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A CCD SURVEY FOR FAINT HIGH-LATITUDE CARBON STARS

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ABSTRACT

We describe a wide-area CCD survey to search for faint high-latitude carbon (FHLC) stars. Carbon giants provide excellent probes of the structure and kinematics of the outer Galactic halo. We use two-color photometric selection with large-format CCDs to cover 52 $\deg^2$ of sky to a depth of about $V = 18$. Of 94 faint C star candidates from our own CCD survey, one highly ranked $V = 17$ candidate was found to have strong carbon and CN bands. We estimate that, to a depth of $V = 18$, the surface density of FHLC stars is 0.02 $\deg^{-2}$. An updated FHLC sample is used to constrain halo kinematic and structural parameters. Although larger samples are needed, the effective radius of FHLC giants, assuming a de Vaucouleurs law distribution, is larger than that for Galactic globular clusters.

Subject headings: stars: carbon — stars: evolution — stars: statistics — surveys

1. INTRODUCTION

Models of the chemical and dynamical properties of the Galactic halo are still only weakly constrained by presently available observations. Intrinsically bright stars visible to large Galactocentric distances (10–100 kpc) provide the best opportunity to measure the velocity ellipsoid and systemic rotation of the outer halo. Carbon (C) stars have been sought as the ideal tracer of the outer halo because they were thought to be virtually all giant stars that might be readily recognizable from their strong C_2 and CN absorption bands. Using objective prisms with photographic plates on a wide-field Schmidt telescope, crude low-dispersion spectra for every object in a large field of view may be obtained. Objective-prism surveys in the near-infrared (see references in Blanco 1989) have concentrated on the low Galactic latitudes of the Galactic disk and are excellent for finding N-type asymptotic giant branch (AGB) stars, but are highly incomplete for early-type C stars. The younger and more massive N-type AGB C stars are only rarely observed at high Galactic latitudes. In a survey of the spheroid, we thus expect to find mostly CH stars, and possibly some R stars. Unless stated explicitly, it is to these warmer types that we refer in further discussions here.

Sanduleak & Phillips (1977) and Westerlund et al. (1986) employed similar low-dispersion photography to identify C stars by the Swan bands at 4737 and 5165 Å, a technique well suited to warm C stars. These and other C star samples have been compiled into a single catalog by Stephenson (1989). Less than 1% of the 6000 stars in Stephenson's catalog are the faint, high-latitude carbon (FHLC) stars ($V > 13$, $|b| > 40°$) most useful as dynamical probes of the outer halo. Although the completeness of previous high Galactic latitude objective-prism surveys is not well quantified, the two most prolific published sources of FHLC stars are the Case low-dispersion survey (CLS) and the Michigan-Tololo survey (hereafter UM). As detailed below in § 6, both the CLS survey (Sanduleak & Pesch 1988) and the southern UM survey (Lewis, MacAlpine, & Weedman 1979) appear to be complete *for* C *stars* to about $V = 16$.

What distances are probed by the objective-prism surveys? The absolute V magnitudes of CH and R-type stars (R0–R4 and C0–C4) have been variously estimated at $-2 < M_V < 0.4$, with the mean estimates for R stars hoveing within a half-magnitude of zero (see references in Alksne & Ikaunieks 1981). If we adopt $\overline{M_V} = 0$, these photographic surveys reliably find such C stars with strong Swan bands of C_2 to distances of at least 16 kpc, nothing at which to sneeze. Nevertheless, these surveys do not effectively probe the outer Galactic halo, and were not specifically designed to find C stars. Extragalactic emission-line objects, not FHLC stars, were the primary goal of these surveys, so that known FHLC stars were not examined to help define consistently applied selection criteria. Occasionally, C stars have been found to fainter apparent magnitudes via less systematic means (e.g., Phillips & Terlevich 1983; Margon et al. 1984). The faintness ($V \approx 18$), and serendipitous discovery of such stars would suggest that a population of outer halo tracers at distances of 40 kpc or more might be recovered by surveys complete to faint magnitudes.

We therefore have attempted a deeper, quantitative CCD survey for faint C stars over a large area of sky at high Galactic latitudes. We sought a sample that could be combined with the less-deep objective-prism survey samples to provide a signifi-

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1994ApJ...434..319G

cant size sample of distant halo C stars. The combined sample could be used for tests of the spheroid density law and for dynamical analysis. Radial velocities of the resulting sample could provide important kinematic data in the outer halo for study of the mass and chemical evolution of the Galaxy and the form of the Galactic potential.

Also, the observed frequency of C stars and C/M star ratios at different Galactocentric radii might offer clues to metallicity gradients in the halo. An observed anticorrelation between metallicity and C to late M star ratios in Local Group galaxies (e.g., Cook, Aaronson, & Norris 1986) is still not explained. The antocorrelation has variously been attributed to the low metallicities encouraging C star formation (by lowering the oxygen abundance in the C/O ratio) and/or discouraging M giant formation (by shifting the giant branch earlier toward K types). However, C/M ratios in the Local Group also correlate well with the luminosity of the parent galaxy. It is difficult to know which of these correlations is primary, because metallicity in turn correlates with parent galaxy luminosity. Low stellar densities have also been suggested to encourage the formation of C stars (e.g., McClure 1984 for globular clusters or Aaronson, Olszewski, & Hodge 1983 for dwarf spheroidal galaxies). The even lower densities found in the outer halo of the Galaxy, which has fostered very similar types of carbon stars, might be expected to result in a still larger fraction of red giants with overabundances of carbon. A survey of the galactic spheroid as a distinct population permits an excellent test of these hypotheses, since a high-mass, low-density, metal-poor system has yet to yield a large sample of C stars.

All these tests could be important for constraining theories of the collapse and formation of the Milky Way (Stephenson 1986). Some initial results on halo velocity dispersions using a small number of faint C star tracers have been presented by Mould et al. (1985). Results from a larger sample were published while the current work was ongoing (Bothun et al. 1991, hereafter B91). The study we describe here provides some important revisions to those samples.

To select carbon stars, we chose a photometric technique that allows the use of sensitive CCD photometric detectors in conjunction with intermediate bandpass filters. In the next section we describe the observational techniques that enabled us to complete a CCD survey covering more than 52 deg^2 of sky. We then describe the selection of C star candidates. We briefly characterize the depth and completeness of our survey by several methods, both for comparison with prior surveys, and to estimate the surface density of C stars in the spheroid to the magnitude limit of the survey. We then discuss our follow-up spectroscopy of candidates and the overall efficiency of the CCD survey.

While this work was in progress, four FHLC stars from the sample of B91 were shown to be high proper motion carbon dwarfs (Green, Margon, & MacConnell 1991; Green et al. 1992). We remove these local stars and add a handful of other FHLC stars from the literature to compile the largest available sample of FHLC giants with radial velocities and photometric parallaxes. In § 7 we use this sample for study of the kinematic and spatial distribution of these halo tracers.

2. OBSERVATIONS AND REDUCTION

Since carbon (C) stars often have broad-band colors that are similar to other late-type (cool) stars, efficient photometric selection is best performed using their strong carbon or cyanogen spectral features. The photometric technique we use has been shown (Cook & Aaronson 1989) to efficiently distinguish C stars from other late-type stars by using intermediate-band ($\approx$200 Å FWHM) filters. One ("77") is centered on a region of TiO absorption near 7752 Å, and the other ("81") is on a CN absorption band near 8104 Å. A color-color diagram ($V-I$ versus $77-81$) thus separates C stars from other stars of similar effective temperature because C stars appear particularly faint in the 81 filter relative to the 77 filter. C stars may have a wide range of $V-I$ colors from G through late M, so that their blue $77-81$ color provides the best separator from the main stellar sequence.

Because the surface density of C stars at high Galactic latitudes is known to be low, and since the area covered by a single CCD frame is small, observing efficiency is a top priority. Therefore (following a suggestion of P. Garnavich), we combined counts in the 77 and 81 filters to form (77 + 81) magnitudes as an approximation to a broad-band red magnitude such as I. The magnitude (77 + 81) has an effective central wavelength close to 8000 Å. In conjunction with the visual magnitude, this provides a "pseudo–($V-I$)" which we may refer to as a "temperature color." Our adopted technique thus requires images in three rather than four filters for every field surveyed.

In Table 1 we give particulars of the six imaging runs at the KPNO 0.9 m telescope. To sample a population of C giants farther out in the spheroid than observed in previous surveys, we decided to aim for a limiting magnitude of $V = 18$ in our CCD survey. The canonical $R^{1/4}$ density law of scale length 2.7 kpc (de Vaucouleurs 1959 as adopted by Bahcall & Soneira 1984) suggests that at $V = 18$ we have nearly "run out of galaxy" for typical Population II giants of $M_V \leq 0$: stellar volume densities are less than 0.2% of those in the solar neighborhood, and a factor of 120 below densities sampled by shallower surveys mentioned above. This, together with the low surface density of C stars found to date, means that wide sky coverage is at least as important as depth. Also, a deeper survey begins to miss brighter C stars where saturation limits

TABLE 1

IMAGING SURVEY RUNS

Start Date	Telescope	Instrument	Observations	Nights Observed
1989 Jun 26	No. 1 0.9 m	Tek2048	Tests	2.5
1989 Nov 6	No. 1 0.9 m	Tek2048	Scans	3.0
1990 Jan 10	No. 1 0.9 m	Tek2048	Scans	4.0
1990 Apr 2	No. 1 0.9 m	Tek1/Tek2 with FRED	Snaps	3.0
1990 Dec 7	No. 1 0.9 m	Tek1024 with FRED	Snaps	3.0
1991 Feb 21	No. 1 0.9 m	Tek1024 with FRED	Snaps	2.5
Total	...	...	...	18.0

photometric accuracy. Last, for the large effective pixel sizes needed to cover a large area on the celestial sphere, sample contamination by galaxies and quasars becomes a concern, since at crude spatial resolution these may be indistinguishable from stars.

We aimed for maximum photometric errors of ≈0.1 mag, which should allow both good color separation of C stars and reasonable integration times. Seeking maximum sky coverage, at the outset of the survey we chose the largest CCD chip available at Kitt Peak, the Tek2048. This we used at the f/7.5 focus of the old No. 1 0.9 m telescope to achieve a field of view ≈26′ on a side. Binning 3 × 3 resulted in 2″.3 pixels, reducing the data volume and increasing the signal-to-noise ratio. Photometry using point response fitting is rendered impossible by the undersampled stellar image profiles, but since high Galactic latitude fields are uncrowded to these depths, aperture photometry yields quite accurate results.

Even when using on-chip binning to diminish the data volume, observing efficiency is reduced by time lost reading out the CCD after an exposure has finished. To minimize readout time, we employed the technique of drift scanning, which allows the CCD to be continuously read out during an integration as a stellar image is allowed to drift over the CCD. A major advantage of drift scanning is that every star on the final image passes down an entire column as the chip clocks. The CCD response function along the column direction is thus averaged, so that a one-dimensional flat field (in the row direction) is sufficient for reduction (see, for example, Caldwell, Keane, & Schechter 1991 or Schmidt, Schneider, & Gunn 1986). Since our red filters required long integration times, rather than redetermining new drift-scan parameters for each filter, we performed three separate scans of the same region in both 77 and 81, and combined them during reduction. The final effective exposure times for drift scans were approximately 160, 480, and 480 s for V, 77, and 81 filters, respectively. A single such frame corresponds to 26′ in right ascension. The largest scan images are 8 frames long, yielding a total of 3°.5 in right ascension, while the shortest are half that. Due to vignetting, all scan images are strips 23′ wide in declination.

The Tek2048 died unexpectedly in 1990 February during engineering tests in Tucson, so we were forced to reconsider our survey observing technique. Fortunately, we were offered the use of a 3 × focal reducer (FRED), designed by M. Shara of the Space Telescope Science Institute, that would allow us to use smaller chips to obtain nearly the same field. By the end of the imaging survey we had used three different Tek chips with FRED (see Table 2). Due to barrel distortion at the field edges and drift-scan software limitations, we could not drift-scan when using FRED. However, due to the improved cosmetics and quantum efficiency of other Tek chips over the Tek2048, snapshots with FRED were at least as efficient as drift scanning. The final effective exposure times for snapshots were approximately 60, 180, and 360 s for V, 77, and 81 filters, respectively.

Survey images were bias-subtracted, flat-fielded, and trimmed, and bad pixels were corrected, using standard IRAF procedures. Some straightforward but nonstandard techniques were necessarily applied in the reduction of drift-scan data. These are described in detail in Green (1992).

3. SKY COVERAGE AND SURVEY DEPTH

The final reduced image sizes on the sky for each chip are listed in Table 2. The number of frames usable for the survey (i.e., full exposures available on all three filters) and the total sky covered with each chip are also listed. The final total sky coverage of the CCD imaging survey is 55 deg^2. The total area useful for photometry is slightly less, since regions near bad columns and edges were not considered in the data analysis. This brings the total effective coverage to 52 deg^2, an area about equivalent to two of the Schmidt plates used in photographic objective-prism surveys.

We attempted, within the observational constraints, to survey regions in the Milky Way that would provide the strongest structural and dynamical constraints. Figure 1 shows the location of regions imaged in our survey. These include areas near the north Galactic pole (labeled NGP in the figure), and several major regions of lower Galactic latitude (also labeled). Radial velocities of a sufficiently large sample of distant stars at these Galactic positions would be well suited to determination of both the sample's rotation and the velocity ellipsoid of the Galactic halo.

To find objects and perform photometry, we used the IRAF tasks DAOFIND and PHOT. The IRAF V magnitude error, averaged from more than 2000 stars on a variety of images. is $\lesssim 0.04$ at $V = 18.0$. For computing errors in colors, such as $77 - 81$, we add the 77 and 81 magnitude errors in quadrature. When combining magnitudes in two filters to create a "pseudo-I" magnitude $(77 + 81)$, we take the magnitude error to be $\Delta m(77 + 81) = 0.5[\Delta m(77)^2 + \Delta m(81)^2]^{1/2}$.

Since only instrumental colors are required for candidate selection, absolute photometry is only needed to estimate the survey depth. For this use, and for possible future uses of the survey data, we tried to observe a reasonably large number of standard stars every night at several different air masses to enable the calculation of reliable magnitudes. Since V is the only well-characterized band in our survey, depth in this band is of primary interest for comparison purposes. To avoid contamination by cosmic rays, stars detected in V are not included in the survey if they are not also detected in the 77 passband. We first briefly characterize the survey depth in V, and then examine the corresponding depths when only objects also found in the 77 band images are included.

TABLE 2

SURVEY COVERAGE BY CCD

	CCD			
PROPERTY	Tek2048	Tek1/Tek2	Tek1024	TOTAL
Use	Drift scan	With FRED	With FRED	...
Frame size	22′.5 × 26′.1	19′.6 × 19′.6	≈24′ circle	...
Effective deg^2 frame^{-1}	0.146	0.102	0.145	...
Number of frames	≈123	72	188	...
Coverage (deg^2)	17.7	7.3	27.3	52.3

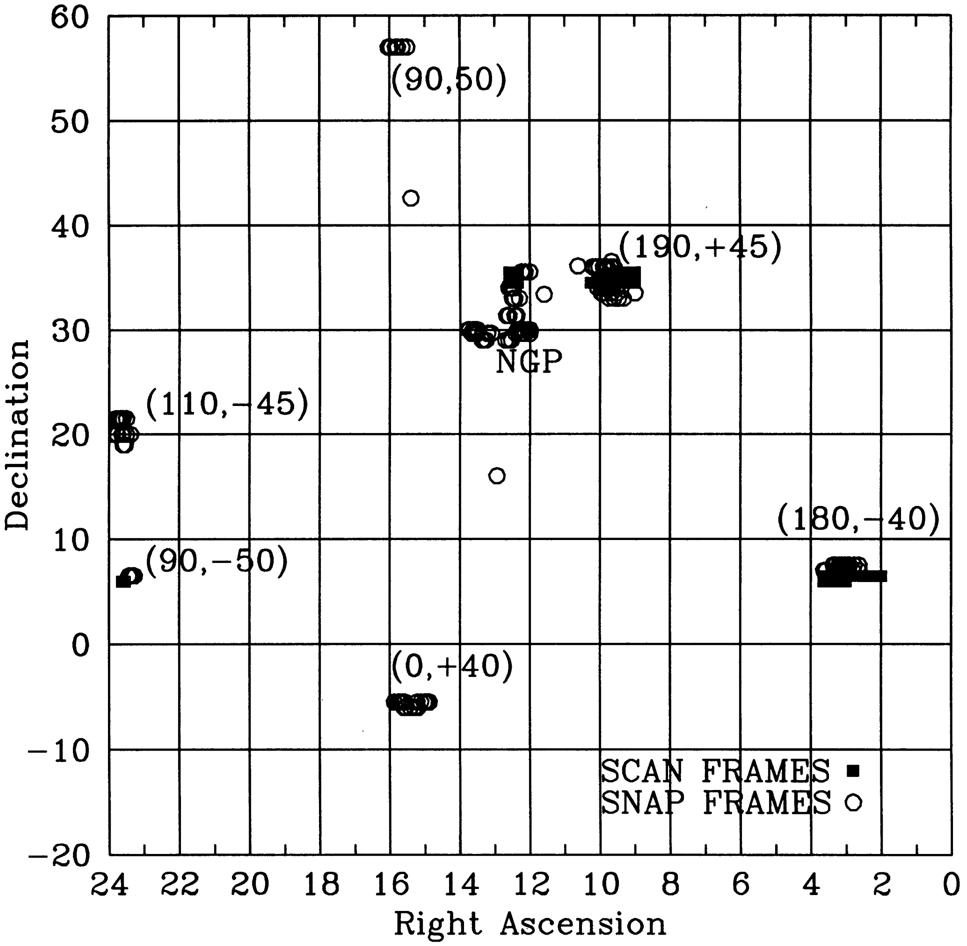

FIG. 1.—Sky coverage of the CCD imaging survey. Drift scans are labeled with filled squares, and snapshots are shown with open circles. Points are plotted larger than true image size for clarity. Approximate Galactic longitude and latitude are marked in pairs (*l*, *b*).

Since V is the only calibrated filter in the survey, individual colors for survey stars are not easily available. Information on the average first-order extinction and color terms are provided by KPNO for the Tek CCDs (Massey 1990), so reasonable calibration of instrumental V magnitudes is possible. We used the average KPNO first-order extinction term in the V band of 0.16. The Tek1 and Tek2 (and the very similar Tek1024) have average color coefficients C_1 of 0.07 ± 0.01. The color coefficient is particularly small (and uncertain) for the Tek2048 (-0.03 ± 0.02). The maximum color range for high Galactic latitude fields for $V < 19$ is $0.2 \lesssim (B-V) \lesssim 2$ (see references in Bahcall & Soneira 1984, hereafter B&S). There are very few stars redder than $(B-V) = 1.5$, but even assuming that *all* faint stars have $(B-V) = 2$, the largest possible error in our V depth estimate due to a color term is 0.14 mag. Color terms of this size are unimportant in selection of candidates, and negligible in estimating depth. The zero-point offsets derived for each night using the average KPNO extinction term and no color term were used to derive instrumental magnitudes. During the snapshot survey, we imaged several fields that had already been drift-scanned to compare photometry. For several hundred stars, the mean difference $\overline{V_{\rm scan} - V_{\rm snap}} = 0.1 \pm 0.1$ mag.

As a first check on depth and completeness in V, we calibrated the V magnitudes for detected objects in all fields and tabulated differential histograms (numbers of stars as a function of magnitude, in bins of 1 mag). To eliminate spurious objects without introducing color biases, we use three test images of SA 57 in the V band, observed in a manner identical to other (snapshot) program fields. In SA 57, Sandage (1987) has photoelectrically calibrated a large number of standards in B, V, and R. The standard calibration technique that we have applied to all survey fields yields by comparison to Sandage's magnitudes a mean difference $\overline{V - V_{\rm Sandage}} = 0.04 \pm 0.03$ mag in the SA 57 field. Although cosmic rays, bad pixels, and other spurious events have been eliminated through matching, the sample is still contaminated by galaxies and quasars. The surface density of quasars for $V < 18$ is near 1 deg^{-2} (Braccesi 1983), so their contribution is of little consequence. Galaxies may contribute at most ≈ 15 deg^{-2} (Tyson & Jarvis 1979), but those of large angular extent will be rejected by the photometry algorithm. A histogram of matched objects in V with photometric errors less than 0.10 mag in each frame shows a mode between $V = 18$ and $V = 19$. Past $V = 19$, the survey becomes seriously incomplete. In summary, snapshots in V are probably complete to $V = 18.5$ mag, and magnitude calibration appears to be quite reliable.

We can estimate the overall three-filter survey depth by examining the surface density as a function of magnitude *after* positional matching with objects in all filters. In this way, no spurious objects are considered, and limiting effects in all filters are automatically included for all objects. As expected in any

1994ApJ...434..319G

multicolor survey, the effective depth of the survey is a function of color. To compare matched surface densities as a function of standard broad-band color, we observed several survey fields in the I band, By fitting I versus (77 + 81) magnitudes for these fields, we can offer a conservative estimate of the survey depth overall. We suggest that the snapshot survey is complete to $V = 18.5$ for $V - I > 1$ and to $V = 18.0$ for all stars. Similar considerations for drift-scan fields suggest completeness to $V = 18$ and $V = 17.5$, respectively, for these groups.

4. SELECTION OF CANDIDATES

Each star included as a C star candidate was required to have a computed photometric error less than 0.1 mag in both V and 77. No error upper bound was required of the 81 photometry. This technique weeds out spurious objects but avoids missing very faint C stars even fainter in 81 due to their cyanogen bands. If there is no detection at all in 81, a magnitude limit is substituted, and color errors are set to zero as a flag.

In the selection of C star candidates from color-color (CC) diagrams, the most important criterion is the offset of candidates from the stellar sequence compared with the width of the sequence itself. Since FHLC stars tend to be of average temperature color ($\approx$G5–K5), we paid most attention to the CN color (77 − 81). Stars received a high color rank if the offset from the mean CN color (77 − 81) at the same temperature color [$V - (77 + 81)$] as the candidate is large compared to the CN color dispersion three. A red (cool) temperature color was an additional separator and also weighed positively in the color ranking of candidates. In sparse fields, where the number of stars on the CC diagram was small ($\lesssim 50$), we would generally combine photometry lists of several fields (from the same part of the sky and the same night) to get a better idea of the width of the main stellar locus.

The intermediate-band filters we employed have been thoroughly tested and are excellent for separating late-type (cool, red) C stars from stars of other spectral type. At the start of this survey it was not known how well such filters would pick out the warmer C stars of the spheroid. The FHLC stars have not been well studied to date, either spectroscopically or photometrically. For this reason, we decided to observe fields with known FHLC stars to test the retrieval efficiency of the filter system. Some of these images were taken when haze or cirrus prevented photometry of the fainter program stars. However, one advantage of two-color selection is that absolute photometry is not essential. All that is required is that the main locus of objects be well defined. Thus, conditions may be photometrically poor (or variable) provided that, integrated over the time of the exposure, obscuration is constant over the field of view. From a total of 16 warm C stars culled from Yamashita (1975), known FHLC stars, and the three brighter CH stars in Draco, 11 are unambiguously retrieved (color rank higher than 3). Two representative two-color diagrams are presented in Figure 2 for the Draco dwarf spheroidal and the $V = 18$ FHLC star 1509−0902. The previously known C stars we observed constitute in no way a large, consistently selected, or representative sample, but under duress we might use a number like 70% to represent the retrieval fraction for warm C stars with this filter system. This number improves if N-type C stars are included.

After assigning a color rank to a candidate, we then examine the quality of the image on the CCD frame, where we check for cosmic rays, cosmetic defects, and morphology of the candidate itself. Obviously fuzzy or unusually oblong objects are ruled out as galaxies or double stars. Objects near very bright stars are also eliminated. If a candidate passes muster to this point, we examine the Palomar Sky Survey images, comparing blue and red plates, checking for morphology and contamination by nearby objects. Occasionally, a double star or galaxy could be recognized on the POSS but not on the CCD image. With candidates ranked from 1 to 5 based on both color and image quality, a total score from 2 to 10 was thus concocted, with 10 as the most-favored-candidate ranking.

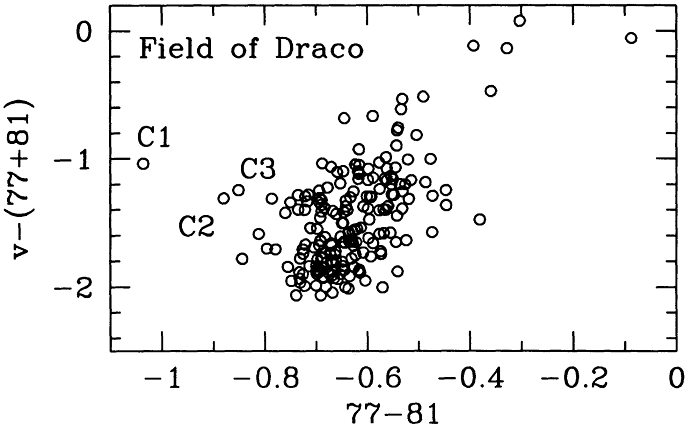

FIG. 2*a*

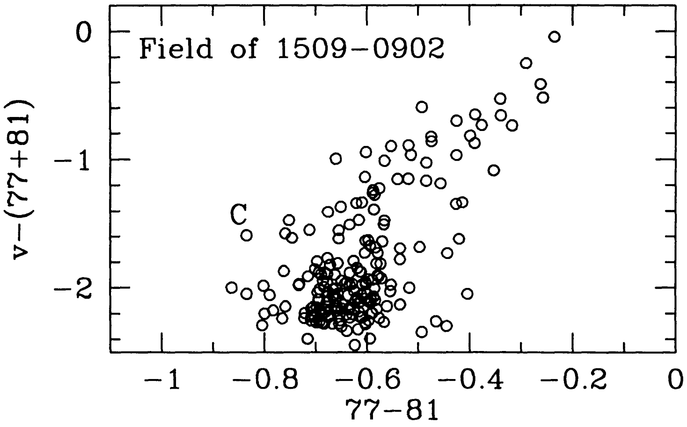

FIG. 2*b*

FIG. 2.—(*a*) Our standard three-filter (instrumental) color selection retrieves three of the four previously known CH stars in the Draco dwarf spheroidal. The fourth is fainter than the survey magnitude limit. (*b*) The $V = 18$ FHLC star 1509−0902, serendipitously discovered by Margon et al. (1984), is also retrieved by the same technique. All these stars have the early-type colors and spectra typical of other FHLC stars.

From color-color plots for all of our CCD survey program fields, we compiled a long, prioritized candidate list. To derive sky coordinates, we used the *Hubble Space Telescope* Guide Star Catalog (GSC; Lasker et al. 1990) as an astrometric reference frame to use with our CCD images. The resulting coordinates are accurate to better than 1″.

5. SPECTROSCOPY OF CANDIDATES

We obtained follow-up optical spectroscopy for a total of 94 C star candidates at the KPNO 2.1 m telescope. To yield relatively high signal-to-noise ratios even for faint candidates and to include the spectral features most relevant to verification of spectral type, we obtained spectra of C star candidates using low-resolution gratings. At the Kitt Peak 2.1 m telescope, we used the Gold Camera CCD spectrograph. A reflection grating with 158 lines $\rm mm^{-1}$ provided coverage of 3700 Å centered at 6750 Å. Together with a (projected) slit width of $1''.5$, this yields a spectral resolution of about 12 Å FWHM. Several candidates were also observed at Lick. The Cassegrain spectrograph of the 3 m Shane Telescope and 600 line $\rm mm^{-1}$ grism, together with a slit width of $1''$, provided 9 Å resolution. Wavelength coverage on the Lick CCD, with its usable pixel dimensions of 290×800, was $\approx \lambda\lambda 4100$–6980.

All spectra were reduced with standard IRAF techniques, detailed in Green (1992). Our main interest during these observations was verification of spectral type: the low-resolution allows neither a determination of meaningful radial velocities nor accurate abundance analyses. We continued to observe brighter candidates under light-to-moderate cirrus, which, together with the narrow slit width, precludes extraction of absolute photometric data.

What is the nature of the candidates that turned out *not* to be C stars? The spectra of these interlopers appeared to be fairly uniform, with MgH, Mg *b*, and Na D in absorption. If no hint of carbon or cyanogen bands was seen, we usually would move to the next star without bothering to acquire a higher signal-to-noise ratio. The spectral classification of the typical interloper is probably an early to mid-K dwarf, although a few extreme spectra are best estimated closer to M0 on the late side, or G0 on the early side. Two facts reinforce the interpretation that interlopers were probably stars with large nonsystematic photometric errors: they lack any significant CN bands, and to these depths it is just such spectral types that dominate star counts.

Some interlopers proved more interesting. We found one $V = 17.2$ emission-line galaxy at a redshift of 0.061, with $\alpha_{1950} = 09^{\rm h}01^{\rm m}37^{\rm s}.1$, $\delta = +34^\circ51'22''.0$. The absence of [O III] $\lambda 5007$ implies that it is an H II region galaxy with strong star formation activity, rather than a galaxy with an active nucleus. At $V = 17.2$, 0901+3451 has $M_V = -20.7$.

To explore other regions of the CC diagram, we obtained spectra of several outliers not likely to be either typical main-sequence or carbon stars. One very blue stellar object was chosen from Figure 3*a* as a possible quasar or white dwarf. The object, at $\alpha_{1950} = 15^{\rm h}42^{\rm m}31^{\rm s}.4$, $\delta = -05^\circ28'56''.2$, is indeed a $V = 16.7$ DA white dwarf. Its spectrum in Figure 3*b* is extremely blue, with broad Balmer lines of hydrogen. Since typically $M_V \approx 11.5$ for these objects, 1542−0525 is ~100 pc from the Sun.

We also spectroscopically observed two stars with cool temperature colors and red 77 − 81, suggesting type M; both indeed proved to be M stars. For example, the CC diagram of a $V = 16.9$ star at $\alpha_{1950} = 02^{\rm h}39^{\rm m}01^{\rm s}.24$, $\delta = +07^\circ36'47''.7$, is shown in Figure 4*a*. Strong TiO, Mg *b*, and CaH bands, with Balmer line emission in its spectrum (Fig. 4*b*) imply that 0239+0736 is probably a dM6e star.

Of 96 C star candidates observed, only 0311+0733 ($\alpha_{1950} = 03^{\rm h}11^{\rm m}44^{\rm s}.08$, $\delta = +07^\circ33'38''.0$), ranked 9 out of a possible 10, was confirmed to be a C star. The color-color diagram for the field is shown in Figure 5*a*. The spectrum (Fig. 5*b*) of this newly recognized $V = 16.9$ C star reveals the deep CN bands responsible for its blue 77 − 81 color on our CC diagram. This and other important absorption features are labeled in the figure, along with the location of the 77 and 81 filter bandpasses. Using the techniques outlined in Green & Margon (1990), we type this star as C1, 2, showing that it is early, similar to FHLC stars discovered by other means. Figure 6 provides a finding chart for the star. A proper-motion upper limit of $0''.07 \ \rm yr^{-1}$ is given by Green et al. (1992).

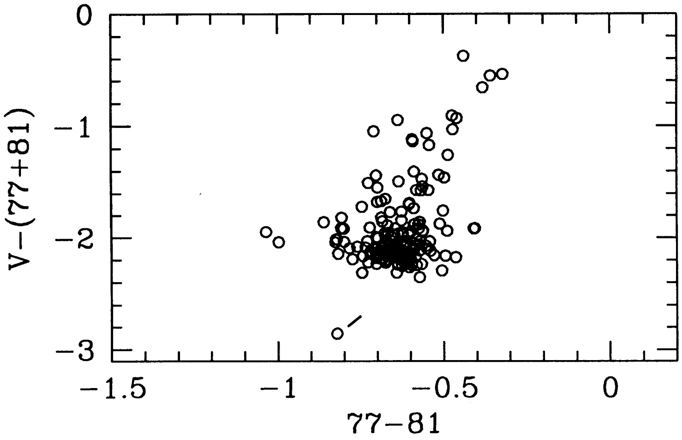

FIG. 3*a*

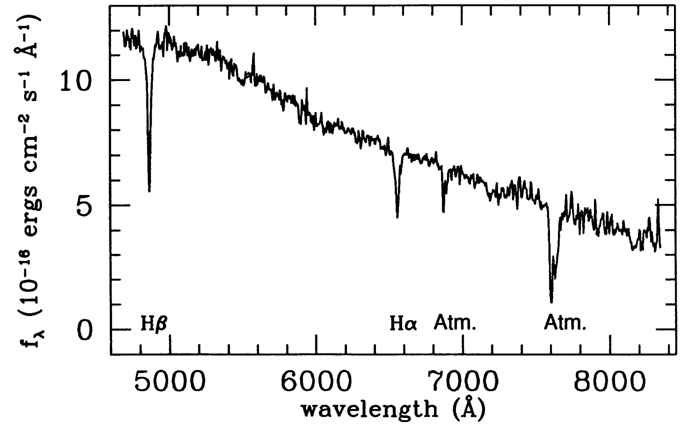

FIG. 3*b*

FIG. 3.—(*a*) We observed the object marked in the lower part of the top diagram to explore outliers in other regions of the CC diagram. The spectrum of this extremely blue object, 1542−0525, is shown in (*b*). Strong, broad Balmer absorption with no evidence of helium reveals this to be a DA white dwarf.

We estimate above that our completeness for known FHLC stars if $\approx 70\%$. However, even if it were feasible to derive meaningful statistics from one object, our survey's selection efficiency is more difficult to estimate. Ours is the first wide-area survey of Galactic high-latitude stars using these filters, so we refined the selection as the survey progressed. Candidate ranking involves many different parameters (temperature and CN color, image quality, morphology, and brightness), and it is difficult to quantify a selection efficiency. *A posteriori*, we can attempt to define our *achievable* selection efficiency. In practice we observed 96 C star candidates between ranks 6 and 10, including 35 stars fainter than $V = 18$. By choosing only candidates of rank 9 or higher within the completeness limit of the survey ($V = 18$), we could attain a selection efficiency of 1/16 (7%).

The Case survey, by contrast, boasts a selection efficiency of 100%. With the work of Mould et al. (1985), Green & Margon

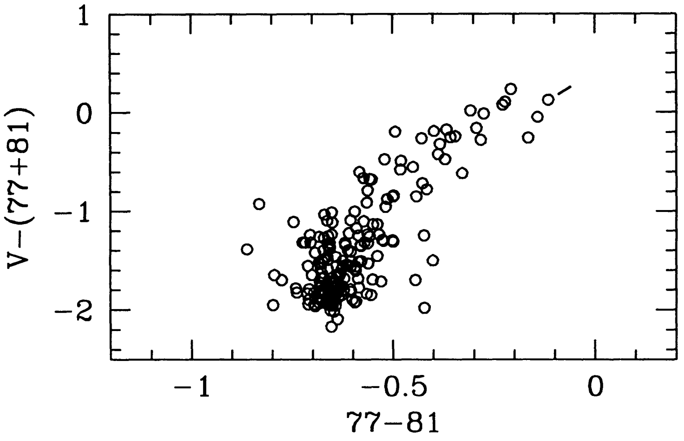

FIG. 4*a*

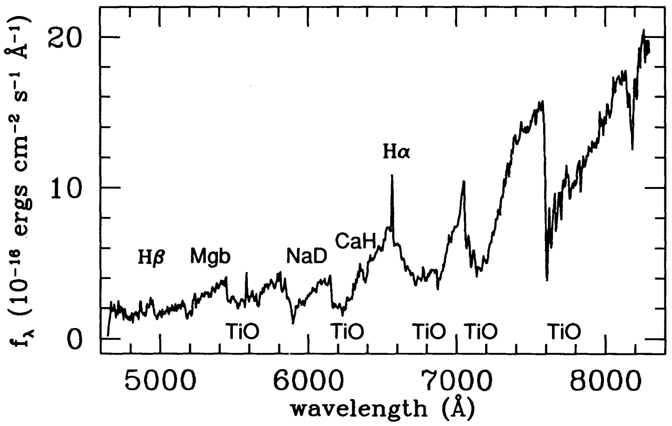

FIG. 4*b*

FIG. 4.—(*a*) We observed the object marked at the upper right of the top diagram to explore the selection efficiency of M stars from the CC diagram. The spectrum of this object, 0239 + 0736, is shown in (*b*). The strong TiO, Mg *b*, and CaH absorption, together with Balmer line emission, verifies that this is a late M dwarf.

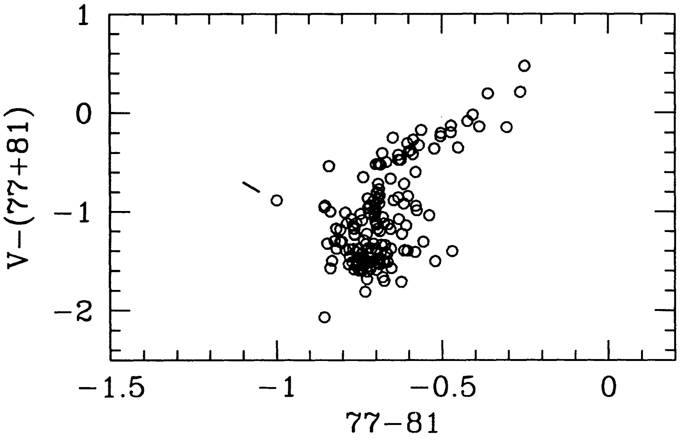

FIG. 5*a*

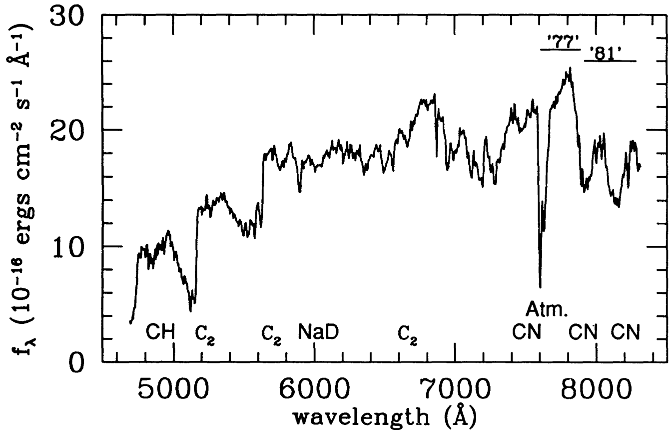

FIG. 5*b*

FIG. 5.—(*a*) Color-color diagram for the newly discovered FHLC star 0311 + 0733. (*b*) The discovery spectrum of this carbon star 0311 + 0733 shows strong CN bands in the near-infrared. Important absorption features are labeled, along with the location of the 77 and 81 filter bandpasses. Strong sodium (Na D λλ5890, 5896) and relatively weak Swan bands of C_2 lead to a Keenan-Morgan classification of C1, 2.

(1990, 1994), and B91, all stars classified as "C" or the less-certain designation "C:" have been spectroscopically observed. We compile in Table 3 one unpublished negative result from recent spectroscopy of our own, along with previously published results compiled from the literature. *All* the candidates classified as "C" indeed have turned out to be C stars upon spectroscopic confirmation, and only 1 of 14 classified as "C:" are carbon stars. For the UM survey, B91 estimate a minimum 50% success rate from the UM survey. It is thus clear that these objective-prism surveys are an excellent technique, as long as completeness to deeper than $V \approx 17$ is not required.

In reconsidering the efficiency of our CCD technique in the halo, we note that the 77/81 filter combination works well to separate M stars from C stars of similar effective temperature because of a complementary effect: the "off-band" (continuum) of one type is the "on-band" (absorption band) of the other. TiO bands, which separate the late K and M stars in 77 − 81 from even those FHLC stars lacking strong CN, are weak or absent earlier than K5. For color separation from most field stars, this is double jeopardy: most FHLC stars known to date have temperature colors similar to the majority of field stars, and are at best offset in 77 − 81 only by virtue of strong CN, without the additional offset provided by TiO in cooler field stars. By contrast, the cool Population I N-type C stars have temperature colors similar to those of late M stars, and strong CN as well. M stars of similarly cool temperature color are offset to the far side of the diagram in 77 − 81. This enables a high selection efficiency when these filters are used to find such late-type luminous AGB stars either in the Milky Way or in other Local Group galaxies (e.g., Hudon et al. 1989; Cook et al. 1986).

To retrieve warm FHLC stars efficiently via CCD photometry, an additional filter set might create better color offsets in two axes. Some possible filter alternatives are suggested in Green (1992). However, wide-coverage CCD photometry may not be the best road to finding large numbers of FHLC stars. An alternative technique is to apply an objective-prism or grism technique to CCDs, as has been done in QSO searches (e.g., Schmidt et al. 1986).

6. SURFACE DENSITY OF FHLC STARS

The estimates of the depth and completeness of our CCD survey presented in § 3 are not needed if the only goal of the

1994ApJ...434..319G

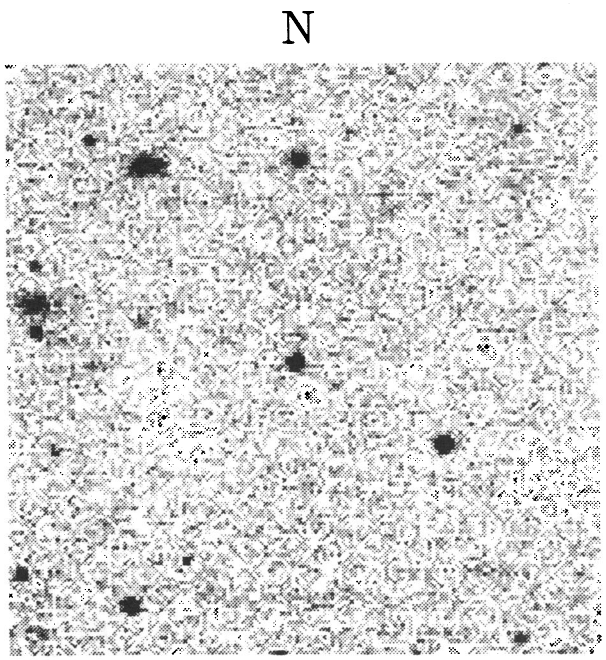

FIG. 6.—A 5′ field centered on the FHLC star 0311+0733, taken on night 5 of the 1990 December 0.9 m imaging run. North is up, and east is to the left.

survey is to find distant kinematic tracers. However, well-defined depth and completeness are essential for constraining models of galactic structure. The surface density of carbon stars as a function of depth may be transformed through color-magnitude relations into a volume density as a function of Galactocentric radius, and the latter may hold valuable clues to the structure and evolution of the Galaxy. Is a model of rapid radial collapse and co-temporal enrichment of our Galactic halo (Eggen, Lynden-Bell, & Sandage 1962) reflected in a radial change in C star number density caused by a metallicity gradient? Does the outer Galactic halo follow a de Vaucouleurs (1959) surface density law like elliptical galaxies? By contrasting observed C star surface densities in surveys of different depth, we might hope to address these questions.

Unfortunately, it is impossible to derive a meaningful surface density from our one object. The usual ploy of determining the uncertainties by assuming Poisson statistics is not valid. Regener (1951) describes a technique applied to small samples of cosmic-ray counts whereby the Poisson fiducial limits corresponding to the usual probability $p = 0.8413$ are given. The result is that lower and upper fiducials to a single count are 0.17 and 3.30, respectively. Naturally, carbon stars do not come in fractional units, but we convert these limits to an uncertainty in the surface density we derive from one star in 52 deg^2. Our result, for comparison purposes at best, is that, to a depth of $V = 18$, the surface density of carbon stars at high Galactic latitudes is $0.19^{+0.044}_{-0.016}$ deg^{-2}

To estimate the effective depth *for C stars* of the Case and UM objective prism surveys, we transform their published C star magnitudes (R and K bands, respectively) to the V band assuming $\overline{V-R} = 0.9$ and $\overline{V-K} = 2.8$. These mean colors are for Population II C stars from Mendoza & Johnson (1965), obtained by averaging colors of 14 stars there with spectral types CH, R4 and earlier, and C4 and earlier. Histograms of the number of C stars as a function of V magnitude reveal that the southern UM survey (Lewis et al. 1979) is complete to about $V = 16$, while the Case survey (Sanduleak & Pesch 1988) is probably complete for C stars to $V = 16.5$.

We now must estimate the surface density of FHLC stars in these photographic surveys. The UM survey resulted in 14 C stars in an area greater than 400 deg^2. However, since B91 did not report what surface area in the UM survey was searched for C stars, we cannot independently estimate the surface density of C stars in the southern Galactic hemisphere. The CLS survey, in an area of roughly 1000 deg^2, found about 20 verified C stars, crudely implying a surface density of C stars of 0.020 ± 0.005 deg^{-2}.

A de Vaucouleurs $R^{1/4}$ model for the spheroid (Bahcall & Soneira 1984) suggests that at high Galactic latitudes when the survey depth increases (as between the Case survey and our own) from 16.5 to 18, we should expect a factor of 2.8 increase

TABLE 3

RESULTS OF FOLLOW-UP SPECTROSCOPY OF CLS CARBON STAR CANDIDATES

CLS Number	CLS Type	Carbon Star?	Notes and References	CLS Number	CLS Type	Carbon Star?	Notes and References
1.........	C:	N	1, 2	54.........	C	Y	3
3.........	C:	N	1, 2	57.........	C	Y	3
9.........	C	Y	1, 2	67.........	C	Y	1, 2
12.........	C:	N	1, 2	75.........	C:	N	2
14.........	C	Y	1, 2	78.........	C:	N	2
20.........	C:	N	2	80.........	C	Y	1, 2
21.........	C:	N	2	85.........	C:	N	6
23.........	C	Y	2, 3	87.........	C	Y	1, 2
26.........	C	Y	1, 2	90.........	C	Y	1, 2
29.........	C	Y	3	94.........	C:	N	4
31.........	:	Y	2, 4, 5	95.........	C:	N	4
35.........	C:	N	1	96.........	C	Y	1, 2, 4, 5
38.........	C	Y	1, 2	98.........	C	Y	1, 2
43.........	C	Y	3	105.........	C	Y	2
45.........	C	Y	3	107.........	C:	N	6
48.........	C:	Y	1, 2	108.........	C:	N	4
50.........	C	Y	3, 4, 5	112.........	C	Y	2

NOTES AND REFERENCES (CLS numbers and types refer to the list of Sanduleak & Pesch 1988).— (1) Green & Margon 1990; (2) Bothun et al. 1991; (3) Mould et al. 1985; (4) Green & Margon 1994; (5) high proper motion dwarf; (6) this work.

1994ApJ...434..319G

in the surface density of *spheroid stars*. Extrapolating from the Case surface density to that expected in our deeper CCD survey implies a result of 0.056 ± 0.014 deg^{-2} to $V \approx 18$, which, given the large uncertainty, is entirely consistent with our result.

7. REVISED ESTIMATES OF HALO KINEMATICS AND STRUCTURE

Bothun et al. (1991) have used a large sample of FHLC stars for study of the kinematics of the halo. Their NGP sample included 20 stars from the CLS survey and 12 stars from the southern UM survey. Radial velocities and near-infrared colors were avilable for most of the sample. Here we derive photometric distances to all FHLC stars by comparing the apparent K magnitudes with the FHLC giant branch of Aaronson & Mould (1985), or (for $J-K < 0.65$) to the M92 giant branch of Cohen, Frogel, & Persson (1978). B91 used a similar method for distance calibration, but since their study, several FHLC stars have been recognized as dwarf carbon (dC) stars by their high proper motions. Without the benefit of proper-motion measurements, their data placed some dwarf C stars at distances several orders of magnitude too large. These include CLS 50, CLS 31, CLS 96 (LP 328-57) in the north, and C∗22 (LHS 1075) in the south. Although these four dCs are kinematically associated with the halo, because they are solar neighborhood stars and represent a different phase of stellar evolution we exclude them in the revised sample presented here.

The apparent magnitudes and proper motions of the remaining stars in the sample are such that if they have halo kinematics, they are almost certainly giants (Green et al. 1992).

Several other FHLC stars may be added to the sample. To the NGP sample we add CLS 54 and CLS 57, using *JHK* colors from S. Kleinmann (1990, private communication) and 1252+103, 1599−090 (data from Mould et al. 1985). To the SGP sample, we add KA-1 (Ratnatunga 1983). Relevant data for these additions are compiled in Table 4. In sum, we have excluded four dCs but added data for five other FHLC stars, resulting in a total sample of 33 FHLC stars. Since none of these show large proper motions, the probability that any halo carbon dwarfs remain in the sample is less than a few percent (Green et al. 1992). The probability that low proper motion *disk* dC's remain in the sample is unknown, but none of the FHLC sample show the *JHK* colors characteristic of halo dC's.

The ensemble properties of the revised NGP and SGP samples are summarized in Table 5. Errors in our mean velocities are 1 σ uncertainties in the mean, while errors in the velocity dispersion σ_v are taken to be $\sigma_v/[2(N-1)]^{1/2}$. We believe that the marginal (2.3 σ) discrepancies in velocity dispersions between the NGP and SGP samples quoted by B91 were the result of error underestimates. There are no significant differences in either velocity dispersion or mean *JHK* colors in our revised sample. A major conclusion of B91—that the velocity dispersion of their combined sample is intermediate between that predicted by the cylindrical velocity ellipsoid model of Ratnatunga & Freeman (1985) and that of the spherical model of Pier (1984)—is unchanged, since the velocity dispersion of our revised sample is similar at 100 ± 12 km s^{-1}.

TABLE 4

ADDITIONS TO THE FHLC SAMPLE

Name	K^a (mag)	$J-K$ (mag)	$H-K$ (mag)	Velocity^b (km s^{-1})	References
CLS 54	8.92	0.87	0.22	-186 ± 4	K/Mo
CLS 57	8.86	0.76	0.14	60 ± 4	K/Mo
1252+103	11.28	0.75	0.17	45 ± 1	Mo/Mo
1509−090	14.47	0.86	0.25	75 ± 40	Ma/Mo
KA-1	...	0.60	...	170 ± 20	R/R

[a] Representative published magnitude errors are $\lesssim 0.3$ mag.

[b] Heliocentric radial velocity.

[c] References for photometry/velocity from K = Kleinmann 1990 (private communication); Ma = Margon et al. 1984; Mo = Mould et al. 1985; R = Ratnatunga 1983.

TABLE 5

PROPERTIES OF A REVISED SAMPLE OF FHLC STARS

Property	NGP	SGP	All
N^a	21/12	13/12	34/34
$\bar{v}_{\rm helio}$ (km s^{-1})	-32 ± 22	-59 ± 22	-42 ± 17
σ_v (km s^{-1})	103 ± 16	96 ± 20	100 ± 12
$\bar{d}$ (kpc)	19 ± 14	28 ± 14	22 ± 14
$\bar{b}$ (deg)	61 ± 15	-60 ± 7	16 ± 60
$\overline{J-K}$ (mag)	0.75 ± 0.07	0.94 ± 0.07	0.81 ± 0.05

[a] Sample size for $\bar{v}_{\rm helio}$ and σ_v/sample size for $\bar{d}$, $\bar{b}$, and $\overline{J-K}$.

In Figure 7 we present a histogram of FHLC stars by distances, summed in 5 kpc bins. The same data from B91 is also shown for comparison. For several giants, slight differences between our and B91's distance calibrations result in differing bin assignments. The revised histogram suggests an apparent cutoff in the distribution at about 60 kpc, previously masked by the erroneous distances assigned to dC's. For carbon giants with $-2 < M_V < 0$, 60 kpc corresponds to $17 < V < 19$, for which the objective-prism surveys are incomplete. Extant C star data are still not sufficiently deep to determine whether the apparent cutoff is intrinsic to the halo.

To examine how the distribution of halo carbon giants might look to an observer in a distant galaxy, we compare the

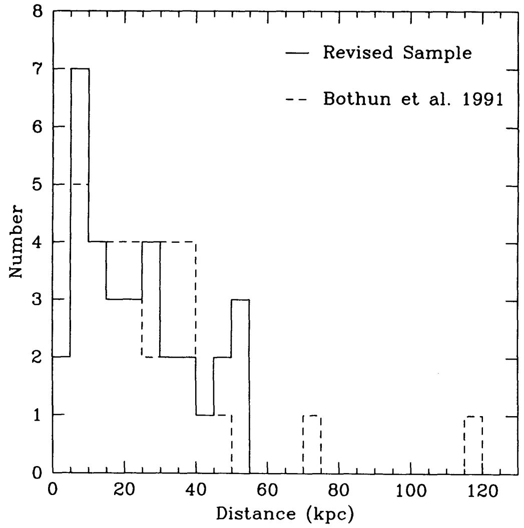

FIG. 7.—Histogram of FHLC stars as a function of distance. The dashed line is the sample of 33 stars studied by Bothun et al. (1991) assuming that all FHLC stars are distant giants. The solid line is our revised sample of 33 objects, wherein several additional FHLC stars are added but an identical number of high proper motion C dwarfs are removed. The two outliers in the sample of Bothun et al. are now recognized to be dwarfs (Green, Margon, & MacConnell 1991).

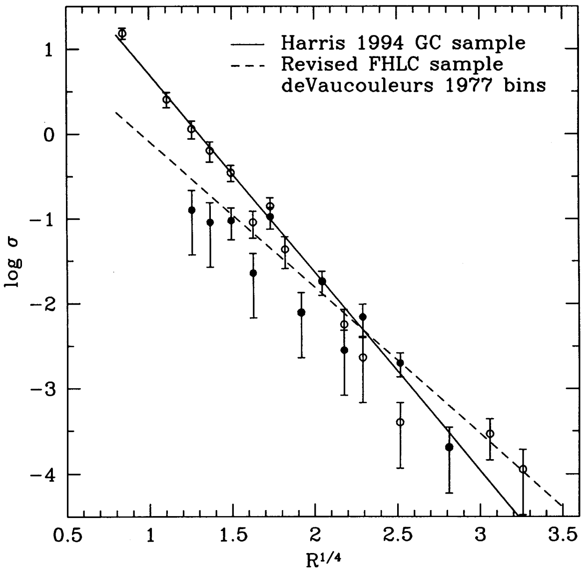

FIG. 8.—Surface density distribution of FHLC stars (*filled circles*) and Galactic globular clusters (*open circles*) projected on the *YZ* plane. De Vaucouleurs (1977) bins are used for both samples. The clusters follow an $R^{1/4}$ of $R_{\rm eff} = 4.2$ kpc (*solid line*) rather closely out to at least 30 kpc. A fit to the distribution of our revised sample of FHLC stars yields $R_{\rm eff} = 14$ kpc (*dashed line*), with greater scatter.

distribution of projected distances $R = (Y^2 + Z^2)^{1/2}$ for FHLC giants to Galactic globular clusters and to an $R^{1/4}$ law. To minimize selection bias, we use a sample restricted to objects having $X < R_0$ (assuming $R_0 = 9$ kpc), and we double the counts in each R bin (see de Vaucouleurs 1977 and Harris 1976). The (log) projected distribution, denoted as $\sigma(R)$ with units of objects kpc^{-2}, is plotted against $R^{1/4}$ in Figure 8 for both cluster and FHLC giants. We use updated globular cluster data kindly provided by W. E. Harris. For comparison purposes we use the same bins as Harris (1976), with extensions out to 125 kpc to include new cluster data. Weighted least-squares fits to the data yield effective radii of $R_{\rm eff} = 4.2^{+0.4}_{-0.3}$ kpc for clusters and $R_{\rm eff} = 14^{+19}_{-4}$ kpc for FHLC stars. Fits to the data excluding bins with $R < 5$ kpc, where the FHLC sample may be incomplete due to overexposure of objective-prism plates, are not substantially different. We caution that the effective radius we derive for C stars is uncertain, and we find the choice of bin size to have a strong effect on this value. This is largely due to poor statistics of the FHLC star sample with only 27 objects having $X < R_0$, compared with the cluster sample, with 99 such objects. A still larger sample of FHLC giants is clearly of interest. However, the larger $R_{\rm eff}$ for FHLC stars we derive here appears to be robust.

It thus seems likely that (1) the distribution of FHLC giants was determined by a dynamical history different from that of globular clusters or (2) the percentage of giants that are C stars increases as a function of Galactocentric radius, resulting in a larger effective radius. Trends noticed in Local Group galaxies (Aaronson et al. 1983) indicate that lower metallicity populations show a higher fraction of C giants. If a model of radial collapse and co-temporal enrichment of our Galactic halo is correct (e.g., Eggen et al. 1962), and if the metallicity trend of C/M giant ratios also applies *within* a population, then C stars would indeed be expected to constitute a higher fraction of giants in the outer halo. Unfortunately, it is difficult for us to test this model, or to extend the correlations to the low metallicity and high luminosity of the Galactic halo, because C/M giant ratios are much more difficult to estimate here than in external galaxies. In external galaxies, dwarfs are too faint even to be observed; they contribute only to the unresolved background light. In our Galaxy, the spectral features that distinguish M dwarfs from M giants are rather subtle at objective-prism resolutions. The same problem pertains to carbon stars, now that faint C star samples, long assumed to be virtually all giants, have been found to contain a substantial fraction of dwarfs (Green et al. 1991; Green et al. 1992).

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