979). Quite satisfactory agreement to a few percent was found. However, given the coarseness of the various flux integration procedures, the $m_{\rm bol}$ values in Table 1 for either carbon or noncarbon stars should not be considered more accurate than ~ 0.1 mag.

Temperatures from $V-K$ colors for the oxygen-rich giants come from the occultation scale of Ridgway *et al.* (1980), after applying a shift of 0.02 mag to their photometric zero point (see the Appendix). Temperatures from $J-K$ were found by transforming the adjusted Ridgway *et al.* T_e, $V-K$ scale to a T_e, $J-K$ scale using the mean $V-K$, $J-K$ relation discussed in the Appendix, where our final adopted temperature calibrations are also presented.

The relative merits of using $J-K$ or $V-K$ colors to derive temperatures for metal-poor, oxygen-rich stars has been a subject of some debate in the literature (see Frogel, Persson, and Cohen 1981; Aaronson and Mould 1982). We shall not rehash the arguments here, but have chosen instead to present temperatures derived from both colors. In our opinion, the principal disadvantage in using $J-K$ color is that its lack of sensitivity to temperature change requires very accurate measurements, else photometric errors will result in large random temperature errors. We will in fact see below that the "scatter" of the data in a K, $J-K$ *C-M* diagram looks somewhat larger than in a K, $V-K$ *C-M* diagram, although we show that in both cases the scatter is partially real. On the other hand, use of $V-K$ color may lead to *systematic* errors in the resulting temperatures. In particular, as we discuss in § IV*a*, the metallicity estimates obtained for Draco and Ursa Minor using a K, $J-K$ *C-M* diagram are far more consistent with recent spectrophotometric abundance measures than are those obtained from the K, $V-K$ *C-M* diagram.

In any event, temperatures derived from $V-K$ and $J-K$ do compare favorably in Table 1 for the noncarbon stars. A difference (in the sense $T_{J-K} - T_{V-K}$) of $\Delta T = 45 \pm 61°$ is found for 11 Leo I and II stars, $\Delta T = 169 \pm 141°$ is found for 14 Ursa Minor stars, and $\Delta T = 15 \pm 76°$ is found for 15 Draco stars. This agreement (or slight disagreement in the case of Ursa Minor) merely reflects the distribution of stars relative to the mean $J-K$, $V-K$ two-color relation seen in Figure 2. (For these comparisons, we have not included two Draco stars with a large temperature discrepancy, 135-324 and 165-513. As discussed in § II*b*, the photometry of these stars may be suspect.)

Our derived bolometric magnitudes and temperatures also compare favorably with those obtained from optical colors by Kinman, Kraft, and Suntzeff (1981). For the nine Draco stars we have in common with their work, a difference of only 0.08 ± 0.04 mag is found for $M_{\rm bol}$, in the sense that our luminosities are slightly brighter than theirs. In addition, we find a difference of only $46 \pm 109°$ (or $66 \pm 46°$) for T_{J-K} (or T_{V-K}), in the sense that our temperatures are slightly cooler than theirs. Within the errors, these differences are independent of position relative to the "two sides" of the Draco giant branch.

d) *H-R Diagrams*

Various types of H-R diagrams are presented in Figures 3, 4, and 5. The carbon stars alone (both confirmed and suspected) are plotted in the ($M_{\rm bol}$, log T_e)-plane in Figure 3 (solely employing temperatures based on $J-K$ color). The principal new result in this figure is the presence of extended giant branches in the Leo systems. Five of the seven spheroidals known to surround the Milky Way have now been demonstrated to have such extended giant branches, implying the presence of intermediate-age stars. Besides the Leo dwarfs, these systems include Fornax (Aaronson and Mould 1980), Carina (Mould *et al.* 1982), and Sculptor (Frogel *et al.* 1982). Note that Frogel *et al.* (1982) did not specifically identify the Sculptor system as having an extended giant branch. However, both Filippenko (1984) and ALW have recently identified Sculptor star V544 (van Agt 1978) as a carbon star (see § IV*b* for further discussion of this peculiar variable). The IR data from Frogel *et al.* (1982) then yields for this object $M_{\rm bol} = -4.3$ mag, or ~ 0.8 mag above the nominal top of the first giant branch.

In contrast, the giant branches of Draco and Ursa Minor appear to terminate at roughly the first giant branch tip of galactic globulars, as can be seen both for the C stars in Figure 3, and for the noncarbon stars in Figures 4 and 5. However, there are several unusual aspects of the Ursa Minor data which require comment. First, *unlike the case for all the other dwarf spheroidals, the most luminous stars in Ursa Minor are not carbon stars.* In fact, four Ursa Minor noncarbon giants have luminosities brighter than either of the stars vA 335 or K (Figs. 4 and 5). It is perhaps further surprising that star K, (technically) a CH star with very weak C_2 Swan bands, is itself more luminous than vA 335, whose spectrum shows the presence of much stronger carbon bands (see Fig. 1 of Aaronson, Olszewski, and Hodge 1983). In Figure 3, star K and vA 335 are seen to be widely separated. (Note that star K cannot be shifted significantly cooler with the $V-K$ color scale, or even by using the oxygen-rich temperature calibration.) The weak C_2 bands in star K presumably reflect its warm temperature,

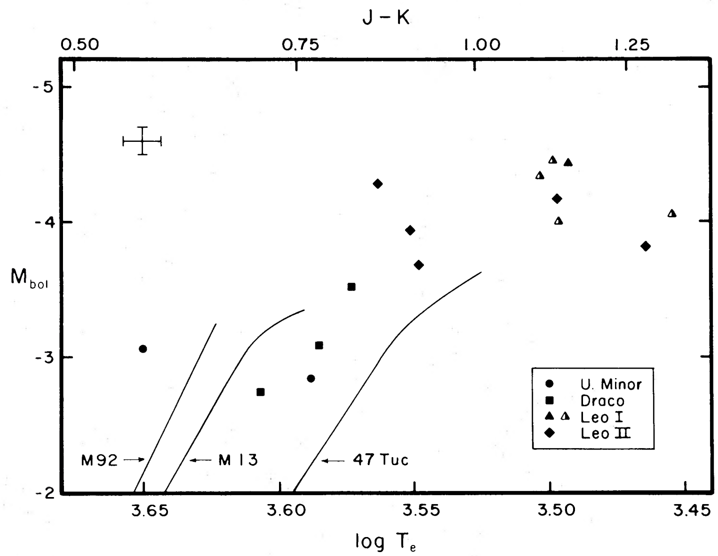

FIG. 3.—The H-R diagram for carbon stars in four dwarf spheroidals. The symbol key is similar to that of Fig. 1. The galactic globular data are from Cohen, Frogel, and Persson (1978), and Frogel, Persson, and Cohen (1981). The temperature scale used is based on $J-K$ color.

but might also be related to less carbon having either been dredged up to or dumped onto the surface than in vA 335. Curiously, though, in the optical *C-M* diagram of Schommer, Olszewski, and Cudworth (1981), star K is located more or less directly on the Ursa Minor giant branch, while vA 335 sits in a peculiar position redward (i.e., cooler) and below the locus of oxygen-rich giants. Similarly, star K lies closer to the Ursa Minor giant branch here in Figures 4 and 5 than does star vA 335. We shall return in § IV to further address the evolutionary state of the latter star.

The most luminous noncarbon Ursa Minor object is star M, whose value of $M_{\rm bol} = -3.7$ mag is of some interest. FCP have shown that the luminosities of the giant branch tip in galactic globulars has a well-defined dependence on metallicity, in rough accord with stellar evolutionary theory (e.g., Sweigart and Gross 1978). As discussed in § IV, the mean abundance of Ursa Minor appears to be ~0.1–0.2 dex more metal poor than that of M92. Comparison with Figure 6 of FCP then indicates that star M is ~0.5 mag brighter than expected. In contrast, the most luminous noncarbon star in Draco is star 315-576, whose $M_{\rm bol}$ value of -3.2 mag is in precise accord with FCP's Figure 6.

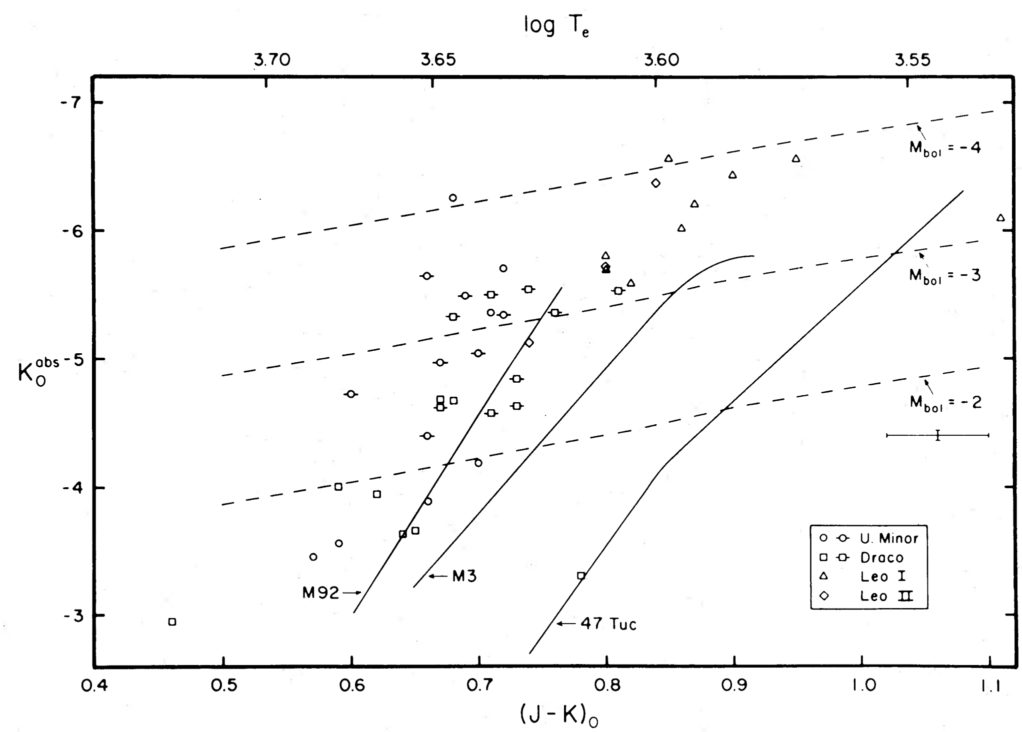

FIG. 4.—A K, $J-K$ *C-M* diagram for oxygen-rich stars in four dwarf spheroidals. Here and in Fig. 5, points surrounded by short dashes are stars having spectrophotometric abundance estimates from Kinman, Kraft, and Suntzeff (1981) (Draco), or Suntzeff *et al.* (1983) (Ursa Minor).

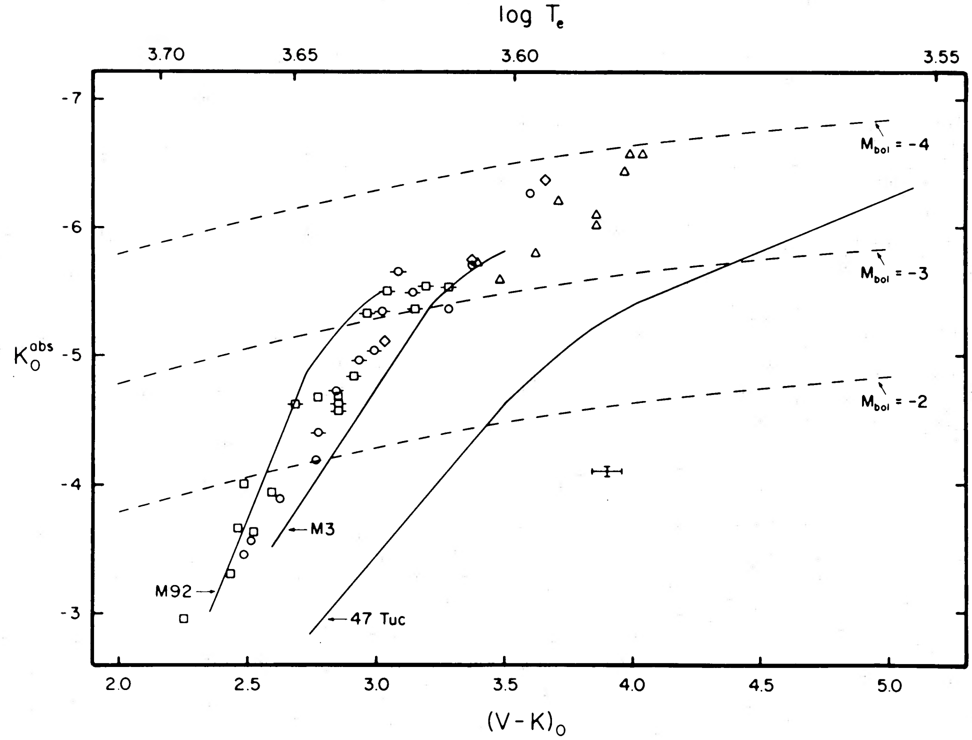

FIG. 5.—A K, $V-K$ C-M diagram for oxygen-rich giants in four dwarf spheroidals. The symbol key is the same as in Fig. 4.

Hence, star M is possibly an AGB star, and Ursa Minor could to have a mildly extended giant branch. (Note that membership of the star is not in doubt—see Table 1). An age 1–2 billion years younger than galactic globulars could account for star M's luminosity, but this seems inconsistent with Ursa Minor's blue horizontal branch, and is in fact not confirmed by recent deep color-magnitude work of Olszewski and Aaronson (1984). Other possibilities include errors in relative distance modulus (although such errors do not seem likely to be greater than 0.1 mag, since both the Ursa Minor and metal-poor cluster distances are determined by assuming a value of $M_V = +0.6$ for the horizontal branch), stochastic mass-loss rates, or the presence of a binary companion. In this regard, it is interesting to note that there is some evidence for variability of the star: 14 objects in Table 1 have B photometry available both from Schommer, Olszewski, and Cudworth (1981) and van Agt (1967), and in but one instance the agreement is within 0.25 mag. The exception is, of course, star M, for which a discrepancy of some 0.75 mag is present, in the sense of the van Agt measurement being brighter. Although van Agt's study was based on plates taken by Baade over 5 yr period from 1953–1958, and variables down to $\sim$0.4 mag in amplitude were detected, star M was not among these and was in fact used as a secondary standard! The possibility remains that star M is a variable of unusually long period. While no other red irregular or long-period variables have been discovered in either Draco or Ursa Minor, two such objects have been noted by van Agt (1978) in Sculptor, including the aforementioned star V544.

In summary, Ursa Minor is alone among the spheroidals in having oxygen-rich tip stars. Whether and how this anomaly is related to the uniqueness (among the spheroidals) of Ursa Minor's blue horizontal branch remains unclear. It is interesting to note, though, that the oxygen-rich tip stars in both Draco and Ursa Minor show evidence for carbon enhancement, a point we return to in the next section.

IV. DISCUSSION

a) Spheroidal Abundances

From the location of the giant stars in Figures 4 and 5, we can estimate mean abundances with the procedures of FCP. Briefly, this involves reading off the $J-K$ or $V-K$ color of the giant branch at some fiducial absolute magnitude, chosen as $M_K = -5.5$ following FCP, and then interpolating between the corresponding quantity for globular clusters of known metallicity. FCP have shown that their globular giant branch colors correlate well with abundances determined from high-dispersion spectroscopy, a finding consistent with the good correlation between the latter and integrated light measurements (e.g., Aaronson *et al.* 1978).

The results of the above exercise are summarized in Table 2, which lists the reddening-corrected giant branch colors $(J-K)_{GB}$ and $(V-K)_{GB}$, along with the corresponding abundances found from equations (7a) and (7b) from FCP. These latter are calibrated using Cohen's (1983, and references therein) high-dispersion cluster measurements. As an alternative procedure, we also derived mean abundances using the Zinn (1980) scale; although presumably less accurate on an individual cluster basis, twice the number of calibrating clusters are then available (see FCP). Fortunately, the results were closely similar to those in Table 2, yielding slightly higher overall metallicities of +0.03 dex using $(J-K)_{GB}$ and +0.07 dex using $(V-K)_{GB}$. There is, of course, considerable present-day controversy surrounding globular cluster abundances (see Cohen 1983; Pilachowski, Sneden, and Wallerstein 1983), but

TABLE 2

ABUNDANCE ESTIMATES IN FOUR DWARF SPHEROIDALS

Name	$(J-K)_{0,GB}$[a]	$[Fe/H]_{J-K}$[b]	$(V-K)_{0,GB}$[a]	$[Fe/H]_{V-K}$[b]	$[Fe/H]_{spec}$[c]
Ursa Minor	0.71	−2.40	3.17	−1.75	−2.53[d]
Draco	0.75	−2.15	3.15	−1.80	−2.27
Leo I	0.80	−1.85	3.38	−1.45	...
Leo II	0.78	−1.95	3.23	−1.65	...

[a] Color of the giant branch at absolute K magnitude = −5.5. Estimated uncertainties are ±0.02 mag for $(J-K)_{0,GB}$, and ±0.1 mag for $(V-K)_{0,GB}$.

[b] Mean abundance estimate obtained from eq. (7) of Frogel, Cohen, and Persson 1983; estimated internal uncertainties are ±0.15 dex.

[c] Mean spectrophotometric estimates based on Ca II H and K line strengths, measured in nine Draco stars by Kinman, Kraft, and Suntzeff 1981 and in seven Ursa Minor stars by Suntzeff *et al.* 1983.

[d] This value reduces to −2.37 if star E is excluded.

the debate centers around the metal-rich end of the scale. The results here should be little affected by whatever problems may be present with the high-abundance clusters, since the values in Table 2 are heavily weighted by clusters whose low [Fe/H] values do not appear to be in dispute.

The final column of Table 2 gives visual spectrophotometric abundances for Draco and Ursa Minor. The Draco results are based on spectra of nine stars analyzed by Kinman, Kraft, and Suntzeff (1981), which yield relative to M92 an abundance of $\Delta[Fe/H] = +0.03$. The Ursa Minor results come from the work of Suntzeff *et al.* (1983), and for seven stars lead to a relative M92 abundance of $\Delta[Fe/H] = -0.23$. However, this latter value is heavily weighted by one extremely metal-poor star (star E), whose elimination would raise the relative Ursa Minor abundance to $\Delta[Fe/H] = -0.07$.[4]

Examination of Table 2 indicates that the abundance values determined from $(J-K)_{GB}$ are in close agreement with the spectrophotometric results, while the ones from $(V-K)_{GB}$ are far too metal rich. However, this discrepancy does not appear to arise from the data presented here, but rather from the deviant colors of the galactic globular cluster giants. That is, the globular giants depart significantly from the mean field $J-K$, $V-K$ two-color relation in a manner not seen for the dwarf spheroidal data here in Figure 2, and it is this effect which results in the differing abundances obtained from $(J-K)_{GB}$ and $(V-K)_{GB}$. In other words, as compared with cluster giants, the dwarf spheroidal stars have $V-K$ colors too red for their given $J-K$ colors, but consistent nonetheless with the mean galactic field relation. Since the spectrophotometric measures should be of high reliability, we can only conclude (as discussed earlier) that systematic temperature errors may arise from using $V-K$ colors. Note that we cannot appeal to possible problems with the V photometry as a way out, since for Draco at least the measurements comes from a number of independent sources (see Table 1), all in reasonably good agreement.

Evidence that the giants in many dwarf spheroidals exhibit a spread in heavy-element abundance continues to mount (Zinn 1978; Demers, Kunkel, and Hardy 1979; Kinman, Kraft, and Suntzeff 1981; Stetson 1984; Da Costa 1984; Suntzeff *et al.* 1983). As we now show, the scatter of the data in Figures 4 and 5 partially reflect the observed abundance range in Draco and Ursa Minor. The IR photometry of these systems includes all of the stars studied spectrophotometrically by Kinman, Kraft, and Suntzeff (1981) and Suntzeff *et al.* (1983); these objects are shown specially marked in Figures 4 and 5. For each of these stars we have determined two quantities, referred to as $\Delta(V-K)$ and $\Delta(J-K)$. These measure the horizontal displacement in color from the mean M92 giant branch lines in Figures 4 and 5. In Figure 6 we plot these quantities against the differential M92 abundances given by Kinman, Kraft, and Suntzeff (1981) and Suntzeff *et al.* (1983).

In all cases in Figure 6, correlations in the expected sense are clearly present. That is, stars with an abundance greater than M92 generally fall to the red of the mean giant branch in the infrared C-M diagram, and stars with a lesser abundance generally fall to the blue. Hence, the observed range of infrared colors is consistent with the presence of a real abundance spread in the Draco and Ursa Minor dwarfs. Curiously, the

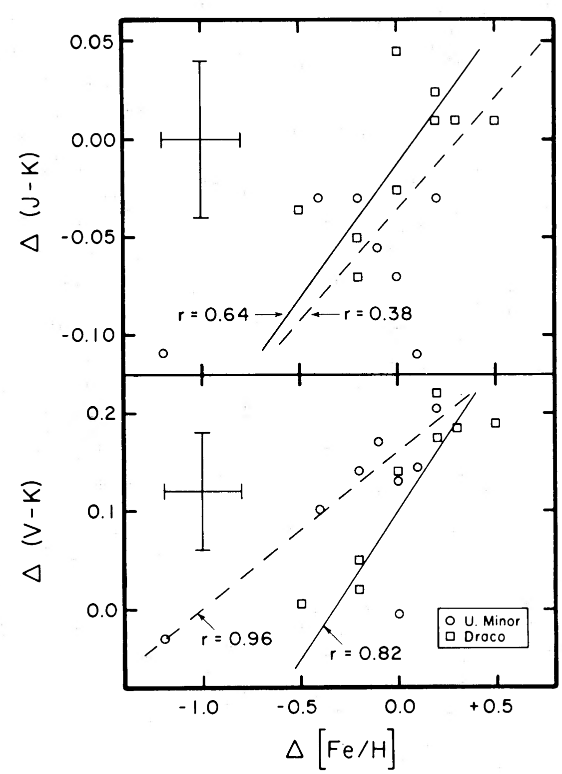

FIG. 6.—This diagram shows residuals from the M92 giant branch track for dashed points in Figs. 4 and 5, plotted against spectrophotometric M92 abundance residuals. The dashed lines are least-squares fits to the Ursa Minor data, while the solid lines are fits to the Draco data. Values for the correlation coefficients are also shown. The positive correlations seen are consistent with the existence of a real abundance spread among the giant stars.

[4] A further small ambiguity is present in Table 2 involving the fact that the spectrophotometric work assumes [Fe/H] = −2.30 dex for M92, while that of FCP assumes [Fe/H] = −2.35 dex.

correlations with $\Delta(V-K)$ are particularly striking, in contradistinction to the problems with $(V-K)_{GB}$ discussed above.

The metal abundances for the Leo dwarfs listed in Table 2 are the first that have been given for these systems, and should of necessity be considered quite preliminary, especially in view of the small number of stars on which the abundances are based, and the possibility that a likely to be present abundance spread in the Leo systems has not been fairly sampled. Furthermore, AGB rather than giant branch stars weight these estimates, i.e., $(J-K)_{GB}$ and $(V-K)_{GB}$ are determined largely by stars above the fiducial luminosity $M_K = -5.5$ mag, rather than below it, as for the globulars and Ursa Minor and Draco systems. This approach nevertheless appears to have some validity, in the sense that for Magellanic Cloud clusters (Aaronson and Mould 1982), the AGB stars brighter than $m_{bol} \approx -3.5$ mag more or less continuously join onto the first giant branch. However, the giant branch locus will itself be affected by age. Since the very existence of the Leo AGB stars indicates these systems to be younger in the mean than the galactic globulars, our mean derived abundances are probably lower limits. The effect here is not large, though: for an age difference of 5 Gyr, the abundance change is only $\sim +0.1$ dex (Sweigart and Gross 1978; Mengel *et al.* 1979), a correction we choose to forego given the various other uncertainties. In any event, the results in Table 2 indicate that the Leo dwarfs are more metal rich than either Draco or Ursa Minor. Some support for this conclusion comes from the work of Demers and Harris (1983), who find the upper giant branch of Leo II to be less steep and redder than those of Draco and Ursa Minor, and also from spectrophotometry of individual Leo I and II giants recently obtained by Suntzeff, Aaronson, and Olszewski (1985).

Mean abundance estimates have now become available for all seven of the halo spheroidals, and we can for the first time examine fully the luminosity-metallicity relation for these systems. The results are presented in Figure 7. Abundances for the four systems studied in this paper are taken from the $(J-K)_{GB}$ determinations given in Table 3, where for Draco and Ursa Minor we have in addition averaged in the spectrophotometric results. For both Carina and Sculptor we adopt $[Fe/H] = -1.9$ dex, based on the $(B-V)_{0,g}$ measures of Mould and Aaronson (1983) and Da Costa (1984), respectively. For Fornax, our adopted value of $[Fe/H] = -1.8$ dex comes from the mean abundance of the four globular clusters observed by Zinn and Persson (1981). We consider this estimate a lower limit to the mean abundance, however, since Fornax contains a significant intermediate-age population (Aaronson and Mould 1980), whose metallicity is likely to be higher than that of the presumably older globulars.[5] Indeed,

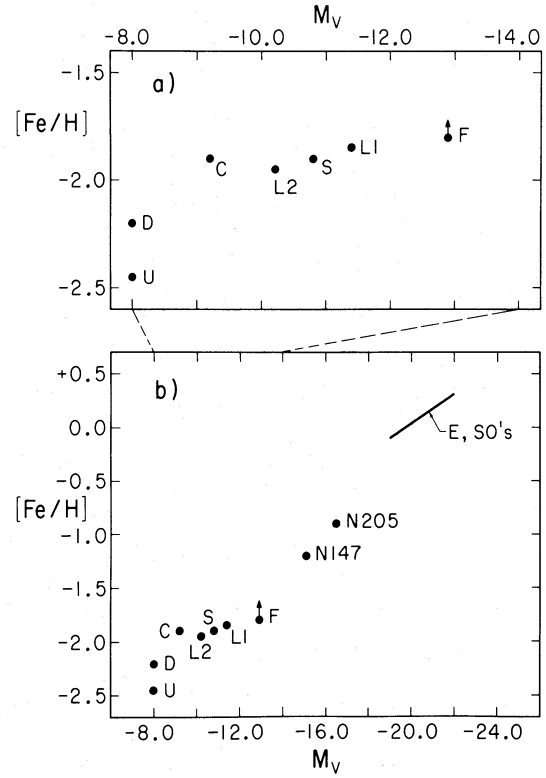

FIG. 7.—Mean abundance plotted against absolute magnitude for early-type systems. Here and in succeeding figures, the symbol key is U, Ursa Minor; D, Draco; C, Carina; L2, Leo II; S, Sculptor; L1, Leo I; and F, Fornax. Abundance values for the spheroidals are discussed in the text. Abundances for M31's dwarf companions NGC 147 and 205 are taken from the work of Mould, Kristian, and Da Costa (1983, 1984). The abundance-magnitude relation shown for luminous E and S0 galaxies is adopted from Aaronson *et al.* (1978).

based on the giant branch slope in the *C-M* diagram, Verner *et al.* (1981) have argued that clusters H1, H3, and H5 do indeed have lower metallicity than surrounding Fornax field stars. Errors in the various mean abundances are perhaps difficult to estimate, but a nominal uncertainty of ± 0.1 dex in [Fe/H] is probably not unreasonable.

A clear trend is apparent in Figure 7: parent galaxy luminosity decreases, the mean abundance diminishes. In fact, as illustrated in Figure 7*b*, the spheroidal abundance–luminosity relation extends naturally onto the similar relation that has been inferred for more luminous E and S0 galaxies. We may conclude that the metal abundance–absolute magnitude correlation for early-type systems is reasonably well defined over the entire 4×10^5 range in luminosity that such objects are known to occupy. This in turn suggests that globally determined physical processes controlled the enrichment history of galaxies which stopped forming stars long ago.

b) Carbon Stars in Dwarf Spheroidals

Various properties of carbon stars in the halo spheroidals, the Magellanic Clouds, and the Milky Way are summarized in Table 3. The first few columns of this table list our adopted reddenings, distance moduli, and absolute magnitudes; references for these values are given in the notes, although there are several important revisions we shall mention here. First, the recent Carina star counts of Demers, Beland, and Kunkel

[5] Interestingly, there were some indications that one of the Fornax globulars, H2, might also be of intermediate age. Aaronson and Mould (1980) measured a red $H-K$ integrated color for H2, and suggested that it could contain at least one AGB carbon star. In addition, Verner *et al.* (1981) found this globular to have a somewhat anomalous *C-M* diagram in comparison with clusters H1, H3, and H5, and they concluded it was metal rich. On the other hand, Zinn and Persson (1981) did not find a significant abundance difference between H2 and H5, and they further argued that the cluster was old, and that if a carbon star was present, it was likely to be a superposed member of the Fornax field C star population. More recently, we have spectroscopically located a carbon star in H2 lying only $\sim 5''$ from the cluster center, and so the probability of chance superposition would seem to be quite low. We have also obtained IR photometry of the star, whose luminosity would imply a cluster age $\sim$3–5 Gyr younger than galactic globulars. However, *C-M* diagrams of H1, H2, H3, and H5 obtained by Buonanno *et al.* (1984) show in all cases the presence of a blue horizontal branch, so the carbon star in H2 may be simply a field interloper after all.

TABLE 3

CARBON STAR CHARACTERISTICS IN HALO DWARF SPHEROIDALS, MAGELLANIC CLOUDS, AND MILKY WAY

Name (1)	$E(B-V)$[a] (2)	$(m-M)_0$[b] (3)	$-M_V$[c] (4)	N_C[d] (5)	$-\log N_{C,L}$[e] (6)	$-M_{bol}^{max}$[f] (7)	$-M_{bol}^{min,C}$[g] (8)	$-\overline{M_{bol}^{C}}$[h] (9)	$(J-K)_0^{max,C}$[i] (10)	$\overline{(J-K)_0}$[j] (11)	Percent[k] (12)
Ursa Minor	0.02	19.3	8:	2(2)	2.90	3.73	2.84	2.95	0.77	0.68	...
Draco	0.03	19.4	8:	3(3)	2.72	3.46	2.74	3.09	0.83	0.77	...
Carina	0.025	19.8	9.2	10(6)	2.68	4.62	2.90	4.07	1.24	1.04	0.70
Leo II	0.00	21.7	10.2	6(5)	3.30	4.39	$\le$3.68	$\le$4.00	1.29	$\le$1.03	0.15
Sculptor	0.00	19.5	10.8	8(6)	3.42	4.30	2.97	3.54	1.20	0.96	0.05
Leo I	0.00	21.7	11.4	14(2)	3.41	4.76	$\le$4.30	$\le$4.26	1.35	$\le$1.17	0.15
Fornax	0.00	21.0	12.9	~65	3.35	5.63	3.8	4.65	1.52	1.20	0.25
SMC	0.03	18.9	16.7	~2900	3.22	5.8	...	4.64	1.7	1.4	0.20
LMC	0.06	18.3	18.4	~11,000	3.32	6.3	...	4.65	2.4	1.6	0.20
Milky Way	...	...	21.5	...	4.50	...	...	4.8:	2.6	1.7	...

[a] Reddening estimates adopted from Zinn 1981 for Ursa Minor, from Stetson 1979*b* for Draco, and from Mould and Aaronson 1983 for Carina. Zero reddening assumed for the remaining dwarfs based on the reddening maps of Burstein and Heiles 1982. Zinn 1981 employs a reddening of 0.03 mag from his own estimate of 0.01 mag and the 0.05 mag field star estimate of Canterna and Schommer 1978; however, the reddening maps of Burstein and Heiles suggest a somewhat lower value.

[b] Distance moduli from Schommer, Olszewski, and Cudworth 1981 and Zinn 1981 for Ursa Minor; Stetson 1979*a* for Draco; Mould and Aaronson 1983 for Carina; Kunkel and Demers 1977 for Sculptor; Demers and Kunkel 1979 for Fornax; and Hodge (1971) for the Leo dwarfs. The latter three dwarfs have distances based on morphology of the upper giant branch; otherwise $M_V = 0.6$ has been assumed for the horizontal branch. The cloud moduli are based on recent work of Schommer, Olszewski, and Aaronson 1984.

[c] Absolute magnitudes, derived as discussed in Aaronson, Olszewski, and Hodge 1983, except for Carina. Value for the latter comes from star counts of Demers, Beland, and Kunkel 1983, and the assumption of a similar luminosity function to M3, for which we take $M_V = -8.65$ mag.

[d] Carbon star numbers from Table 3 of Aaronson, Olszewski, and Hodge 1983, revised as discussed in the text. The quantity in parentheses is the number of carbon stars which at the time of writing have been spectroscopically confirmed.

[e] $\log N_{C,L} \equiv \log N_C + M_V/2.5$.

[f] Luminosity of brightest measured star.

[g] Luminosity of faintest measured carbon star.

[h] Mean bolometric magnitude of all measured carbon stars.

[i] $J-K$ color of reddest measured carbon star.

[j] Mean $J-K$ color of all measured carbon stars.

[k] Fractional carbon star light at V normalized to intermediate age Cloud clusters (see text).

(1983) now indicate an absolute magnitude for this dwarf of $M_V = -9.2$, as opposed to the earlier value of $M_V = -7.2$ quoted by Mould *et al.* (1982). Hence, Carina is apparently no longer the least luminous known dwarf spheroidal. Second, the adopted Magellanic Cloud distances are based on moduli obtained from main-sequence fitting by Schommer, Olszewski, and Aaronson (1984), work which places the Clouds considerably closer than what we have generally used in our earlier papers. The remaining entries in Table 3 are discussed in the paragraphs which follow.

i) *Statistics*

The total number of carbon stars estimated to be present in the nearby spheroidals and the Clouds is listed in column (5) of Table 3. Since the summary of Aaronson, Olszewski, and Hodge (1983), these numbers have been revised in several cases, largely as a result of the work of ALW. The principal change is the increase from 1 to 14 in the number of known or suspected Leo I carbon stars. The apparent "underabundance" of carbon stars in Leo I discussed by Aaronson, Olszewski, and Hodge (1983) appears now to have, in large part, been removed. One additional Leo II carbon star (No. 6) has been found spectroscopically with the MMT. This and another object have also been identified by ALW as probable C star candidates, bringing the total number in this system to six. In Carina, two suspected C star candidates were not confirmed by Lynden-Bell, Cannon, and Godwin (1983), but four new candidates have been found by ALW, bringing the total number here to 10. Besides V544 and the three C stars confirmed by Richer and Westerlund (1983), four additional Sculptor carbon star candidates have been found by ALW. We have spectroscopically confirmed two of these four candidates (ALW1 and ALW3) with the Palomar 5 m telescope. On the other hand, a red spectrum we obtained in 1984 August of V544 did not show the presence of any C_2 or CN bands, even though, as previously mentioned, this star was independently identified in two different grism surveys, as well as apparently confirmed to be a carbon star spectroscopically by Kunth (1984). It may be that V544 is similar to the unusual variable V8 in the SMC cluster NGC 121. As reported by Feast and Lloyd-Evans (1973), the C_2 bands in this latter star appear to come and go. Finally, we note that the early report by Breysacher and Lequeux (1983) claiming detection of large numbers of faint carbon stars in Fornax has been now retracted by ALW.

It is important to emphasize the uncertainty in the carbon star numbers, particularly for the Leo dwarfs. On the one hand, it remains unclear whether the sampling in these systems has been sufficiently deep to pick up low-luminosity C stars of the type found in Draco and Ursa Minor. On the other hand, for Leo I at least, only a small fraction of the stars have been spectroscopically confirmed. The danger here is that with the Swan band technique of ALW, K and M dwarfs may creep into the sample near the plate limit owing to the presence of the Mg $\lambda 5180$ band. For the remaining dwarfs, the available surveys are more or less areally complete and generally reach to $M_{\rm bol} \approx -2$ mag; hence, the C star numbers can be treated with a greater degree of confidence. Nevertheless, spectroscopic confirmation of all the remaining carbon star candidates would be highly desirable. In column (6) of Table 3 we list $\log N_{C,L} \equiv \log N_C + M_V/2.5$. This quantity can be taken as a measure of carbon star number normalized to parent galaxy luminosity (see also Aaronson, Olszewski, and Hodge 1983) and is discussed further below.

ii) *Luminosities and Colors*

The next five columns of Table 3 list the following entries: bolometric luminosity of the brightest measured star (being in all cases except Ursa Minor a carbon star) (col. [7]); bolometric luminosity of the least luminous measured carbon star (col. [8]); mean bolometric luminosity of all measured carbon stars (col. [9]); $(J-K)_0$ color of the reddest measured carbon star (col. [10]); and mean $(J-K)_0$ color of all measured carbon stars (col. [11]). For the spheroidals, these quantities have been compiled from the data in this paper, Aaronson and Mould (1980), Mould *et al.* (1982), and Frogel *et al.* (1982). The Cloud data has been taken from Cohen *et al.* (1981) and Frogel *et al.* (1982) (adjusting the relevant luminosities downward by 0.2 mag for correspondence with our adopted moduli), while the Milky Way results are from a recent grism survey of the Puppis window by Schechter *et al.* (1984), which can be considered to be a "fair" representation of galactic disk carbon stars. To further emphasize the uncertainties with the Leo statistics discussed above, and the likelihood that we have probably only sampled in the IR the reddest and most luminous carbon stars, we have retained in Table 3 and succeeding figures limit symbols for the relevant items. In fact, IR photometry of all known or suspected carbon stars has been obtained only for Draco and Ursa Minor. While a more complete photometric sampling would be valuable, we do not believe the conclusions which follow would be sizeably altered.

As shown in Figures 8 and 9, the various quantities all

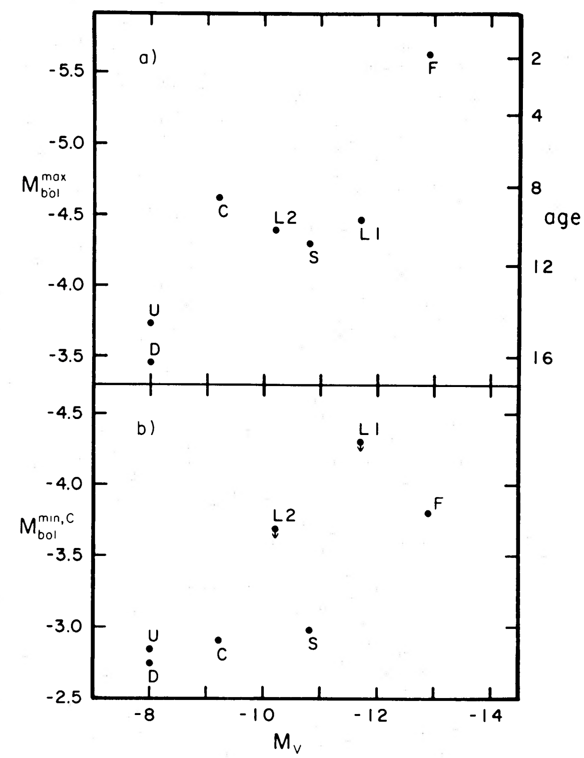

FIG. 8.—(*a*) Luminosity of the brightest measured star plotted against parent galaxy absolute magnitude. For all systems but Ursa Minor, the brightest star is a carbon star. The age calibration on the right is from Mould and Aaronson (1983), and indicates the most recent epoch of star formation. (*b*) Luminosity of the faintest measured carbon star plotted against parent galaxy absolute magnitude. Here and in succeeding figures, the arrows attached to the Leo points reflect the possible incompleteness of the carbon star surveys in these systems.

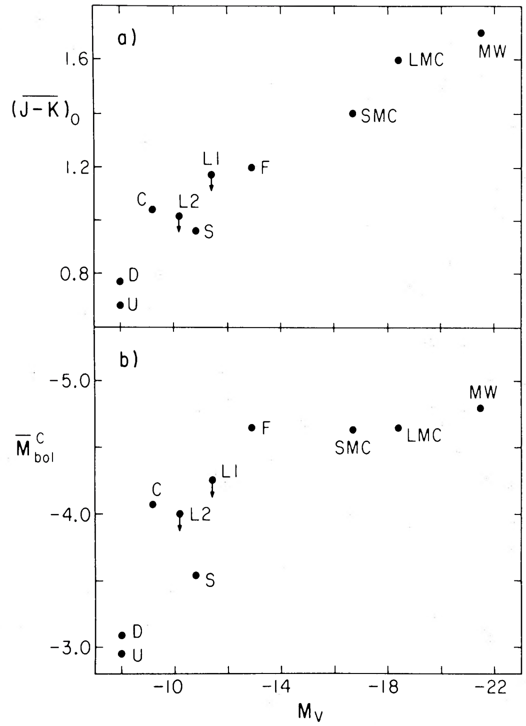

FIG. 9.—(*a*) Mean $J-K$ color of measured carbon stars plotted against parent galaxy absolute magnitude. Here and in succeeding figures, additional symbols are SMC, Small Magellanic Cloud; LMC, Large Magellanic Cloud; and MW, Milky Way. (*b*) Mean bolometric magnitude of measured carbon stars plotted against parent galaxy absolute magnitude.

roughly correlate with parent galaxy luminosity and therefore presumably with metal abundance as well. In particular, redder and brighter carbon stars are found in systems having greater luminosity and metallicity. The mean $J-K$ color is especially well correlated with total absolute magnitude (Fig. 9*a*), an effect which we again attribute to blanketing changes in the infrared (see Cohen *et al.* 1981; Frogel *et al.* 1982). However, as we discuss below, the luminosity variations are probably more a reflection of dependence on stellar age, the carbon star formation mechanism, or both, rather than abundance per se.

iii) *Implications for the Star Formation History of Dwarf Spheroidals*

The existence of an extended giant branch can be taken as prima facie evidence for the presence of an intermediate-age stellar population. From mass-loss theory, we have calibrated AGB extent as a function of the most recent epoch of star formation (Mould and Aaronson 1982). This calibration is shown on the right hand side of Figure 8*a*. Star formation appears to have taken place in the Fornax dwarf as recently as 2 Gyr ago, and in the Carina, Sculptor, and Leo systems ~ 10 Gyr ago. The mean luminosity of the carbon stars in the Fornax dwarf are, in fact, the same as in the Magellanic Clouds (see Table 3), although Fornax lacks the (presumably younger) oxygen-rich AGB stars which in the Clouds are known to rise to $M_{\rm bol} \approx -7$ mag (Wood, Bessell, and Fox 1983).

Deep *C-M* diagrams reaching to the main sequence are now available for four of the spheroidals, and the resulting ages are in quite satisfactory agreement with the estimates in Figure 8*a*. First, Carina has been studied by Mould and Aaronson (1983), who find a turn-off age of 7.5 ± 1.5 Gyr. Second, Da Costa (1984) has found a turn-off age of 13 ± 2 Gyr for Sculptor, i.e., some 2–3 Gyr less than galactic globulars, with hints for the presence of a still younger population. Finally, the *C-M* diagrams obtained by Da Costa and Mould (1984) and Carney and Seitzer (1984), for Draco and by Olszewski and Aaronson (1984) for Ursa Minor do not appear to indicate any significant population of stars younger than M92.[6]

The rough correlation apparent in Figure 8*a* suggests that the more massive a dwarf, the longer is the time over which it is able to retain gas and form successive generations of stars. The question of exactly how the dwarfs were able to hold onto their gas remains problematic, though. Even for Fornax, and allowing for the presence of dark matter, the gas expansion rate for giants undergoing mass loss is larger than the escape velocity (see Aaronson 1983).

One theory which avoids this problem involves the notion that all the dwarf spheroidals were formed from a single parent galaxy, which was torn in a tidal encounter with the Milky Way (e.g., Gerola, Canevali, and Salpeter 1983; Lin and Lynden-Bell 1982). If all star formation ceased at the instant of separation, one would then expect similar stellar contents in the progeny, with the possible exception of mean metallicity differences depending on the homogeneity of the parent. However, we have presented evidence for real differences in the carbon star content of the dwarfs. Since the AGB luminosity function is a uniform magnitude distribution, systematic differences with galaxy luminosity are not easily explained as statistical. To retain this theory of the dwarfs origin, we need to postulate a final generation of exhaustive star formation following separation. Alternatively, perhaps the seven dwarfs are the offspring of more than one parent galaxy.

We turn now to a comparison of the fractional carbon star light in the various systems, and in Figure 10 plot $\log N_{C,L}$ against both total luminosity and mean abundance. Rough trends are again apparent, with the Milky Way being clearly underpopulated in carbon stars, and the three lowest luminosity and possibly most metal-deficient dwarfs having the largest fractional carbon star population. However, there appears to be a wide range in luminosity and abundance over which $N_{C,L}$ remains more or less constant, from the LMC ($M_V = -18.4$ mag) to Sculptor ($M_V = -10.8$ mag) or perhaps Leo II ($M_V = -10.2$). More detailed interpretation of Figure 10 is complicated by the order of magnitude variation of abundance in (possibly all) the systems, by incompleteness of the C star surveys (which may actually contribute to the trends that are seen), by the relatively uncertain total luminosities for Draco and Ursa Minor, and by the small number statistics of the C star populations in the latter two systems.

Richer and Westerlund (1983) have suggested that a smooth relation exists between carbon star number and metal abundance. The data presented in Figure 10, however, show much more scatter than their original trend. In a sense this is not surprising, when one considers the problems mentioned above, along with the diversity of star formation histories exhibited by the various galaxies. Addition of a point for the combined globular clusters of the Milky Way emphasizes this fact, since only four globulars are known to contain a total of ~ 10 carbon or CH stars (see McClure 1984 for a summary). Of course, whatever the detailed mechanism(s) for carbon star formation involved, stars of lower metal content should be easier

[6] Aaronson and Mould (1985; see also Mould 1984) have also found a measure of agreement between the AGB age-dating method and main-sequence turn-off ages for Magellanic Cloud clusters older than ~ 1 Gyr. The AGB method appears to break down, however, for Cloud clusters younger than this, apparently owing to increasing mass-loss rates in higher mass stars.

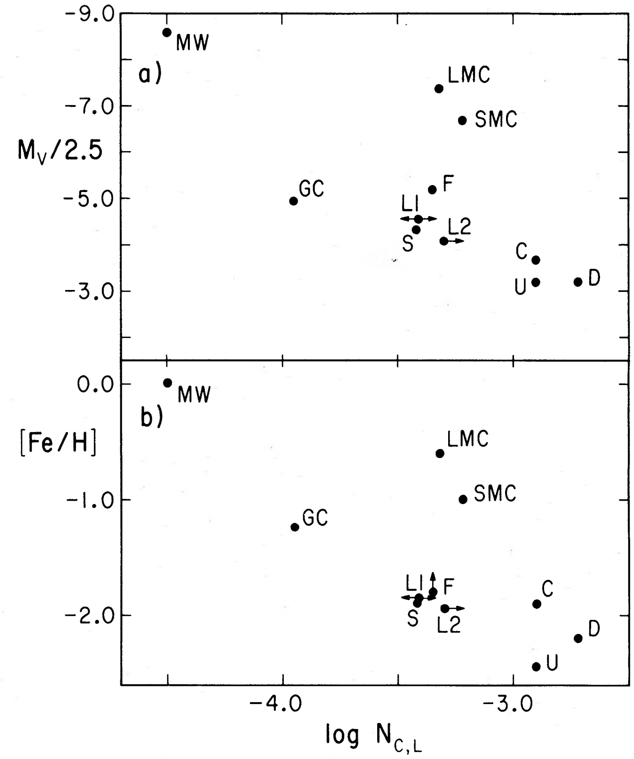

FIG. 10.—(*a*) Normalized carbon star number ($\log N_{C,L} \equiv \log N_C + M_V/2.5$) plotted against parent galaxy luminosity. "GC" is a representative (although highly uncertain) point for galactic globulars, placed by adopting the mean abundance and total luminosity from Table 2 of Harris and Racine (1979). (*b*) Normalized carbon star number plotted against mean abundance.

to turn into carbon stars, because there is less oxygen to "neutralize." Possibly the general behavior in Figure 10 expresses no more than this.

Figure 10 also provides some gauge of the proportion of intermediate-age stars relative to those that are young or old. In this context, we take "young" to be less than 1 Gyr, "old" to be greater than 13 Gyr, and intermediate age to be the entire range in between. A more quantitative estimate of the percentage intermediate-age population can be obtained following the procedure of Aaronson and Mould (1980). Briefly, this involves determining the fractional contribution of the carbon star light at V (where the C star magnitudes are more nearly constant than at K or bolometrically) and normalizing this contribution to the fractional C star light of a "pure" intermediate-age population. The fiducial we choose here is the mean fractional C star contribution of -1.55 dex to the V light in intermediate-age SMC clusters (Aaronson and Mould 1982). The results of this exercise are listed in column (12) of Table 3. (No entry is given for Draco and Ursa Minor, which do not have extended giant branches.)

The computations indicate that the majority of the Carina population is of intermediate age, while in the remaining dwarfs, the fractional intermediate-age component ranges from 5% in Sculptor to 25% in Fornax. Given the uncertainties, the finding for Carina agrees well with the work of Mould and Aaronson (1983), who saw little evidence for the presence of any old stars. The finding for Sculptor also seems consistent with the results of Da Costa (1984), who identified in this system a small blue-straggler component. Luminosity functions determined from very deep *C-M* diagrams obtainable with Space Telescope should provide a further test of our predictions for Fornax and the Leo systems.

Comparable results for the LMC and SMC are also listed in Table 3. For this purpose we have adopted a mean carbon star V magnitude of 16.3 and 16.5 for the LMC and SMC, respectively. This comes from the mean R photometry given by Blanco, McCarthy, and Blanco (1980), and the mean $V-R$ colors of Richer, Olander, and Westerlund (1979), transformed to the Kron-Cousins system following the prescription of Bessell (1979). Now roughly half of the integrated V light comes from the young population (see Blanco and McCarthy 1983). Therefore, the results in column (12) suggest that $\sim 40\%$ of the population older than ~ 1 Gyr in the Clouds is of intermediate age. The uncertainty in these estimates is probably a factor of 2, and we should perhaps regard the results as simply consistent with the now-accepted notion that the intermediate-age component of the Clouds is substantial, rather than as an argument against the view that the bulk of Cloud star formation occurred 3–5 Gyr ago (e.g., Butcher 1977; Hardy and Durand 1984). However, similar sorts of numbers are obtained from examining the contribution of Cloud carbon stars to the total bolometric light, which Blanco and McCarthy (1983) give as $\sim 4\%$ in both Clouds. In contrast, detailed surveys of intermediate-age Cloud clusters indicate the average bolometric contribution of the C stars to be $\sim 25\%$ (see Table 6 of Persson *et al.* 1983),[7] implying that only $\sim 30\%$ of the population older than ~ 1 Gyr is of intermediate age.

iv) *How Do the Carbon Stars Form?*

The final question we wish to address concerns the nature and number of mechanisms involved in the formation of the carbon stars found in dwarf spheroidals. At present, there seem to be two leading contenders: the first invokes dredge-up of carbon during He shell flashes on the AGB (e.g., Iben and Renzini 1983), and the second involves binary mass transfer of carbon from a once more massive but now degenerate companion. While mixing at the helium core flash or on the lower AGB have been discussed as possible ways for producing carbon stars, these ideas have not been fully demonstrated (but see Dominy 1984, and Deupree and Cole 1981).

In the past, many authors have drawn a distinction between the luminous C stars with $M_{\rm bol} < -4$ mag and red JHK colors, and the C stars falling near the first giant branch tip with $M_{\rm bol} \approx -3.5$ mag and blue colors similar to the low-luminosity carbon stars found in several galactic globulars (notably ω Cen). (At present, Carina and Sculptor are the only spheroidals known to contain both types.) Such a dichotomy could be naturally interpreted to mean that thermal pulses produce the more luminous C stars, while binary mass transfer yields the less luminous one. Furthermore, Draco, Sculptor, Ursa Minor, and possibly Carina all possess oxygen-rich star(s) more luminous than the lowest luminosity member carbon star, although this situation is a very rare occurrence among the intermediate-age globulars in the Magellanic Clouds (e.g., Aaronson and Mould 1985). The implication is again that a process besides dredge-up is at work here, since we would otherwise expect to find a well-defined transition luminosity (unless the population age spread is implausibly larger in these dwarfs than thought).

However, this two-fold distinction in carbon star properties may in reality be a somewhat artificial one, a point illustrated

[7] We consider the 25% value a more representative mean estimate than the one of 50% adopted by Blanco and McCarthy (1983).

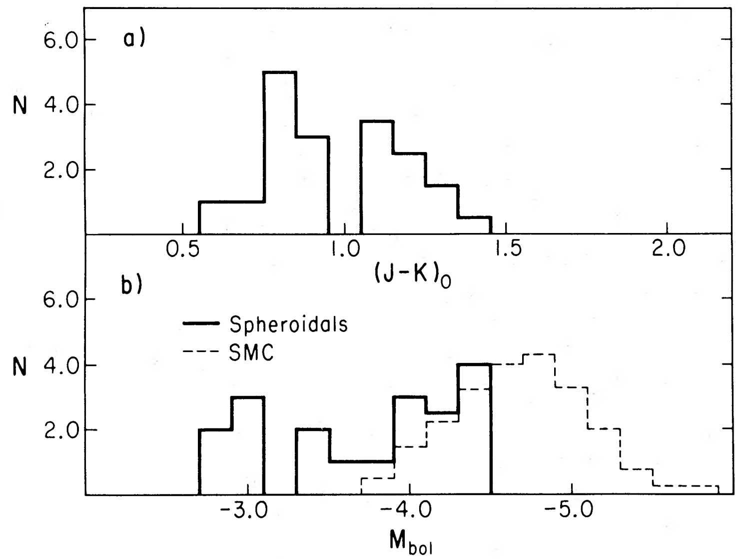

FIG. 11.—Number histograms of carbon star color and luminosity in six halo dwarf spheroidals (Fornax excluded). Also shown for comparison is the luminosity function of field SMC carbon stars taken from Frogel *et al.* (1982).

in Figure 11. Here we have plotted histograms depicting the color distribution and luminosity function of carbon stars with available data in six dwarf spheroidals (Fornax excluded). Also shown is the SMC C star luminosity function from Frogel *et al.* (1982) (shifted by 0.2 mag for consistency with our distance scale). Frogel *et al.* (1982) have compared the SMC and Fornax C star luminosity functions and found reasonable agreement. On the other hand, unless the distance moduli are considerably more uncertain than is believed, it is clear from Figure 11 that the luminosities of the remaining spheroidal carbon stars do not well match those in the SMC, even if we restrict the sample to $M_{bol} < -4$ mag, a difference which presumably reflects the younger Small Cloud population. Furthermore, there is only a hint at best of bimodality in the spheroidal carbon star luminosities, although the effect is perhaps more pronounced with the colors. While again it would be very useful to complete the IR sampling of the C stars in Sculptor, Carina, and Leo I, we do not anticipate that the results in Figure 11 would be substantially changed.

Weak evidence in support of the thermal pulse mechanism is possibly provided by Figure 8*b* and Figure 12. In these figures $M_{bol}^{min,C}$ from Table 3, which we can take to be a measure of transition luminosity between oxygen-rich and carbon-rich stars, is plotted against M_V (an abundance measure) and M_{bol}^{max} from Table 3 (an age measure). A qualitative prediction of AGB theory is that the transition luminosity should be a function of metal abundance and age in the sense that Figures 8*b* and 12 show. Unfortunately, the trends in these figures may be again entirely artificial, arising instead simply from incompleteness of the C star surveys in the more distant spheroidals.

The principal difficulty with invoking thermal pulses as the sole mechanism involved is the theoretical failure of dredge-up in stars having $M_{bol} \approx -3$ mag. In fact, the lowest luminosity carbon star model that has been published is found in Iben (1983). For this low-mass, low-metallicity computation ($M = 0.7\ M_\odot$, $z = 0.001$), significant carbon is not dredged up until a core mass $M_c > 0.6\ M_\odot$ is attained. This in turn corresponds to a bolometric magnitude of ~ -4.7 during most of the interpulse phase, which can be lowered to ~ -4.0 during the interpulse dip (e.g., Fig. 4, Iben and Renzini 1983). The entire parameter space of such models has yet to be fully explored, so perhaps this limit can be pushed down still further (and in this regard A. Renzini has privately suggested to us that current models are compatible with a minimum magnitude of -3.7 in the interpulse dip). However, canonical theory appears to have trouble even accounting for the more luminous C stars in the Carina and Leo dwarfs, unless one has the unlikely situation that all of these objects are presently undergoing an interpulse dip, because none of them are as bright as -4.7 mag in M_{bol}.

An interesting result to emerge from the Iben (1983) study is that only one dredge-up cycle is required to turn the $M = 0.7\ M_\odot$, $z = 0.001$ model into a carbon star. This may be of additional relevance in understanding the lack of any really strong dependence of carbon star number on abundance found here in Figure 10. Given that dredge-up occurs in the first place, a low-mass star with [Fe/H] $= -1.5$ then becomes no harder to make into a carbon star than one having [Fe/H] $= -2$, at least because of the relative surface compositions.

Perhaps fortunately, new evidence has recently emerged to

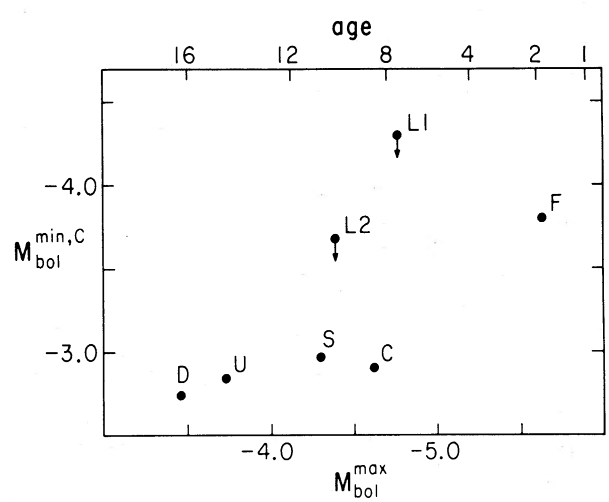

FIG. 12.—$M_{bol}^{min,C}$ (a measure of transition luminosity from oxygen-rich to carbon-rich stars) plotted against M_{bol}^{max} (a measure of stellar age). The trends here and in Fig. 8*b* are in qualitative accord with dredge-up theory, although they may be largely due to selection effects.

suggest that binary mass exchange does indeed play a role in forming at least some of the low-luminosity carbon stars. First, McClure (1984) reports that a number of galactic CH stars are members of binary systems. Furthermore, Aaronson and Cook (1983) have detected radial velocity variations in Draco C1 and Ursa Minor vA 335 which indicate that these stars are also likely members of binaries. These latter results might not be considered too surprising, though, in view of the unusual emission-line spectrum of Draco C1, which probably indicates the presence of a degenerate companion (see Aaronson, Liebert, and Stocke 1982), and of the peculiar position in the H-R diagram of vA 335 discussed earlier.

On the other hand, there is also evidence to suggest that the production of *all* low-luminosity carbon stars may not be accounted for by mass transfer. First, Aaronson and Cook (1983) have not yet found any radial velocity variations in either Draco C2 or C3, two stars which have "normal" locations at the top of the *C-M* diagram (unlike vA 335). Second, Kinman *et al.* (1981), Suntzeff *et al.* (1983), Stetson (1984), and Smith (1984) have all reported enhanced carbon abundances in some of the *noncarbon* stars in both Draco and Ursa Minor, by factors of $\gtrsim 3$ in comparison to globular cluster giants having similar metallicity. Furthermore, Suntzeff *et al.* (1983) find the two tip oxygen-rich giants in Ursa Minor to have the largest carbon enhancements. Where did this excess carbon come from? It seems unlikely that all of these stars are members of binaries whose companions dumped only a limited but highly selective amount of carbon onto their surfaces. Rather, the implication is that these objects have begun dredging carbon up and will eventually turn into low-luminosity C stars similar to Draco C1 and C2. Strangely, though, the fraction of stars showing C enhancement seems larger than the fraction that should be on the AGB, which may be indicating that dredge-up has somehow begun as early as the first giant branch ascent, or more likely that the carbon enhancements are largely primordial.

In conclusion, it appears that two mechanisms may be involved in making dwarf spheroidal carbon stars, but their relative importance remains to be seen. However, if binaries do account for all the low-luminosity C stars, then we should surely expect such objects to be present in the Leo dwarfs and Fornax as well, although carbon giants having $M_{\rm bol} \gtrsim -3.5$ have yet to be detected in any of these systems.

V. SUMMARY

We have obtained infrared photometry of carbon stars in the Ursa Minor, Draco, Leo I, and Leo II dwarf spheroidals. Data for a number of noncarbon giants in these systems have been secured as well. Our principal conclusions can be summarized as follows:

1. Extended giant branches are present in both Leo I and II. Five of the seven dwarf spheroidals which surround the Milky Way now appear to contain intermediate-age populations.

2. The most luminous stars in nearby dwarf spheroidals are C stars, except in Ursa Minor. While this system has carbon stars, they are located well below the giant branch tip. Ursa Minor is also the only dwarf spheroidal known to have a blue rather than red horizontal branch. If and why these two unique attributes are related is unclear.

3. At least two mechanisms appear responsible for the formation of dwarf spheroidal carbon stars, the first involving thermal pulses for the higher luminosity objects, and the second involving binary mass transfer in the lower luminosity ones. The relative importance of these processes is uncertain; in particular, it is not yet clear that all of the low-luminosity carbon stars are members of binary systems. Furthermore, the luminous C stars in the Carina and Leo dwarfs only populate the faint end of the Magellanic Cloud luminosity function, seemingly in conflict with dredge-up calculations available at present.

4. The mean $J-K$ carbon star colors are tightly correlated with parent galaxy absolute magnitude over a range extending from Ursa Minor at $M_V = -8$, to the Milky Way at $M_V = -21.5$. This result can be understood as reflecting a systematic increase in metal abundance with increasing galaxy luminosity.

5. The mean bolometric luminosity of the carbon stars also increases as a function of absolute magnitude up to Fornax, which contains C stars having a mean brightness similar to those found in the Magellanic Clouds and the Galaxy. This result is consistent with an abundance change but is primarily an age effect. It appears the gas retention time is dependent on dwarf mass, so that the more massive dwarfs somehow managed to retain gas the longest and form new stars.

6. Using the infrared *C-M* method, mean abundances have been derived for Ursa Minor, Draco, and the Leo systems. Good agreement is obtained with the spectrophotometric results when $J-K$ colors are used, but the abundances seem to come out far too metal rich when $V-K$ colors are utilized. The precise reasons for this discrepancy remain obscure, but the results may be indicative of systematic problems in using $V-K$ to determine effective temperatures for metal-poor stars. In any event, our photometry does support the existence of a real spread in metals among the giants in Draco and Ursa Minor.

7. A mean metallicity-absolute magnitude relation for the seven nearby spheroidals is clearly present which joins naturally onto the well-known abundance-magnitude distribution of more luminous early-type galaxies. The correlation of mean abundance with total luminosity can be traced over some 14 mag. On the other hand, the fractional carbon star number appears at best only weakly correlated with mean abundance.

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APPENDIX

In this Appendix we discuss in more detail the procedures for deriving the effective temperatures presented above, and carefully examine the relations between the Elias *et al.* (1982) photometric system used here and that of Johnson (1966).

I. TEMPERATURES

Our values of T_e for noncarbon stars are based on the occultation scale of Ridgway *et al.* (1980). The photometric system employed by these authors is ostensibly that of Johnson (1966), but as pointed out by McGregor and Hyland (1984), the Ridgway *et* *al.* $J-K$ colors systematically differ from those of Johnson. However, the K magnitudes of Ridgway *et al.* (1980) do appear to agree well with these of Johnson *et al.* (1966): we find a magnitude difference of only $\Delta K = 0.001 \pm 0.011$ for the 12 stars in common between these two studies, and no evidence for any color-term dependence of ΔK. It thus seems safe to assume that the Ridgway *et al.* (1980) $V-K$, T_e scale is on the Johnson (1966) system.

To derive T_e from $V-K$, we must then transform the colors to the Elias *et al.* (1982) system. As discussed below, this simply involves a zero-point shift of 0.02 mag. To derive T_e from $J-K$ colors, we then employ a mean relation between $V-K$ and $J-K$. The mean relation adopted is from Johnson (1966) for spectral types G5–K5, and from Lee (1970) for spectral types M0–M6, after converting the colors from the Johnson (1966) to the Elias *et al.* (1982) system using the procedures discussed below.

Our final color temperature calibration for oxygen-rich giants is given in Table 4. Note that the method we have used for determining the $J-K$, T_e relation differs somewhat from that employed in the recent calibration offered by McGregor and Hyland (1984). These authors transform the Ridgway *et al.* (1980) $J-K$ data for individual occultation stars to the Johnson (1966) system and then derive a strictly empirical $J-K$, T_e scale. We, on the other hand, have chosen to transform the smoothed Ridgway *et al.* $V-K$, T_e relation to a $J-K$, T_e relation using the mean field giant colors. There are certain advantages and disadvantages with both approaches. In any event, the agreement between the two final calibrations is satisfactory, although we obtain temperatures warmer than those of McGregor and Hyland (1984) by ~ 60 K on average at fixed $J-K$ color. However, both scales provide a better match to the occultation data than either those of Johnson (1966) or Cohen, Frogel, and Persson (1978) (see Fig. 1, McGregor and Hyland 1984).

Our temperature values for carbon stars are based on the color temperatures of Mendoza and Johnson (1965), again transformed to the Elias *et al.* (1982) system. For completeness we list in Table 4 the adopted scale.

II. COMPARISON OF THE JOHNSON AND ELIAS *et al.* PHOTOMETRIC SYSTEMS AND THE MEAN *VJK* RELATIONS FOR FIELD GIANTS

The subjects we want to address in this section include the relative K magnitude zero points of the Johnson (1966) and Elias *et al.* (1982) standard systems, the relation between $J-K$ colors in these two systems, and the mean VJK relations for oxygen-rich field giants. These issues are of considerable importance with regard to the reliability of the effective temperatures presented in the main body of the paper, and may also be of relevance for understanding the discrepancy in the $J-K$, $V-K$ two-color relation between metal-poor cluster giants and galactic field giants (e.g., Fig. 2).

Turning first to the zero point question, we begin by noting that previously (Aaronson and Mould 1982) we had suggested the presence of a 0.02 mag shift between the Elias *et al.* (1982) and Johnson (1966) systems, owing to the fact that by definition in the former system $K(\alpha \text{ Lyr}) \equiv 0.0$ mag, while in the latter system $K(\alpha \text{ Lyr}) = 0.02$ mag. This possibility was recently examined by Frogel, Persson, and Cohen (1983), who concluded there was no evidence for any zero-point difference. However, these authors only considered the data in Frogel *et al.* (1978), although there is a considerably larger body of measurements with which the issue can now be addressed. In particular, many new standard stars also having photometry from Johnson *et al.* (1966) have been presented by Elias *et al.* (1982), and these authors have also revised some of the Frogel *et al.* (1978) standard star values. The comparison sample can be further supplemented with data from Aaronson (1977) and Carney and Aaronson (1979). While observations from these two latter sources were obtained on the "Harvard" system, at K the Elias *et al.* and Harvard systems appear identical.

In Table 5 we summarize the difference in K magnitude for various samples of stars measured on both the Johnson (1966) and

TABLE 4

ADOPTED TEMPERATURE CALIBRATIONS

T_e	$(J-K)_0$	$(V-K)_0$
Oxygen-rich Stars		
5000........	0.535	2.17
4750........	0.585	2.36
4500........	0.65	2.64
4250........	0.74	3.01
4000........	0.83	3.49
3750........	0.95	4.25
3500........	1.065	5.49
3250........	1.16	6.86
Carbon Stars		
5000........	0.43	2.14
4750........	0.50	2.28
4500........	0.57	2.55
4250........	0.65	2.84
4000........	0.72	3.19
3750........	0.82	3.59
3500........	0.94	4.01
3250........	1.06	4.42
3000........	1.22	5.01
2750........	1.43	5.87
2500........	1.69	6.89
2350........	2.06	7.81

TABLE 5

COMPARISON OF K MAGNITUDE ZERO POINT BETWEEN JOHNSON AND ELIAS *et al.* PHOTOMETRY SYSTEMS

Sample	n	$K_J - K_{CIT}$
Standards	22[a]	0.022 ± 0.006
$V-K \leq 5$	41[b]	0.019 ± 0.005
$V-K > 5$	8[c]	-0.024 ± 0.009
All stars	49	0.012 ± 0.005

[a] Thirteen stars from Elias *et al.* 1982, seven stars from Frogel *et al.* 1978, and two stars from Aaronson 1977.

[b] In addition to standards, two stars from Aaronson 1977, seven stars from Frogel *et al.* 1978, and 10 stars from Carney and Aaronson 1979.

[c] Two stars from Aaronson 1977, and six stars from Frogel *et al.* 1978.

Elias *et al.* (1982) systems, and in Figure 13 plot the individual values. We see that by considering either just the standards, or all stars bluer than a $V-K$ color of 5 mag, a zero-point difference is evident, given by

$$K_J - K_{CIT} = 0.02 \ . \tag{1}$$

Only by including stars redder than $V-K = 5$ mag does the zero-point difference diminish, and in fact becomes negative when the reddest stars alone are considered.

We conclude that the expected zero-point difference of 0.02 mag between the Johnson and Elias *et al.* systems is really present, at least for stars having $V-K < 5$ mag. Frogel, Persson, and Cohen (1983) have reached the opposite conclusion simply because they considered a smaller sample which was heavily weighted by the half-dozen red stars from Frogel *et al.* (1978). It remains unclear whether the downturn in zero-point difference redward of $V-K = 5$ mag reflects the presence of a real color term, or is just an artifact of the Frogel *et al.* (1978) red star observations having been single epoch measurements which either have a small but systematic photometric error, or have an unlucky phase placement among stars that are minor variables. Our results may also explain the 0.011 mag zero-point difference reported by Elias *et al.* (1983) between the CIT and AAO systems, since the Mount Stromlo/AAO system is believed to be close to that of Johnson (Jones and Hyland 1982). In fact, a straight mean of the 21 values listed in Table 1 of Elias *et al.* (1983) yields $K_{AAO} - K_{CIT} = 0.017 \pm 0.005$ mag.

We turn now to the $J-K$ color. The data in Elias *et al.* (1982), Frogel *et al.* (1978), and Johnson *et al.* (1966) provide 20 standards and observations of 13 other giants with which to determine the relevant $J-K$ transformation. A mean least-squares fit to all 33 points shown plotted in Figure 14 yields

$$(J-K)_{CIT} = -0.008 + 0.916\,(J-K)_J \ . \tag{2}$$

Equation (2) is close to the transformation given by Frogel, Persson, and Cohen (1983), based on the smaller sample of 24 stars from

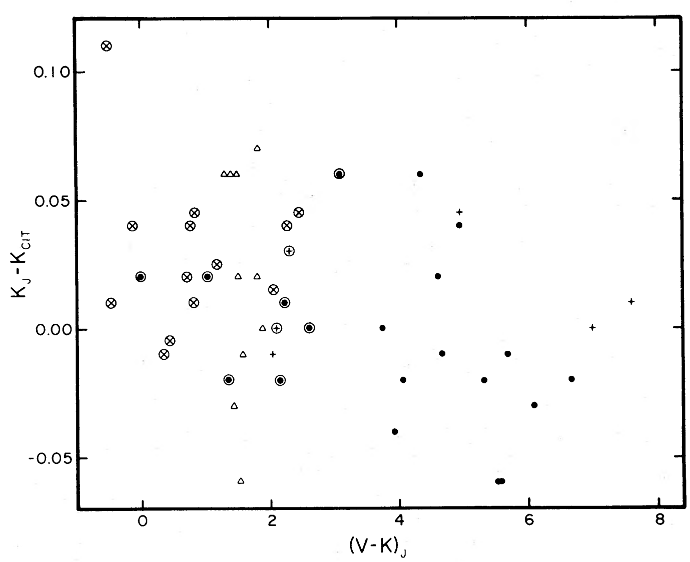

FIG. 13.—K magnitude zero-point difference between the Johnson (1966) and Elias *et al.* (1982) photometry systems, plotted against $V-K$ color on the Johnson system. Data are adopted from Aaronson (1977) (+), Frogel *et al.* (1978) (●), Carney and Aaronson (1979) (Δ), and Elias *et al.* (1982) (X). Points surrounded by circles are standard stars.

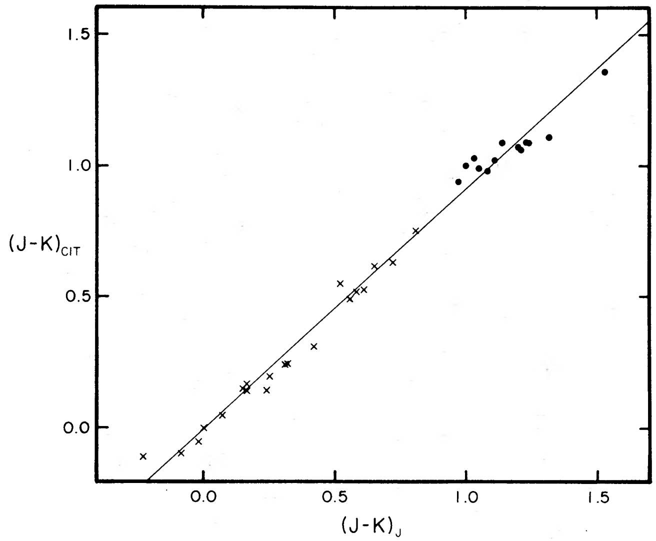

FIG. 14.—The $J-K$ color on the Elias *et al.* (1982) system plotted against $J-K$ color on the Johnson (1966) system. The crosses (X) are standard stars from Elias *et al.* (1982) and Frogel *et al.* (1978), while the filled circles (●) are giants from the latter reference only. The least-squares fit shown was obtained by first treating $(J-K)_{CIT}$ and then $(J-K)_J$ as the independent variable, and averaging the results.

Frogel *et al.* (1978). (Note, however, that contrary to the claim by Frogel, Persson, and Cohen 1983, their relation does not identically reproduce the mean $J-K$ colors of Frogel *et al.* 1978.)

Johnson (1966) and Lee (1970) give mean color relations for giants based on a large number of stars. Using equations (1) and (2) above, we can now transform their results and obtain mean VJK relations on the Elias *et al.* (1983) system; these are given in Table 6. (Note that we have made a 0.01 mag adjustment in $J-K$ at spectral type K5 in order to more smoothly tie on the Johnson results to the Lee results adopted for spectral types M0 and longward.) For completeness, we also give in Table 6 the mean $H-K$ relation from Frogel *et al.* (1978). The latter is based only on measurements of a small number of stars, because unfortunately, the relation of $H-K$ between the CIT and Lee photometry does not seem well defined (see Frogel, Persson, and Cohen 1983). At fixed $J-K$ color, the results in Table 6 yield $H-K$ colors for red stars bluer than those of Lee (1970) by $\sim$0.05 mag; CIT photometry also leads to bluer $H-K$ colors than the Mount Stromlo/AAO system (Elias *et al.* 1983).

TABLE 6

MEAN COLOR RELATIONS FOR FIELD GIANTS ON ELIAS *et al.* SYSTEM

Spectral Type	$V-K$	$J-K$	$H-K$
G5	2.10	0.50	0.05
G8	2.18	0.54	0.06
K0	2.37	0.58	0.08
K1	2.50	0.61	0.09
K2	2.61	0.65	0.10
K3	2.94	0.72	0.12
K4	3.26	0.80	0.13
K5	3.69	0.86	0.15
M0	3.76	0.88	0.16
M1	3.92	0.92	0.17
M2	4.18	0.94	0.18
M3	4.65	1.00	0.20
M4	5.36	1.05	0.23
M5	6.22	1.13	0.26
M6	7.22	1.18	0.30

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Note added in proof.—In a recent preprint, Buonanno *et al.* (1984) obtain a mean abundance value for the Fornax field of -1.40 ± 0.15 dex, strengthening the mean abundance–absolute magnitude relation found here. The deep $C-M$ diagrams obtained by these authors and also by Seitzer and Frogel (private communication) reach the Fornax horizontal branch, yielding a shorter distance modulus than we have used, and implying that the absolute bolometric magnitudes of the Fornax C stars (and the absolute magnitude of Fornax itself) should be decreased by ~ 0.25 mag. This would place the most recent epoch of star formation in Fornax from the AGB age-dating method at ~ 3 Gyr ago. Other conclusions of the paper remain unaffected.

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