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CARBON STARS IN THE FORNAX DWARF SPHEROIDAL GALAXY

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ABSTRACT

A number of the very red stars in the Fornax dwarf galaxy recently discovered by Demers and Kunkel have been observed spectroscopically and in the infrared. For $B - V$ greater than ~ 2.1, the giant branch of Fornax may consist entirely of carbon stars. The luminosities of these stars range from -4.5 to -5.5 in $M_{\rm bol}$, placing them on the upper asymptotic giant branch, in analogy with the carbon stars we have found in Magellanic Cloud globular clusters. We argue that such stars can be produced only by a population of intermediate age. A comparison of the fractional carbon-star light in Fornax and the Cloud globulars suggests that roughly 20% of Fornax is of intermediate age (i.e., 2–8 $\times$ 10^9 years old). We propose that the width of the Fornax giant branch in $B - V$ can thus be understood to be a result of ongoing chemical enrichment occurring over successive generations of stars. We further suggest a correlation between age spread in dwarf spheroidals and their total masses. In particular, as the most massive dwarf spheroidal known, Fornax seems to have retained longest the gas necessary for continued star formation.

Subject headings: galaxies: stellar content — infrared: general — stars: carbon — stars: evolution.

I. INTRODUCTION

Fornax (A0237 − 34) is a dwarf spheroidal member of the Local Group first recognized on Harvard plates by Shapley (1938). Fornax is distinguished among the dwarf systems near our Galaxy by a number of characteristics. It has the brightest absolute magnitude ($M_v \sim -13$), the largest diameter (~ 3 kpc), the highest central surface brightness, and is the only dwarf spheroidal with its own globular clusters (de Vaucouleurs and Ables 1968; van den Bergh 1968; Hodge 1971). Demers and Kunkel (1980, hereafter DK) have recently discovered a large number of very red stars ($1.6 < B - V < 2.9$) forming a well-defined extension of the Fornax giant branch.

To investigate the nature of the red Fornax stars, we have obtained vidicon spectra (§ II) and infrared photometry (§ III). The evolutionary history of Fornax is considered in § IV, where we conclude that, like the globular cluster system of the Magellanic Clouds, Fornax contains a significant population of intermediate age.

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II. VIDICON SPECTROPHOTOMETRY

In selecting stars for spectroscopic study, we attempted to span the full color range of the very red stars identified by DK. The spectra were obtained in the course of a vidicon run on the Cerro Tololo Inter-American Observatory 4 m telescope during 1979 October 28–30. Details of the instrumental configuration and reduction procedure are given by Mould and Aaronson (1980).

Spectrophotometry of these stars is presented in Table 1, and six of the spectra are shown in Figure 1. The flux ratio in magnitudes between 4930 and 6540 Å (15 Å bandpass) is given in column (2) of Table 1. Column (3) gives the strength of the $C_2(0, 1)$ Swan band at 5635 Å for carbon stars or the TiO $\gamma'(0, 0)$ band at 6162 Å for M stars (see Mould and Aaronson 1979). The magnitude in column (4) is an integration over the V bandpass and corresponds fairly closely to a V magnitude. We estimate the uncertainty in the colors and magnitudes to be ± 0.1 mag. The classification given in column (5) of Table 1 is discussed by Mould and Aaronson (1980). One star (DK 6) has a basically featureless spectrum and is classified Ctm for "continuum" in column (5). Columns (6) and (7) give the V and $B - V$ values from DK.

With the caveat that the present subset of the DK

TABLE 1

SPECTROPHOTOMETRY OF RED STARS IN FORNAX

Star[a] (1)	[4930] – [6540] (2)	Band Strength (3)	Mag (4)	Type (5)	V^a (6)	$B - V^a$ (7)
DK 2	1.24	0.74	17.6	C, 2	17.70	2.14
DK 6	1.50	. . .	17.6	Ctm	17.47	2.02
DK 7	1.30	0.68	18.5	C, 2	18.08	2.48
DK 22	1.55	1.36	18.3	C, 4	18.19	2.58
DK 29	1.19	0.32	17.9	M1	17.93	1.88
DK 46	1.68	1.34	17.6	C, 4	17.68	2.38
DK 60	1.41	1.36	18.2	C, 4	18.44	2.75

[a] Adopted from Demers and Kunkel 1979.

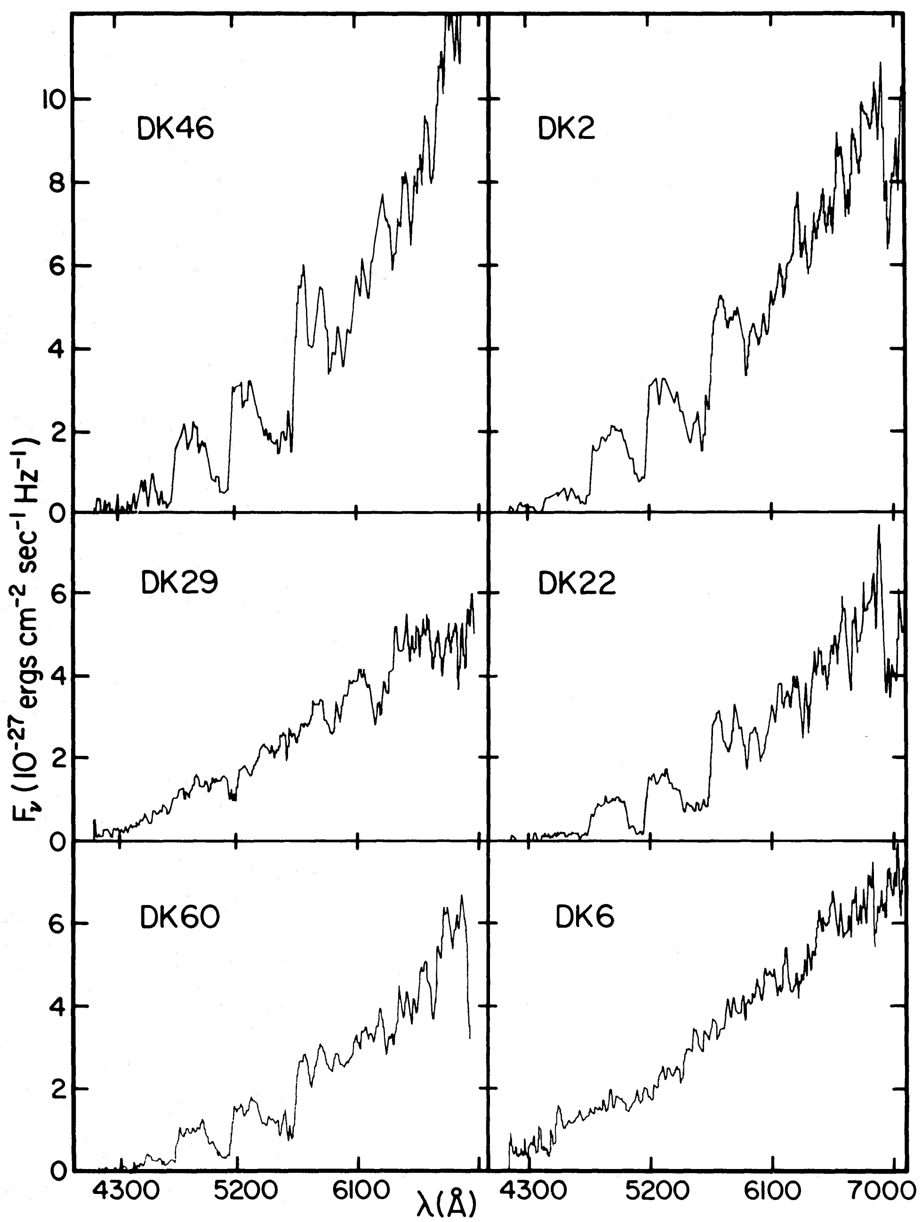

FIG. 1.—Spectra of six giant stars in Fornax. Note the Swan bands of C_2 at 5636 and 5165 Å in the carbon stars DK 2, 22, 46, and 60; and the γ' band heads of TiO at 6112 and 5850 A in the M star DK 29.

TABLE 2

INFRARED PHOTOMETRY, LUMINOSITIES, AND TEMPERATURES[a]

Star[b] (1)	H (2)	$J-H$ (3)	$H-K$ (4)	m_{bol} (5)	$-M_{bol}$ (6)	$\log T_e$ (7)
a) Fornax Stars						
DK 2	13.69	0.78	0.40	16.10	4.90	3.494
DK 6	14.02	0.75	0.21	16.60	4.40	3.572
DK 7	13.93	0.87 (05)	0.38 (04)	16.45	4.55	3.479
DK 22	13.61	0.87	0.46	16.10	4.90	3.465
DK 46	12.86	0.88	0.48	15.35	5.65	3.461
DK 60	13.90	0.84 (04)	0.40	16.40	4.60	3.483
b) Additional Fornax Stars						
DK 3	15.17 (06)	0.94 (12)	...	18.0	3.0	...
DK 4	15.12 (07)	0.64 (12)	...	17.4	3.6	3.58:
DK 10	14.31 (05)	...	...	16.7	4.3	...
DK 33	14.00	0.96 (08)	...	16.6	4.4	3.46:
DK 49	14.26 (06)	0.68 (08)	...	16.6	4.4	3.57:
DK 58	14.56 (05)	0.82 (09)	...	17.1	3.9	...
DK 64	13.74 (04)	0.86 (06)	...	16.2	4.8	3.48:
DKH 6737	14.32 (05)	0.79 (07)	...	16.8	3.9	3.55:
DKH 11179	15.03 (10)	0.97 (16)	...	17.8	3.2	3.54:
DKH 11325	13.35 (04)	0.87 (05)	...	15.8	5.2	3.48:
c) Sculptor Stars						
H222	14.04 (06)	0.75 (10)	...	16.6	2.9	3.62:
H453	13.43 (04)	0.73 (05)	...	15.9	3.6	3.595
d) Fornax Globular Clusters[c]						
Hodge 2	11.97	0.54	0.17	...	...	...
Hodge 3	10.94	0.47	0.10	...	...	...
Hodge 4	11.50	0.54	0.10	...	...	...
Hodge 5	11.69	0.45	0.08	...	...	...

[a] Errors larger than 0.03 mag are given in parentheses in hundredths of a magnitude.

[b] DK numbers are from Demers and Kunkel 1979; DKH numbers are from Demers, Kunkel, and Hardy 1979; H numbers are from Hodge 1963; Hodge cluster numbers are from Hodge 1961.

[c] These measurements were made with a 30″ aperture and a 70″ chopping throw. The latter is sufficiently large so that no correction is required for cluster flux in the "reference" beam.

sample is very small, we suggest the following from perusal of Table 1:

1. For $B - V > 2.1$, the giant branch of Fornax may consist entirely of carbon stars.
2. The colors of these carbon stars are positively correlated with their C_2 band strengths.
3. The M star DK 29 is probably a valid member of Fornax. The alternative that it is a foreground dwarf is contradicted by (*a*) the red $B - V$ value for its spectral type, (*b*) the probability of its variability indicated by DK, and (*c*) the absence of strong MgH, Na D, and Ca H features.

III. INFRARED PHOTOMETRY

In Table 2*a* photometry is given for six of the seven stars for which we have vidicon spectra (§ II) and was obtained with the CTIO 4 m telescope during 1979 November 3–5. Table 2*b*–*d* presents measurements gathered with the 2.5 m du Pont telescope at Las Campanas during 1979 December 5–8. Additional Fornax stars are in Table 2*b*, the two very red stars discovered in Sculptor by Hodge (1965) are in Table 2*c*, and integrated photometry of four of the Fornax globular clusters is in Table 2*d*. A complete description of the instrumentation, observing technique, and photometric system is given in Mould and Aaronson (1980). In this paper we adopt $E(B - V) = 0$ for both Fornax and Sculptor.

Figure 2 shows a plot of $J - H$ against $H - K$ color for the stars in Table 2*a*. Also sketched are the regions occupied by the reddest stars in the Magellanic Cloud clusters discussed in Mould and Aaronson (1979, 1980). Infrared data for ~45 of these stars are now available from the work of Mould and Aaronson (1980) and of Frogel, Persson, and Cohen (1980). Several conclusions can be drawn from Figure 2. First, the carbon stars form a well-defined, continuous

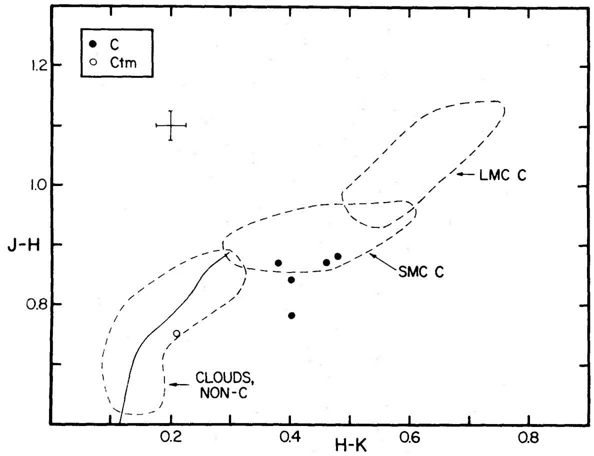

FIG. 2.—A $(J - H, H - K)$ two-color diagram. The closed circles are Fornax carbon stars; the open circle is the Fornax continuum star DK 6. The dashed contours enclose the areas where LMC cluster carbon stars (with one exception), SMC cluster carbon stars (with one exception), and non-carbon cluster stars in both Clouds lie. The solid line indicates the mean relation for field giants in the Galaxy. The nominal uncertainty in the Fornax star measurements is shown by the error bar.

extension of the non-carbon stars in the *JHK* plane. Second, the Fornax carbon stars appear similar in color to the SMC carbon stars in that both groups have significantly bluer *JHK* colors than do LMC carbon stars. It is tempting to speculate that this difference is due to warmer temperatures resulting from lower metallicities in the SMC and Fornax as compared with the LMC. Various color-color and band strength–color relations are further discussed in Mould and Aaronson (1980).

Apparent bolometric magnitudes were derived for the stars in Table 1, by using Figure 2 of Frogel, Persson, and Cohen (1980), which gives the bolometric correction to the K magnitude as a function of $J - K$ color. From the discussion in that paper, we estimate the uncertainty in m_{bol} in Table 2*a* to be ~ 0.1 mag. To derive magnitudes for stars in Table 2*b*–*c*, we first estimated types (C or non-C) from a $(B - V, V - H)$ diagram, and then used Figure 2 here to estimate K magnitudes. Fortunately, over the range of stars considered, the resulting magnitudes are rather insensitive to variation in either type or $J - K$ color, and we estimate the uncertainty in these m_{bol}'s to be no more than ~ 0.25 mag. To derive absolute bolometric luminosities, we adopt a Fornax modulus $(m - M)_0 = 21.0$ mag (DK). For Sculptor, we adopt $(m - M)_0 = 19.5$ mag (Kunkel and Demers 1977). Uncertainties in these distances do not qualitatively affect the conclusions of this paper.

The effective temperatures given in Table 2*a* were derived from $J - K$ colors as discussed in Mould and Aaronson (1980). For most of the stars in Table 2*b*–*c*, $J - K$ was estimated both from Figure 2 and from a $(J - K, V - H)$ two-color diagram constructed from Table 2*a*. No estimate was made for variables with amplitude $\Delta V > 0.3$ mag (DK). The resulting temperatures are ~ 2–3 times more uncertain than those in Table 2*a*.

In Figure 3 we have plotted M_{bol} against log T_e by using the data in Table 2. Also shown in Figure 3 is a dashed contour within which lie all but two of the Magellanic Cloud cluster stars in Mould and Aaronson (1980) and Frogel, Persson, and Cohen (1980). Also shown in Figure 3 are the giant branches for three Galactic globular clusters with a wide range in metallicity, whose tips are seen to terminate in the range $M_{bol} \sim -3.3$ to -3.6 mag. This luminosity range agrees well with the fitst giant branch tips of theoretical tracks calibrated by Sweigart and Gross (1978). For plausible variation in helium abundance, metallicity, and mass, the latter fall in the range $M_{bol} \sim$

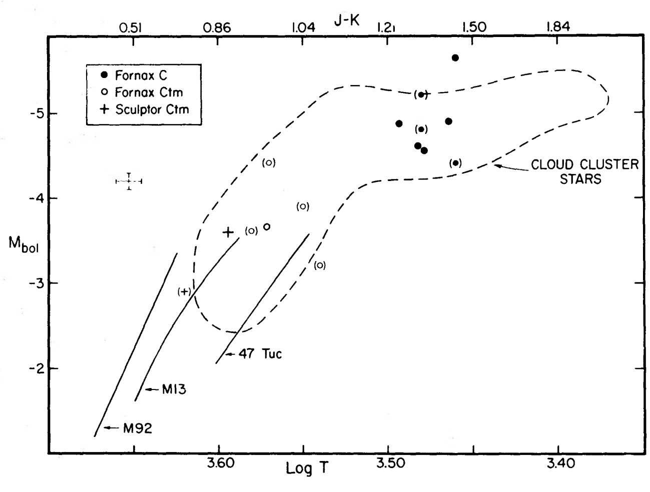

FIG. 3.—The H-R diagram. Points surrounded by parentheses have 2–3 times the uncertainty of the other points. The error bar gives the nominal uncertainty in the data of higher accuracy. Also shown are the mean giant branches of three Galactic globulars (adopted from Cohen, Frogel, and Persson 1978 and Frogel, Persson, and Cohen 1980), and a dashed contour indicates the area where Magellanic Cloud cluster stars lie.

-3.3 to -3.8 mag. However, we see from Table 2 and Figure 3 that the luminosities of the red Fornax stars lie, for the most part, considerably above both the observed and theoretical first giant branch tips. The confirmed carbon stars average 1–2 mag above the tip, clearly placing them on the asymptotic giant branch. (The reddest 47 Tuc variables in Frogel, Persson, and Cohen 1980 scatter in the mean only ~ 0.4 mag above the first giant branch tip.) With the distances adopted here ($[m - M]_0 = 21.0$, 19.3, 18.7 mag for Fornax, the SMC, and the LMC, respectively), the mean carbon star luminosities in Fornax agree well with those in the Magellanic Clouds.

The bolometric magnitudes of the two red Sculptor stars indicate they are not carbon stars like those of Fornax. An unpublished spectrum which we have obtained for H222 in fact confirms our assignment of this star to type "Ctm." The position of the Sculptor stars in Figure 3 is consistent with the [Fe/H] value of -1.9 estimated by Kunkel and Demers (1977).

An interesting question arises as to whether any of the Fornax globulars themselves possess carbon stars. Integrated $H - K$ colors (Table 3) provide the easiest test of this possibility. The $H - K$ colors of Hodge 3, 4, and 5 (Hodge 1961) range between 0.08 and 0.10 mag, values typical for Galactic globular clusters of moderate metal deficiency (Aaronson *et al.* 1978). However, the $H - K$ color of Hodge 2 is 0.17 mag, a value comparable in redness to the most metal-rich Galactic globular clusters. The UBV colors of Hodge 2 (Harris and Racine 1979) do not indicate such a high metallicity, and we conclude that the cluster probably contains carbon stars. Our data and interpretation agrees with that of Persson and Cohen (1979, private communication). Note that the $H - K$ colors for the other Fornax clusters do not preclude the presence of carbon stars, since similar $H - K$ colors are measured for some of the Cloud clusters in which we have found carbon stars (Aaronson and Persson 1979).

IV. EVOLUTIONARY IMPLICATIONS

In the definition of Mould and Aaronson (1980) an "extended giant branch" is one which reaches farther in luminosity than the giant branch of Galactic globular clusters of similar metallicity. The existence of an extended giant branch in an old stellar system is an indicator that more massive stars are present than in a comparable Galactic globular cluster, and that the system is younger. These more massive stars can better survive the attrition of their outer envelope by mass loss and nuclear burning and reach higher luminosities on the asymptotic giant branch (see, e.g., Iben and Truran 1978).

The extended giant branch discovered in Fornax by DK indicates that this galaxy has a considerable intermediate age population. The photometry presented in § III of this paper allows us to put an *upper limit* on the epoch of most recent star formation—the maximum observed luminosity of $M_{\rm bol} = -5.65$ mag

TABLE 3
FRACTION OF THE VISIBLE LIGHT DUE TO CARBON STARS

Object (1)	V_{60} (2)	V_t (3)	#C (4)	$\Sigma_c V$ (5)	$0.4(V_t - \Sigma_c V)$ (6)
a) SMC Globulars					
Lindsay 1	13.32[a]	12.0	1	16.4	-1.76
Kron 3	12.08	11.4	2	16.1	-1.87
NGC 152	13.12	12.3	2	16.2	-1.56
NGC 339	12.99	11.9	1	16.2	-1.72
NGC 419	10.66	10.0	3	15.4	-2.15
Mean					-1.8 (± 0.1)
b) LMC Globulars					
NGC 1783	10.97	10.3[b]	1	15.4	-2.04
NGC 1846	11.40	10.7[b]	5	14.6	-1.56
NGC 1978	10.74	9.9	3	15.3	-2.17
NGC 2209	13.15[c]	12.5[b]	2	16.1	-1.44
Mean					-1.8 (± 0.2)
c) Fornax Galaxy					
...	...	8.2	41	14.4	-2.5

[a] Magnitude from Alcaino 1978.
[b] Obtained from $V_t = V_{60} - 0.7$ (Harris and Racine 1979).
[c] Magnitude from Bernard 1975.

corresponds to an age of 2×10^9 years (Mould and Aaronson 1980). The uncertainty in this estimate may be a factor of 2.

We can also obtain an estimate from the present data of the fraction of the stellar population of Fornax that is of intermediate age. This can be done by comparison of the fraction of the total light in Fornax owing to carbon stars with the corresponding fraction in the intermediate-age globular clusters of the Magellanic Clouds. This calculation is carried out in Table 3, which lists the globular clusters in the Clouds with carbon stars that we have identified on the upper asymptotic giant branch. (NGC 2190 is missing from Table 3 because of a lack of integrated photometry.) Column (2) gives the integrated V magnitude of the cluster within a 60″ aperture from van den Bergh and Hagen (1968), except where noted. An estimate of the total visual light within the tidal radius of the cluster is provided in column (3) (Harris and Racine 1979). In columns (4) and (5) we note the number of carbon stars and their total visual light, respectively. This allows the logarithmic fraction of the total cluster light in carbon stars to be estimated (col. [6]). The mean value of the fractional carbon-star light seems to be rather well determined (the standard error $\sigma/\sqrt{n}$ is given in parentheses) and appears identical for both SMC and LMC clusters. The possible systematic errors in this number therefore require emphasis.

1. The survey for C stars is probably incomplete, especially in the centers of the clusters. Blanco and Richer (1979) have, in fact, identified three additional carbon stars in NGC 419.

2. Intermediate-age clusters which, due to small number stochastic effects, have no C stars at all are missing from Table 3.

3. Some listed C stars may be nonmembers of their respective clusters. Field contamination is, however, less than 10% (Mould and Aaronson 1979). We will not try to correct for these effects, which tend to cancel, but note that the mean value of -1.8 is probably good only to 0.3 dex.

The corresponding fraction for Fornax is estimated in Table 3*c*. For the total visual light of Fornax, we have taken the mean of values given by de Vaucouleurs and Ables (1968) ($V = 8.41$ mag) and Hodge (1979, private communication) ($V = 7.82$ mag). A correction of 0.07 mag was added to account for the areal completeness of the C-star survey by DK, using the growth curve of de Vaucouleurs and Ables (1968), to arrive at the value given in column (3). The total visual magnitude in carbon stars was estimated, supposing that all DK stars with $B - V > 2.05$ (§ II) are carbon stars. The resultant value of the logarithmic fraction of the total light in Fornax from carbon stars is given in column (6). We conclude from the difference between this value and that obtained for the Cloud clusters that 20% of the stellar population of Fornax is of intermediate age. The uncertainty in this estimate is a factor of ~ 2.5. In this context "intermediate age" refers to the range of ages corresponding to the carbon star luminosities, i.e., $2–8 \times 10^9$ years.

At this point, two cautionary remarks are in order. First, there is *no information* in the present data on the epoch of *first* star formation in Fornax. Second, the width of the Fornax giant branch (see Demers, Kunkel, and Hardy 1979) probably cannot be *directly* attributed to an age spread of the magnitude discussed above. The sensitivity to age of the theoretical giant branches of Sweigart and Gross (1978) and Ciardullo and Demarque (1977) is not sufficient to explain the observed giant branch spread in $B - V$. However, the history we are suggesting for Fornax, in which the galaxy retains its gas and continues to form stars for many billions of years, provides the indirect cause of the giant branch spread through ongoing chemical enrichment. In this scenario the bluest stars on the giant branch at a given luminosity are metal-poor (as has been inferred for Draco by Zinn 1978). They are also the oldest stars. The age sensitivity of $B - V$ is lost in the metallicity sensitivity. Nonetheless, the occurrence of successive generations of star formation in Fornax remains the underlying cause of the giant branch spread. Accurate *JHK* photometry of stars further down the giant branch would be most useful in further clarifying this situation.

Finally, in a more speculative vein, we wish to suggest a correlation between the degree of age spread in the dwarf spheroidal galaxies and their total masses. The Fornax galaxy, with its well-developed, extended giant branch, is the most massive of the dwarf spheroidal satellites of the Galaxy. Sculptor, with the two red stars discussed here (but perhaps surveyed with less completeness than Fornax), comes next. Draco, with the only other really well-studied giant branch (Stetson 1979), has no very red stars but does show signs of an age spread in its metallicity distribution and is the least massive of the three dwarf spheroidals. This suggests that the length of time a dwarf spheroidal can retain its gas varies directly as its mass and may point to tidal removal of the gas by the Milky Way as the responsible process.

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