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CARBON STAR LUMINOSITY INDICATORS

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ABSTRACT

Except for one odd dwarf, G77−61, it has long been assumed that carbon (C) stars are always giants, as carbon is thought to reach the photosphere only during dredge-up in asymptotic giant branch stars. However, we recently confirmed the existence of high proper motions in three other faint C stars (Green et al.). These three C stars are thus also inferred to be dwarfs. Not all dwarf C stars will have detectable proper motions, so other luminosity/distance indicators are needed. All four C dwarfs have similar *JHK* colors, suggesting IR colors as a possible luminosity indicator. We also find an unusually strong λ6191 bandhead of carbon in our spectra of the dwarf C stars known to date. We present results of a proper motion survey of known faint high-latitude C stars using plates spanning a 30 yr baseline that reveals at least one additional new dwarf C star and also confirms the utility of our proposed luminosity indicators. Kinematic simulations suggest that virtually all Population II C dwarfs will have detectable proper motions in a survey as sensitive as our own, and that to a limit of $V \approx 18$, at least 10% of faint high-latitude C stars are dwarfs. The local space density of dwarf C stars may thus substantially exceed that of luminous C stars.

Subject headings: stars: carbon — stars: fundamental parameters — stars: kinematics

1. INTRODUCTION

Carbon (C) stars, readily recognizable from their strong C_2 and CN absorption bands, have been detected as faint as $V \approx 18$ on objective prism plates of the Case Low-Dispersion Survey (CLS, Sanduleak & Pesch 1988), the University of Michigan Thin Prism Survey (MacAlpine & Lewis 1978), and in our own recent CCD survey (Green 1992). Samples of distant objects are invaluable for understanding the structure, dynamics, and evolution of the Galaxy. Faint high galactic latitude C (FHLC) stars, assumed to be giants at galactocentric distances as large as 50–100 kpc, have thus been sought as useful dynamic tracers of the outer halo.

Until lately, this scheme was troubled only by the puzzling existence of one dwarf C star: G77−61 has $V = 13.9$ and a parallax of 58 pc (Dearborn et al. 1986). Recently, we recognized three more dwarf carbon (dC) stars by their high proper motions (Green, Margon, & MacConnell 1991, hereafter Paper I). Estimated distances of 170, 100, and 400 pc for these stars suggest space densities sufficiently high that C stars may actually be dwarfs more often than giants. The assumption made by several groups (ourselves included) that faint C stars are distant, and thus useful halo dynamic probes, is obviously incorrect for some fraction of these objects. In an effort to determine what that fraction might be, we have undertaken a proper motion survey of known FHLC stars to search for more dwarfs. Since a dC star's velocity may not have a large component in the plane of the sky, luminosity indicators other than high proper motion are needed to separate dwarfs from giants. For these indicators, we look to the high proper motion dC's and compare their photometric and spectral properties to C stars showing no proper motions.

2. NEAR-INFRARED COLORS

Published *JHK* colors for FHLC stars (Mould et al. 1985; Bothun et al. 1991; Kleinmann 1990; Dearborn et al. 1986) are shown in Figure 1, along with a representative error bar. Also shown are published colors of several bright, warm (R or CH-type) stars (Dominy et al. 1986). Cooler Population I (N-type) C stars, redder in both colors, are generally off the plot, as are the two FHLC stars CLS 1523 (Mould et al. 1985) and C*07 (Bothun et al. 1991). A crude locus defined by the C dwarfs (labeled in the lower right of the diagram) is bounded by $(H - K) > 0.25$, $(J - H) < 0.7$. The *JHK* colors of dC's fall near the mean IR color-color relation for late-type field dwarfs (Frogel et al. 1978) and are well-separated from the mean field giant branch. As recognized by Dearborn et al. (1986) for the case of G77−61, both higher gravity and low metallicity may contribute to these distinctive colors by encouraging the association of hydrogen, thereby reducing the flux excess in the *H* band due to the H^- opacity minimum (Mould & Hyland 1976).

One or two other faint C stars fall suspiciously near the dwarf region of the IR color-color diagram, but we find them to have neither detectable proper motions (see § 4) nor the spectral signature discussed in § 3. A larger sample of dC's would certainly be useful, but a conservative conclusion is that high luminosities can no longer be assumed for field C stars with IR colors similar to those of late-type dwarfs, whether or not they are high proper motion objects.

Included in Figure 1 are the galactic bulge C stars of Azzopardi et al. (1991). Bulge C stars, like most FHLC stars, are early R or CH-type stars, but are considerably more metal-rich than halo population C stars. Although more (and more

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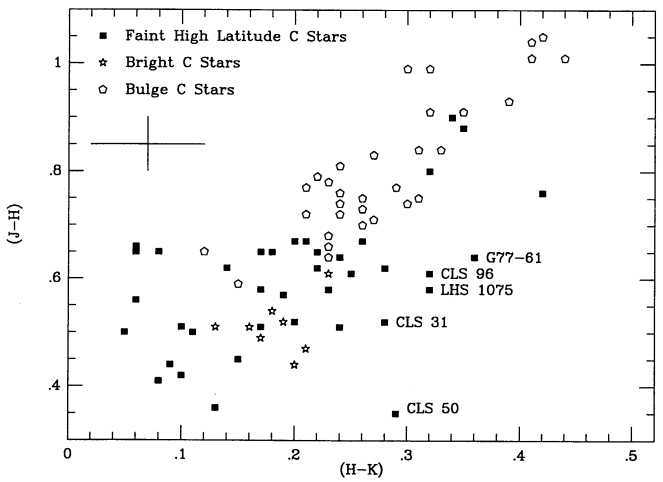

FIG. 1.—Published near-infrared colors of warm carbon stars. FHLC stars (*filled squares*) and bulge C stars (*open pentagons*) are shown along with a handful of bright ($V < 12$) C stars (*open stars*). Cooler Population I (N-type) C stars, redder in both colors, are generally off the plot. Stars with detected proper motions are labeled, and a representative error bar is provided.

consistent) *JHK* photometry of FHLC stars is necessary, the bulge C stars appear to fall along the same *JHK* branch as FHLC giants. The mean *JHK* relations for both these samples appear considerably steeper than those of asymptotic giant branch (AGB) C stars in the galactic disk or the Magellanic Clouds. The CN bands of bulge C stars are far stronger than those of the FHLC stars. CN abundance, which depends through nitrogen on metallicity, affects the *J* band most strongly (Cohen et al. 1981). For constant C_2 strength, metallicity variations will thus cause vertical shifts in the *JHK* diagram. In addition, carbon abundance and effective temperature both affect the strength of C_2 blanketing in the near-infrared. FHLC and bulge C stars appear to have similar effective temperatures. If we assume that most of the C stars discovered in the direction of the bulge are giants, then, since their mean *JHK* branch appears to be similar to the FHLC branch, it is possible that the lower metallicity of FHLC giants is compensated on this diagram by their weaker carbon band strengths. The difference in both C_2 and CN band strength is readily discerned by comparison of the low-resolution spectra of FHLC and bulge C stars (Green & Margon 1990; Azzopardi et al. 1991).

The spectra of dC stars, described in the next section, show that they may have stronger carbon bands than FHLC giants. However, it is not possible using the currently available data and models to ascertain whether the distinctive *JHK* colors of dCs are attributable to extremely low metallicity, to high gravity, to high C abundance, or to a combination of these factors. This question would be in part resolvable by direct comparison to a sample of *disk* dC's, if such objects are ever found.

3. LOW-RESOLUTION SPECTRA OF C DWARFS

Over several different observing runs, we obtained low (≈ 12 Å) resolution spectra of all four dC's at the KPNO 2.1 m using the GoldCam spectrograph and TI CCD. Our spectra of the dC stars CLS 96, G77−61, LHS 1075, and CLS 31 are shown in Figure 2. CLS 50, also included in this figure, is discussed in § 4 below. Pertinent features are marked on the plot of LHS 1075, which is expanded for clarity. These dC's exhibit an unusually strong, sharp bandhead of C_2 at λ6191 that is rare among C giants. Of ≈ 25 FHLC star spectra covering that wavelength region that we have obtained or seen in the literature, *only* the dwarf C stars have this feature. In Paper I, we speculated that this feature in dC's may be due to strong $\Delta v = -2$ bands of $^{13}C^{12}C$ and $^{13}C^{13}C$, which flatten the otherwise choppy region just blueward of the bandhead. Lloyd Evans (1992) has since shown that the dC LHS 1075 indeed has enhanced ^{13}C. Similar features have been noted in photographic spectra of the bright, ^{13}C-rich AGB (J-type) carbon stars (Gordon 1971). In three of the dC's (CLS 96, G77−61, and LHS 1075), the particular prominence of this feature suggests that the nearby bands of ^{13}CN at λ6206 and λ6260 may be anomalously weak. This spectral region is expanded in Figure 3, highlighting the difference between the feature's strength in a dC (CLS 96) and in three other high-latitude C stars of similar apparent magnitude, which show neither dwarflike *JHK* colors, nor large proper motions (§ 4). Figure 3 also highlights that carbon bands appear to be stronger in dC's than in FHLC giants, which may indicate either larger C abundances or gravity effects. The answer awaits higher resolution spectra and carbon star models that can better reproduce dC features.

We have synthesized pseudocolors from our low-resolution spectra of 30 C stars. Some of these spectra were obtained in nonphotometric conditions, so after performing standard bias subtraction, flat-fielding, and wavelength calibration, for higher accuracy we have normalized the spectra via division by a continuum fit. A second- to fourth-order cubic spline is fitted to the data (excluding the deep C_2 and CN bands) to estimate this continuum. We then synthesize magnitudes by summing the flux over the desired bandpass using a simple step transmission function. These bandpasses are drawn over the spectrum of LHS 1075, and their central wavelengths and bandwidths are listed in Table 1. For C stars, 77–81 estimates the strength of the CN band near λ8100 relative to the nearby continuum (Cook & Aaronson 1989). The pseudocolor 60–62 quantifies the depth of the λ6191 bandhead. Redder (larger) indices imply weaker CN for 77–81, and stronger λ6191 bandheads for 60–62. Both these pseudocolor indices are derived from narrow, proximal bandpasses, and so are fairly reddening and color-independent. Pseudocolors derived for the same stars observed on several different nights and at different airmasses suggest average color uncertainties of 0.03 mag.

We have derived pseudocolors from 12 of our spectra of C stars in the HD catalog, and 18 spectra of FHLC stars. The color-color diagram thus produced (Fig. 4) conveniently illustrates and quantifies the gross apparent spectral differences between dC's and FHLC giants. FHLC stars tend to have weak CN bands, while the brighter C stars may have both very strong CN and also a strong depression blueward of the λ6191

TABLE 1

BANDPASS DATA FOR SYNTHESIZED COLORS OF CARBON STARS

Label	Central Wavelength (Å)	Bandwidth (Å)
60.....	6050	260
62.....	6250	100
77.....	7752	284
81.....	8104	365

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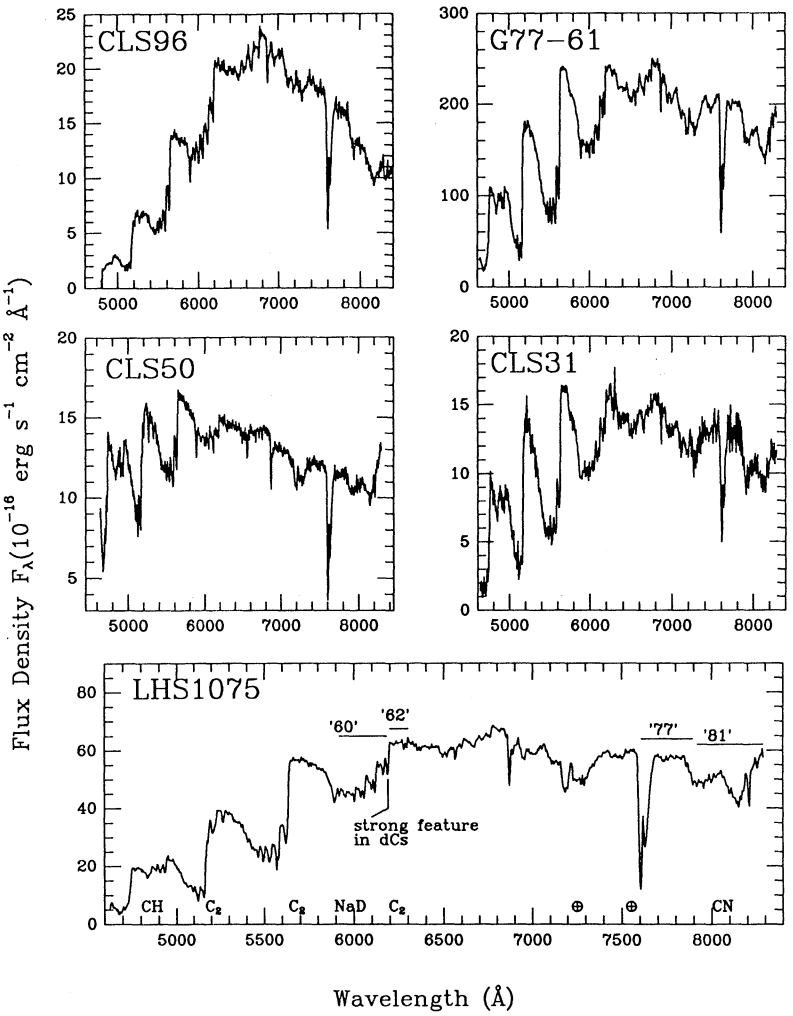

FIG. 2.—Low-resolution spectra of the known dwarf carbon (dC) stars CLS 96, G77 – 61, CLS 31, and LHS 1075. We also include CLS 50, for which we present here a newly recognized proper motion at the 4 σ level. These dC's exhibit an unusually strong, sharp bandhead of C_2 at λ6191 that is rare among C giants. This feature is marked on the plot of LHS 1075 (expanded for clarity) along with other major spectral features. The bandpasses used in deriving the CN and λ6191 indices, listed in Table 1, are also shown. Due to variable photometric conditions, fluxes should be viewed as approximate.

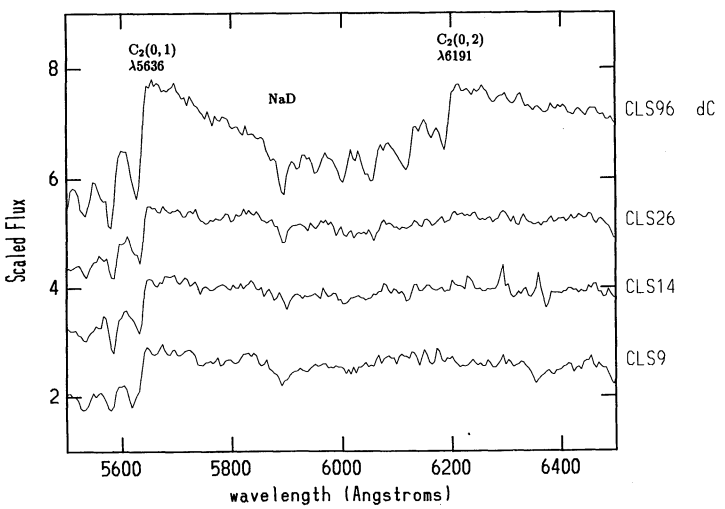

FIG. 3.—The λ6191 spectral region in four FHLC stars of similar apparent magnitude. CLS 96 is representative of the known C dwarfs, while the other spectra are typical of other FHLC stars, most of which show neither dwarflike *JHK* colors, nor large proper motions. Note that the λ6191 bandhead is stronger in the dC's than in FHLC giants.

break. The dC stars have strong λ6191 bandheads for their relatively weak CN indices.

4. ASTROMETRY

High proper motions in faint stars, along with the assumption that the star is bound to the galaxy, indicate low luminosities. To check for large motions in brighter C stars, with the kind help of Dennis Crabtree of the DAO we have searched for positional associations between Stephenson's (1989) C star catalog and existing proper motion catalogs archived at the National Space Science Data Center. No motions indicating subgiant or lesser luminosities were recovered for these brighter C stars. We should emphasize that, both for proper motion catalogs and for the sky surveys used to find C stars, sky coverage favors disk and galactic polar regions, and completeness is variable. However, very large proper motions and significant parallax as well would be expected for dwarf C stars at these bright apparent magnitudes.

To measure proper motions of FHLC stars, we used the digital data base assembled for the *Hubble Space Telescope* Guide Star Catalog (GSC) (Lasker et al. 1990), together with a digitization of the original Palomar Observatory Sky Survey

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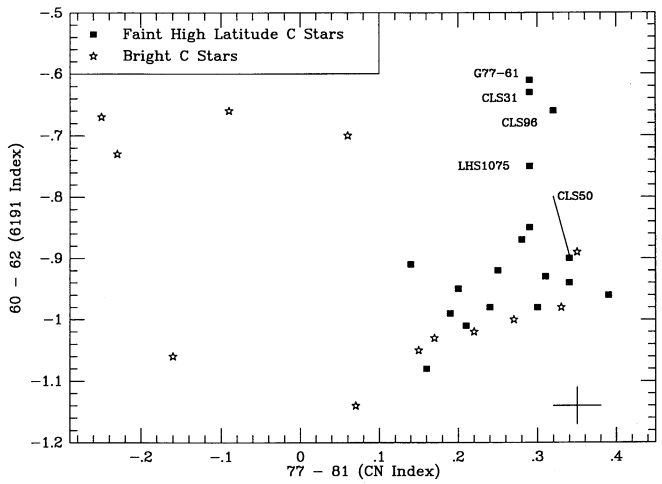

FIG. 4.—Pseudocolors of stars synthesized from our KPNO low-resolution spectra. Bandpasses are defined in Table 1 and marked on Fig. 1. The dC stars tend to have strong λ6191 bandheads for their relatively weak CN indices. Other FHLC stars tend to have weak CN bands (high CN index), while brighter C stars may have both very strong CN and also a strong depression blueward of the λ6191 break (high 6191 index). CLS 50 is a dC star that has only a slightly enhanced λ6191 break.

(POSS). Using this technique, our initial measurements of high proper motions in the C stars CLS 31, CLS 96, and LHS 1075 (Paper I) verified that they have main-sequence luminosities. We present here new proper motion measurements of 46 faint high-latitude C stars ($V \gtrsim 13$, $|b| > 40°$). A few additional known FHLC stars lie on POSS plates not yet scanned. Internal uncertainties in the GSC (Taff et al. 1990; Russell et al. 1990) are less than 0".5. In fields of $\approx 10'$ on a side at both epochs, we measured x, y positions of each program star along with 25 or more comparison stars. Using only these comparison stars, we derive a linear least-squares solution (with cross terms) to transform between the plates. In a few cases, the fit is repeated if necessary, removing stars with residuals greater than 3 σ from the solution. The rms residuals in the fits are 0.25 pixel for either x or y, corresponding to a 3 σ detection limit 1".8 for any position angle. From our shortest epoch-to-epoch baseline of 26 yr, we therefore conservatively adopt an overall proper motion detection limit of greater than 0".07 yr^{-1}. Table 2 lists the IAU format coordinates, names, and references for the FHLC stars with proper motion upper limits measured in our survey. From our sample of spectroscopically confirmed C stars, one additional new motion has been detected.

We have detected proper motion between epochs 1956.3 and 1983.1 for the C star CLS 50 based on 28 comparison stars. We measure $\Delta\alpha = -1".82 \pm 0.08$ and $\Delta\delta = -0".36 \pm 0.06$ The extreme JHK colors of CLS 50 (see Fig. 1) fall far from the region of C giants. CLS 50 is indeed a dwarf C star, the fifth known member of the class. CLS 50 was first identified by Sanduleak & Pesch (1988) as a faint ($R \approx 16$) C star. A spectrum, infrared colors, and a radial velocity have been published by Mould et al. (1985). We obtained a CCD spectrum of the object at the Kitt Peak 2.1 m telescope that covers a wider wavelength range at somewhat lower resolution (Fig. 2) and confirms that CLS 50 shows a slightly enhanced λ6191 band.

The proper motion of CLS 50 derived from the above measurements is $\mu = 0".069 \pm 0.003$ yr^{-1} at a position angle of 259° ± 2. From our measurements and published data, we can estimate its space velocity. As detailed in Paper I, we assume M_K identical to that of G77–61 for which a parallax has been measured (Dearborn et al. 1986). With an estimated distance of 260 pc, the velocity of CLS 50 in the galactic frame is thus (U, V, W) = (20, −60, −170), yielding $v_{space} = 190$, $v_{trans} = 90$, all in units of km s^{-1}.

One other of the stars in our newly measured sample is worthy of special mention. KA-2 is an FHLC star discovered by Ratnatunga (1985), who measured a V magnitude (15.6), a radial velocity (−70 km s^{-1}), and a proper motion (0".035 yr^{-1} at $\theta = 314°$). We measure a marginally significant proper motion of similar magnitude but quite different position angle; this object clearly needs more observations. Assuming an escape velocity from the galaxy of 400 km s^{-1}, KA-2 is constrained by the quoted proper motion to have absolute magnitude $M_V > +3.7$. KA-2 could thus be a subgiant CH (sgCH)

TABLE 2

FHLC STARS WITH PROPER MOTION UPPER LIMITS

Coordinate	Previous Names	References
0002+009.....	C*01	1
0039−266.....	SKB 2	4
0047−193.....	BD-19 132	4
0100−163.....	C*23	1
0102−059.....	C*07	1
0106−286.....	SKB 4	4
0108−003.....	C*03	1
0113−135.....	SKB 5	4
0138−192.....	BD-19 290	4
0207−022.....	C*30	1
0217+009.....	C*31	1
0222−136.....	C*15	1
0228−029.....	C*08	1
0229−033.....	C*09	1
0311+076.....	...	8
0911+337.....	CLS 9	2
0939+365.....	CLS 14	2
1015+357.....	CLS 23	2, 3
1025+294.....	CLS 26	2
1037+360.....	CLS 29	2, 3
1116−165.....	KA-2	9
1123+374.....	CLS 38	2
1135+334.....	CLS 43	2, 3
1149+375.....	CLS 45	2, 3
1231+364.....	CLS 54	2, 3
1239+314.....	CLS 57	2, 3
1241+026.....	UM 515	5
1252+103.....	PT 1252	2, 6
1313+356.....	CLS 67	2
1415+296.....	CLS 80	2
1500+334.....	CLS 85	2
1509−090.....	...	7
1525+292.....	CLS 87	2
1532+327.....	CLS 90	2
1538+346.....	CLS 94	2
1545+319.....	CLS 95	2
1605+294.....	CLS 98	2
1637+346.....	CLS 105	2
1642+338.....	CLS 107	2
1643+320.....	CLS 108	2
1706+333.....	CLS 112	2
2346+028.....	C*10	1
2354+003.....	C*02	1
2304−139.....	C*13	1

REFERENCES.—(1) Bothun et al. 1991; (2) Sanduleak & Pesch 1988; (3) Mould et al. 1985; (4) Slettebak et al. 1969; (5) MacAlpine & Williams 1981; (6) Phillips & Terlevich 1983; (7) Margon et al. 1984; (8) Green 1992; (9) Ratnatunga 1983.

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star, since several examples exist fainter than this limit (e.g., Luck & Bond 1991). Only by assuming an absolute magnitude greater than or consistent with the least luminous CH subgiants ($M_V = 4.8$, Šleivytė & Bartkevičius 1990) can we derive a reasonably probable orbit. The results (e.g., a rotation speed around the galaxy $V \lesssim +70$ km s^{-1}) imply that this star does not have halo kinematics. Since sgCH stars typically have thick or old disk kinematics, this could be a very faint example of that class, but sgCH stars are warmer, have C/O < 1, and so do not show the strong C_2 absorption seen in the spectrum of KA-2 (Ratnatunga 1985). We therefore conjecture that if KA-2's proper motion is real, it may be the first known disk dC star. More precise proper motions measurements, near-infrared observations, or a spectrum of the λ6191 region should help to resolve this question.

The results of our proper motion survey substantiate the validity of our proposed luminosity indicators discussed below: C stars with dwarflike *JHK* colors are likely to show evidence of high proper motions. Strong λ6191 bandheads may be a universal feature of dwarf C stars, or at the very least must serve as a warning that the assumption of giant luminosity is suspect.

5. KINEMATIC SIMULATIONS

In Paper I, we pointed out that it is unlikely that *all* known FHLC stars are dwarfs. The several faint *IRAS*-detected C stars at high galactic latitude are dust-enshrouded, mass-losing AGB stars. But how many of the remaining, warmer FHLC stars could be dwarfs with proper motions too small for us to detect? Now that we have measured proper motions for the entire available sample, it is worthwhile to estimate what number of these stars might have detectable proper motions *assuming* that they are all dwarfs.

Since the sky distribution of our sample is not uniform (concentrated mostly toward the galactic poles), we use only the actual stars in our proper motion sample, incorporating those with published photometry and radial velocity measurements (a total of 39 stars). The majority have published K or V magnitudes available (see references in Table 2). A photometric distance is derived for each star by assuming that it is a dwarf with absolute magnitude and colors identical to G77−61 (Dearborn et al. 1986). Most surveys that have yielded FHLC stars are complete to $V = 18$ or brighter, so that dC stars similar to G77−61 are detected only to about 400 pc. To these distances, our simple assumption of a Gaussian halo velocity *spheroid* with $\sigma = 100$ km s^{-1}, and mean ($\langle U \rangle$, $\langle V \rangle$, $\langle W \rangle$) = (0, −220, 0) is warranted. This assumption of halo kinematics, with its large rotation velocity relative to the Sun, increases the predicted number of proper motion detections to which we compare our actual detection rate. With only a handful of unambiguous examples, the kinematics of the dC population are not yet well constrained, but halo kinematics are strongly suggested by the velocities estimated here and in Paper I. Furthermore, the line-of-sight velocity dispersion (Bothun et al. 1991) and the colors and spectral class of stars in the FHLC sample are consistent only with halo population C stars.

For each star, we first generate galactic velocities U and V following the Gaussian distribution outlined above. We then derive the W required to reproduce the published radial velocity. If the resulting space velocity exceeds the escape velocity of the galaxy (taken to be 400 km s^{-1} in the nonrotating galactic frame), the trial is thrown out and another self-consistent velocity is generated. From an acceptable velocity so generated, the total proper motion is derived and compared to a detection limit of greater than 0.″10 yr^{-1}. This procedure is repeated for all 39 warm FHLC stars in the sample, and the number of detections tallied. From 500 such simulations, we estimate a proper motion detection fraction D of 98 ± 2% if all warm FHLC stars are dwarfs, where the uncertainty is the 1 σ dispersion of D from 500 simulations. Since we detect 5/39 or 13%, many FHLC stars are in fact distant giants. Furthermore, the FHLC stars with detected proper motions (i.e. the dC's) are not at positions on the sky particularly favorable to such detection: we performed the identical test on the sample of known dC stars (ignoring their measured proper motions), and 500 runs recovered an estimated detection rate of $D = 94 \pm 11\%$.

We can estimate the fraction of FHLC stars that are dC's by randomly assigning (with probability P) dwarf or giant status to the 39 stars in the sample and rerunning the simulations. For dwarf status, absolute magnitude and colors identical to G77−61 are again assumed. If giant status is assigned in this test, a photometric distance is calculated by comparing the K magnitude to the FHLC giant branch of Mould et al. (1985) or (for $J - K < 0.65$) to the M92 giant branch of Cohen, Frogel, & Persson (1978). Consistent with the very high estimated detection fraction of halo dwarfs found in the first simulation, here any assigned fraction P of carbon dwarfs in the FHLC sample results in a detection fraction D only slightly less than P. This again suggests that for warm FHLC stars our proper motion survey is very complete, i.e., our actual detection fraction of 5/39 = 0.13 is a reasonable estimate of the actual dwarf fraction, at least for a population of C stars with halo kinematics.

Although the five known dC's appear to have halo kinematics, this may be a proper motion selection effect, since the large rotation of halo population stars relative to the Sun facilitates proper motion detection.

6. DISCUSSION

Since five dC's are now known within about 400 pc of the Sun, the automatic assumption of giant (or even subgiant) luminosities for C stars is no longer valid. In objective prism surveys at high galactic latitudes, FHLC stars are found with an approximate surface density of one per 30 deg^2. If, to a similar depth of $V = 18$, 13% of these are Population II dwarfs, then since they would only be detectable to less than 400 pc, there should be at least 180 Population II dC's within that volume. Jura (1991) recently estimated that there are 14 classical Population I (N-type) AGB stars within a similar volume. From the catalog of Šleivytė & Bartkevičius (1990), there are four known or suspected CH stars within that volume, and 13 subgiant CH stars all brighter than $V = 10.5$. These admittedly crude estimates are made from a hodgepodge of surveys of varying completeness, but since samples of known giants and subgiants in such a volume are far more complete than samples of the much fainter dwarfs, the local space density of dC's may surpass that of any other type of C star, and probably all other types combined. Faint C stars may not be used as kinematic probes of the outer halo, or of Local Group galaxies, without first considering the possibility that they are foreground dwarfs.

In summary, FHLC stars with detectable proper motions show *JHK* colors similar to late-type field dwarfs. Many prob-

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ably also exhibit a strong depression blueward of the λ6191 bandhead of carbon. Our proper motion survey of FHLC stars shows that only those with large proper motions show evidence for *both* these features, substantiating their uniqueness in C dwarfs. We suggest that some combination of *JHK* colors, proper motion measurements, and/or low-resolution spectroscopy should thus obviate the painstaking high resolution spectral analysis required for many types of stars to distinguish giants from dwarfs. This is of particular utility in the case of carbon stars, for which reliable models of stellar atmospheres have been hampered by the tangle of C_2 and CN molecular absorption bands. Via kinematic simulations, we show that slow halo rotation, combined with our proper motion survey detection limit, suggests that we have found virtually all halo population dC's hidden among the FHLC sample. Since none of the FHLC stars were originally selected by proper motion, we can estimate that $\gtrsim$10% of Population II C stars are dwarfs.

Disk population dC's may also exist. The luminosity indicators we detail here are useful for expansion of the currently small dC sample by identifying even those dC's without detectable proper motion. Since the current dC sample is associated kinematically with the halo, these indicators may not apply to any disk dC's confirmed in the future. However, the number of such objects may be small, since an anticorrelation between population metallicity and C/M star ratio is known to exist (Richer & Westerlund 1983; Cook, Aaronson, & Norris 1986). Other effects, possibly age, must be involved, since otherwise, luminous C stars would be more common in globular clusters. The discovery of 33 C stars in the galactic bulge (Azzopardi, Lequeux, & Rebeirot 1985) also indicates that parameters other than metallicity are important. However, correlations between evolution and environment that apply to C giants may not hold for dC's, since their origin is still uncertain.

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