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CONSTRAINTS ON THE ORIGIN OF DWARF CARBON STARS

PAUL J. GREEN[1,2]
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
e-mail: pgreen@cfa.harvard.edu

AND

BRUCE MARGON[2]
Astronomy Department, FM-20, University of Washington, Seattle, WA 98195
e-mail: margon@astro.washington.edu
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ABSTRACT

As main-sequence stars do not produce carbon, the newly recognized class of carbon-rich dwarf (dC) stars is most easily explained if dC's are main-sequence bystanders polluted by mass transfer from a giant companion that has since become a white dwarf. We analyze intermediate (≈ 2 Å) resolution spectra of six dC's to constrain their radial velocities and abundances and to place them in context with other known or suspected mass-transfer binary (MTB) systems.

We find that barium is enhanced in all dC's observed. Carbon isotope ratios appear to span a wide range in our sample, with ^{13}C often as strong as in the ^{13}C-rich "J" stars. Both these abundance patterns are reminiscent of the CH stars, which are now accepted to be MTB systems. Wihin our velocity resolution, we find no evidence for radial velocity (RV) variability. This is consistent with the RV variations observed in wide binary systems like CH stars, but not with close post–common-envelope white dwarf + red dwarf systems. We suggest that dC's are the main-sequence progenitors of CH giants and/or that CH giants are the high-luminosity tail in a distribution of MTB systems numerically dominated by dC's.

Two recently discovered composite-spectrum DA/dC systems are also examined. The brighter DA/dC, PG 0824+289, has shown evidence for variable Balmer line emission, but has a previously unresolved close neighbor. We find that the neighbor is an unrelated M dwarf, so that the emission must arise from the DA/dC system. We examine two possible causes of the emission—chromospheric activity intrinsic to the dC, or reprocessing in a close binary of the DA's UV flux on the dC atmosphere.

Subject headings: binaries: spectroscopic — stars: abundances — stars: carbon — stars: evolution

1. INTRODUCTION

Because main-sequence stars do not produce carbon, it has been widely assumed that faint carbon (C) stars are more distant examples of the classical, bright C giants. Until recently, the only known flaw in this assumption had been the existence of one odd star, G77−61. This $V = 13.9$ object has a classical C spectrum but a high proper motion (Dahn et al. 1977), and thus most certainly has main-sequence luminosity. G77−61 was found to be a spectroscopic binary with measurable trigonometric parallax (yielding a distance of 58 pc; Dearborn et al. 1986). These authors argued that the most reasonable explanation of the prominent C bands in the dwarf's spectrum is mass transfer from a now unseen companion during the companion's second ascent of the giant branch (AGB). We recently reported (Green, Margon, & MacConnell 1991; Green et al. 1992; hereafter Paper I and Paper II) the discovery of four further dwarf carbon (dC) stars, each found due to high proper motion. At least two more dC's have subsequently been discovered by similar means (Warren et al 1993). In addition, Heber et al. (1993) report that PG 0824+289, a hot DA white dwarf, is in a double-line spectroscopic binary with a dC companion of absolute magnitude very similar to G77−61 ($M_V \approx +10$). Another DA/dC composite system, CBS 311, was recently discovered by Liebert et al. (1993).

If we assume all known dC's to be of luminosity similar to G77−61, then they are remarkably close; eight within 400 pc. Samples of classical bright (giant) C stars are far more complete within this same volume than are samples of the much fainter dwarfs. With 10 dC stars now known from only a smattering of small or incomplete surveys, the conclusion seems inescapable that many more C giants than C dwarfs are presently known only by virtue of the much greater luminosities of the former class. Contrary to the formerly prevailing paradigm, *dwarf C stars may be the numerically dominant type of carbon star in the Galaxy.* If each dC was indeed created in a mass-transfer binary (hereafter MTB), analysis of their orbits and atmospheres will be invaluable for our understanding of past generations of AGB stars and late phases of interacting binary evolution.

Radial velocity (RV) variability serves first as a check on the MTB hypothesis, but also as a start toward determining orbits of those dC's exhibiting such variability. In a statistical sense, low-eccentricity orbits are considered strong evidence for previous mass transfer (via Roche lobe overflow) in binaries (e.g., McClure & Woodsworth 1990). Single-epoch RVs for a number of dC's were obtained by Mould et al. (1985) and

[1] Hubble Fellow.
[2] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, which is operated by AURA, Inc., under cooperative agreement with the National Science Foundation.

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Bothun et al. (1991) during studies of faint C star samples then presumed to be composed entirely of distant halo giants. New measurements of dC RVs provide an important start in the search for RV variability. In addition, neither of the recently discovered DA/dC composite systems have yet been observed at sufficient resolution for any useful RV measurements. The relatively high temperature of their white dwarfs suggest an origin in the galactic disk, but even a single RV would be useful to characterize their galactocentric velocity as consistent with halo or disk kinematics.

CH stars, Population II C giants now widely accepted to be MTB systems (e.g., McClure & Woodsworth 1990), also exhibit large abundances of *s*-process elements known to be synthesized only in thermally pulsing (TP) AGB stars. In R-type carbon giants, no *s*-process element enhancements are seen (Dominy 1984). If *s*-process enhancements are detectable in dC's, this would suggest that their atmospheres have been polluted by mass transfer from AGB C stars, just as for the CH stars. To probe this question, we have undertaken here to measure both Ba II at λ4554 and λ4934, as well as Sr I λ4607.

In Paper II, we found that high proper motion C stars might be distinguished from other faint C stars by their strong λ6191 spectral feature and suggested that the feature's sharpness is caused by strong isotopic bands of carbon. Two of the brightest dC's, G77−61 (Dahn et al. 1977) and LHS 1075 (Lloyd Evans 1992), have indeed been shown to be ^{13}C-rich. For this reason, it has also been suggested that dC's are related to the ^{13}C-rich "J" type carbon giants (Lloyd Evans 1992; Gordon 1968). CH stars show a range of $^{12}C/^{13}C$ ratios, possibly with a bimodal distribution, from about 3 to greater than 25 (Vanture 1992). The distribution of carbon isotope ratios in dC's will help to identify their now-defunct polluters, and can be estimated from observations of the C_2 1–0 Swan band at λ4737. This region provides the greatest contrast and separation for isotopic analysis, with the $^{12}C^{13}C$ and $^{13}C^{13}C$ bandheads at λ4744 and λ4752, respectively.

In the next sections, we analyze our intermediate-resolution optical spectroscopy to attempt all of the observational tests of the evolutionary history of dC stars just described: radial velocity variability, *s*-process enhancements, and carbon isotope ratios. New results on the DA/dC systems PG 0824+289 and CBS 311 comprise the following two sections. The final discussion then updates our understanding of the dwarf carbon stars known to date.

2. OBSERVATIONS

From 1993 February 2 to 5, we obtained spectra of dwarf carbon stars at the KPNO 2.1 m telescope, using the GoldCam spectrograph and 600 lines per mm grating in second order. the spectra resulting from this configuration, with slit width 1.″5, cover the wavelength region 3900–5800 Å at a resolution of about 2 Å FWHM. To increase signal-to-noise ratio (S/N), we binned 2 pixels in the spatial direction of the Ford 3k CCD. The only available dC stars bright enough for this resolution at the 2.1 m were PG 0824+289, G77−61, and CLS 96.

Spectra at the MMT on Mount Hopkins, 1993 April 26 and 27, were obtained with the 1200 lines per mm grating in first order on the Loral 1200 × 800 CCD of the Red Channel spectrograph. This yields coverage from about 4300 to 5200 Å, and the 1.″5 slit width we used resulted in a spectral resolution of about 2.4 Å FWHM. We were able to obtain useful spectra for both RV and crude abundance analysis for the dC's PG 0824+289, CLS 31, CLS 50, CLS 96, and KA-2; these objects range from $15 < V < 18$. Several additional low-resolution red spectra were taken on 1993 April 25 at the MMT with the 150 lines per mm grating.

We thus obtained spectra for a total of seven dC stars. Six of these provided spectra of sufficiently high S/N at 2 Å resolution to permit further study of individual atomic or isotopic lines. All spectra were reduced using standard techniques in IRAF.

We also observed several remaining unconfirmed faint, high-latitude C star candidates from the objective prism survey of Sanduleak & Pesch (1988). Other such candidates have been spectroscopically confirmed previously by Mould et al (1985), Green & Margon (1990), and Bothun et al. (1991). We find the candidate C stars CLS 94, CLS 95, and CLS 108 (all tagged in Sanduleak & Pesch 1988 as questionable) to be M, K, and G dwarfs, respectively.

3. RADIAL VELOCITIES

Care was taken during wavelength calibration to sum the same columns along the CCD for both the object and HeNeAr arc spectra. Before RV cross-correlation, dispersion-corrected spectra for a given telescope were rebinned to the same wavelength solution, and a 20–30th order polynomial fit to the continuum was subtracted. The spectral regions we chose for cross-correlation avoid the strong carbon band heads. Large difference in band strengths and sloping of the band heads due to isotopic shifts can increase the errors of the cross-correlation when carbon bandheads are included.

On each night, we observed at least three or four carbon star RV standards (McClure & Woodsworth 1990; McClure 1990), some of them repeatedly. The R star HD 122547 ($v_{\rm Helio} = -14.4$) was also observed on all nights. Derived velocity uncertainties when cross-correlating between bright RV standards are less than 5 km s^{-1} for KPNO data, and less than 8 km s^{-1} for MMT spectra. The lowest velocity errors result from cross-correlation with a standard star of similar spectral type and abundance to the object. Errors increase when cross-correlating two stars of very different spectral type, or stars with lower S/N, as expected.

To derive the best estimate of the true RVs and their errors, we have chosen to cross-correlate each dC observation with several RV standard stars on each night. In Table 1 we present the mean velocities derived on each of six nights of observations for five dC's. The number of standard stars used is shown for each night. The quoted velocity errors include the uncertainty in each cross-correlation as well as the dispersion in RV between different templates. Adopted mean heliocentric velocities of each star are listed in the last row, where errors are the dispersion in the mean (except for CLS 31, observed only on 1993 April 26). We claim 15 km s^{-1} as a conservative overall estimate of our nightly RV errors for dC's. Our conclusions are robust to the choice of RV standards used.

Although we also have KPNO RV results for G77−61, we merely report here that they are consistent with the published orbits of Dearborn et al. (1986). CBS 311, a composite DA/dC, lacks sufficiently sharp lines at this resolution and wavelength coverage to permit an accurate velocity from cross-correlation with any of the RV standards. For PG 0824+289, we find an overall mean heliocentric velocity of -27 ± 5 km s^{-1}, whose importance we discuss in another section. Comparison of our results to the published RV for CLS 31 of -44 ± 9 km s^{-1} (Bothun et al. 1991) may indicate RV variability for this star. Our mean velocity of CLS 50 is consistent with the value of

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TABLE 1

NIGHTLY MEAN RADIAL VELOCITIES OF DWARF CARBON STARS

UT DATE (1993)	NO. OF RV STANDARDS	HELIOCENTRIC VELOCITY (σ) (km s^{-1})				
		PG 0824+289	CLS 96	CLS 31	CLS 50	KA-2
Feb 2	3	−30 (6)	202 (6)	...	...	...
Feb 3	3	−27 (10)	196 (16)	...	...	...
Feb 4	3	−30 (14)	...	...	...	...
Feb 5	3	−24 (7)	247 (10)	...	...	...
Apr 26	6	−23 (13)	202 (14)	16 (12)	−154 (13)	−34 (12)
Apr 27	4	...	182 (14)	..	−178 (7)	−7 (13)
Adopted Mean RV		−27 (5)	206 (24)	16 (12)	−166 (17)	−21 (20)

-167 ± 4 found by Mould et al. (1985). Ratnatunga's RV of -69 ± 20 for KA-2 is consistent with ours. More, preferably higher resolution, observations are required to claim unambiguously RV variability, or especially to measure orbital parameters.

When possible, within a given run where we observed a dC several times, we cross-correlated a star against itself to look for RV variability, both between nights and within a night. We find no significant ($>3\ \sigma$) inter- or intra-night RV variability for PG 0824+289, CLS 96, CLS 50, or KA-2 within our velocity resolution.

CH giants with well-determined orbital elements have $K < 15$ km s^{-1} and periods exceeding 300^d (McClure & Woodsworth 1990). It is worth noting that the only dC to date with a well-determined orbit, G77−61, is in a tighter orbit ($P = 245^d$, $K = 20$ km s^{-1}, Dearborn et al. 1986) than any CH giant measured thus far. Even so, neither our velocity resolution nor temporal baseline would detect RV variability in a system similar to G77−61. We do, however, provide ($3\ \sigma$) upper limits to such variability of less than 45 km s^{-1} within timescales of several days to all five dC systems so observed.

In the case of PG 0824+289, which shows variable Balmer emission, the $3\ \sigma$ limit of $\Delta RV \leq 15$ km s^{-1} is particularly interesting. Known white dwarf + main-sequence (WD + MS) binaries showing Balmer emission have periods from an hour to several days (deKool & Ritter 1993; Saffer et al. 1993) and K velocities for the red dwarfs exceeding 70 km s^{-1} (e.g., Feige 24; Thorstensen et al. 1978). In order for PG 0824+289 to have such a K velocity and still not show RV variability in our observations, the inclination angle must be $\lesssim 7°$.

4. SPECTRAL FEATURES

We chose the C star RV standards to have a variety of abundances useful for comparison to the dC target objects. Some are strong ^{13}C (or J) stars, while others have strong lines of Ba or Sr. A variety of molecular band strengths of both C_2 and CN are also represented.

Most of the dC's in our program are faint ($V \gtrsim 16$), so high-resolution echelle spectra are not yet feasible. Also, accurate dC model atmospheres are not available, so that reliable abundances are impossible to measure. Instead, we have chosen to measure equivalent widths and line intensities for comparison to carbon giants of various types. We find that differences between MMT and KPNO measurements were very small compared to the differences between objects. For comparisons of spectral properties, we measure spectra that have been divided by ninth order polynomial fits to their continua. All line equivalent width and intensity ratios for C_2 band heads are presented in Table 2 for summed spectra of six dC's and nine previously studied carbon giants. We estimate uncertainties in our measurements to be less than 20%. All lines except those marked with a superscript b (for uncertain identification) we believe to be safely detected.

For direct comparison of line equivalent widths in dC stars alone, we removed the flux contribution of the white dwarf in PG 0824+289 before dividing the DA/dC spectra by a continuum fit. Since Heber et al. (1993) found this WD to have a temperature of about 40,000 K, we subtracted from our data a 40,000 K blackbody spectrum, matched by eye to the blue end flux level of the original spectrum. Except near the Balmer lines (i.e., for our CN λ4832 measurement), measured equivalent widths and line intensities vary by $\lesssim 10\%$ when varying the subtracted blackbody temperature by 5000 K. A more critical choice is the blue flux level chosen for the blackbody spectrum. However, reasonable fits by eye cannot possibly vary more than a few percent in flux. Even invoking such extremes for this star results in equivalent width variations of less than 30%. None of our conclusions changes with uncertainties of this order.

4.1. *Barium and Strontium*

We measure the equivalent widths of Ba II λ4554 and λ4934 from continuum points at λ4546 and λ4928, respectively. The Sr I λ4607 line can be weak and difficult to identify at this resolution. In carbon giants, this line generally increases in strength toward lower temperatures (Yamashita 1972). Our spectra of CBS 311 are of too low S/N for comparison, but our measurements for six other dC's are presented in Table 2.

The λ4554 spectral region for all six dC's observed are plotted in Figure 1, together with that of BD +42°2173, a C3,2ch star with strong s-process lines. The spectra are arranged so that Ba strength increases from top to bottom. Of the dC's, only KA-2 and PG 0824+289 have strong, unambiguous Sr I λ4607 lines. These same stars also show particularly strong enhancements of Ba. This confirms Heber et al.'s suggestion that Ba II and Sr I "might possibly be present" in PG 0824+289. Although Dahn et al. (1977) did not detect "abnormally strong" Ba II or Sr I in their low-resolution spectra of G77−61, our results do clearly show enhancement. Figure 2 shows that our λ4544 equivalent width measurements for Ba show a reasonable correlation with the indices measured by Yamashita (1972) for nine bright carbon giants.

Twilight sky, Moon, or G2 V stellar spectra that we obtained with the identical instrumental configuration yield upper limits to Ba equivalent widths at least a factor of 2 lower

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TABLE 2

LINE EQUIVALENT WIDTHS AND BAND RELATIVE INTENSITIES

STAR	BARIUM λ4554	BARIUM λ4934	STRONTIUM λ4607	CARBON BANDS $^{12}C^{12}C$ λ4737	CARBON BANDS $^{12}C^{13}C$ λ4744	CARBON BANDS λλ4744–4737	CYANOGEN λ4832
Carbon Dwarfs							
G77−61	0.81	0.80[a]	0.31	0.17	0.26	0.09	0.92
PG 0824+289	1.5	0.83[a]	1.1[b]	0.34	0.71	0.37	0.27[b]
CLS 31	1.4	1.27[b]	...	0.23	0.36	0.13	0.2[a,b]
KA-2	2.1	1.21	1.09	0.43	0.85	0.42	0.34
CLS 50	0.74	1.05	...	0.49	...	0.51	0.61
CLS 96	1.0	0.72[a]	0.98[b]	0.37	0.80	0.43	1.1
Carbon Giants[c]							
BD +42°2173	1.9	1.2	0.75	0.55	0.84	0.29	0.22
BD +75°348	1.5	0.87	0.64	0.77	0.86	0.09	0.22
HD 122547	0.94	0.97	0.82	0.29	0.43	0.14	0.40
HD 52432	1.8[a]	0.81	...	0.10	0.12	0.02	0.79
HD 57884	2.3	2.3[a]	2.4[a]	0.15	0.40	0.25	0.83
HD 79319	2.0:	0.6[a,b]	0.93	0.08	0.15	0.07	0.73
HD 156074	1.0	0.52	1.15	0.55	0.74	0.19	0.34
HD 201626	0.87	0.66	...	0.68	...	...	...
BD 30°2637	0.70	0.32	0.60	0.81	0.93	0.12	0.20
G2 V Comparison Star[c]							
HD 23169	0.35[b]	0.26	...	...	...	...	0.08

NOTE.—: = poor fit or MMT and KPNO values discrepant.

[a] Blended.

[b] Uncertain line identification or noisy.

[c] Values for these bright stars have been determined previously to much greater accuracy by high-resolution spectroscopy; they are included here to provide an indication of the scatter expected at our more modest resolution, and as input data to Fig. 2.

than any dC observed, so it appears that all six dC's show significant enhancement of Ba. Enhanced *s*-process abundances in these dwarf stars provide further evidence of contamination by material from a thermally pulsing AGB star.

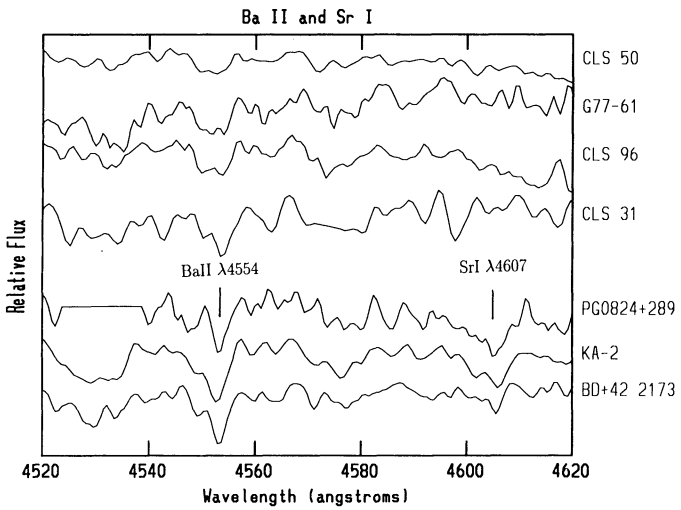

FIG. 1.—Summed ≈2 Å resolution spectra near the region Ba II λ4554 for six dC's together with BD +42°2173, a C3,2ch star with strong *s*-process element lines. The spectra are arranged so that Ba II λ4554, enhanced in all objects, increases from top to bottom. The Sr I line at λ4607 is strong in only two of the dC's. A synthetic WD spectrum has been subtracted from PG 0824+289 as described in the text.

4.2. *Carbon Molecular Bands and* ^{13}C

We measure an index of λ4737 $^{12}C^{12}C$ and λ4744 $^{13}C^{13}C$ band strengths as the intensity at these wavelengths divided by the intensity at a continuum point near λ4756. We also measure the equivalent width of CN λ4832. Table 2 lists our measured indices for carbon and cyanogen bands. For the eight bright giant C stars also listed in Yamashita (1972), we find tight correlations between our carbon indices and his (Fig. 2).

The region of the λ4737 C_2 Swan band is shown in Figure 3 for six dC's and the ^{13}C-rich J star HD 79319, with ^{13}C strength increasing from top to bottom. Two of the dC's observed, G77−61 and CLS 31, clearly have strong ^{13}C, with corresponding Yamashita indices of at least 4 (out of 5). Indeed, Gass, Liebert, & Wehrse (1988) measured a low $^{12}C/^{13}C$ ratio of 4 for G77−61 from echelle spectra. One other dC not included in the current analysis, LHS 1075 (Paper I) was also found to have very strong ^{13}C by Lloyd Evans (1992). PG 0824+289 clearly shows isotopic bands, but at somewhat lower strengths. In the dC's CLS 50, CLS 96, and KA-2, however, we detect no ^{13}C at all. We therefore find a remarkably wide range in ^{13}C abundance for dC stars.

AGB stars produce carbon in triple-α shell burning, which gives the N (Population I) type C stars their $^{12}C/^{13}C$ isotope ratios of 30–50 (e.g., Lambert et al. 1986). The occasional very bright N star will have a low isotope ratio, possibly indicating that ^{13}C-rich material is being dredged up between He flash periods (Wood, Bessel, & Fox 1983). Population II K giants on their first ascent of the giant branch instead show ratios between about 3 and 10 (e.g., Brown & Wallerstein 1989). All R

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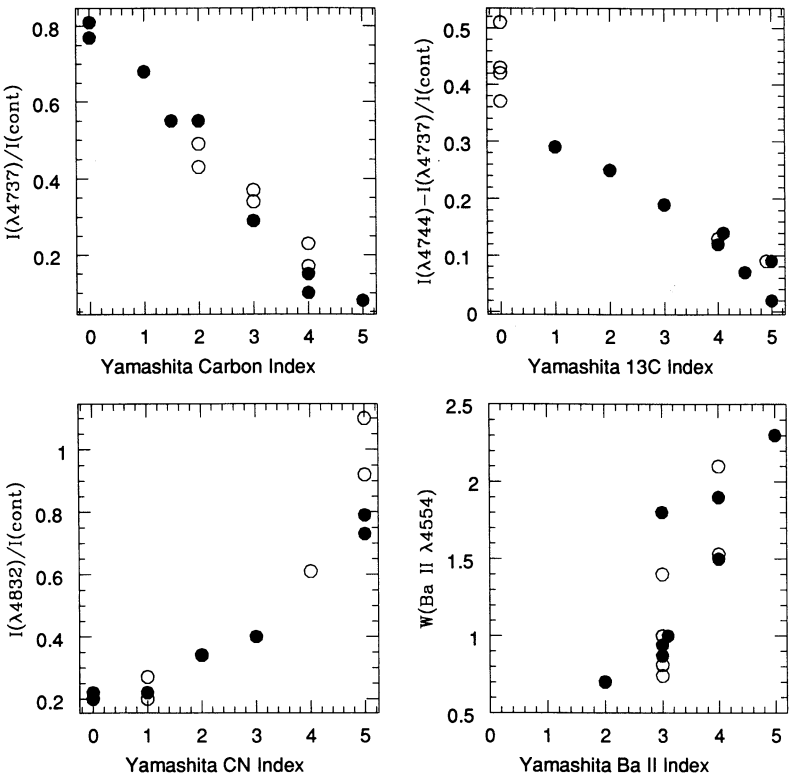

FIG. 2.—Measurements of relative intensity from MMT and KPNO spectra are plotted againt Yamashita's (1972) strength indices for eight bright C giants in common with our work (*filled circles*). Based on this crude relationship, we use our measurements for the dC's (*open circles*) to assign each an approximate Yamashita index. The dC's show a range of carbon, ^{13}C, and CN indices. All these dC's appear to show *s*-process enhancements.

(old disk) type C giants are also ^{13}C-rich. In a study of eight CH giants, Vanture (1992) found bimodal ^{13}C abundance. Although the majority had isotope ratios near the equilibrium value of the CNO cycle ($^{12}C/^{13}C \approx 3$), several also showed values of 25 or above. Those with high isotope ratios showed weak CN, and vice versa. We find no evidence for such a trend in dC's, although our ability to measure CN is limited only to the λ4832 line. In their wide range of carbon isotope ratios, however, the dC's are most similar to the CH giants.

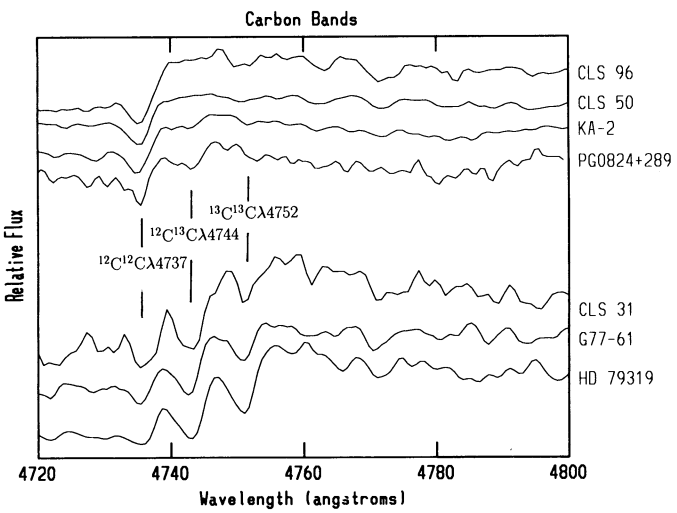

FIG. 3.—The region of the λ4737 C_2 Swan band for six dC's and the ^{13}C-rich J star HD 79319, with ^{13}C strength increasing from top to bottom. In the dC's CLS 50, CLS 96, and KA-2, we detect no ^{13}C. G77−61 and CLS 31 show isotopic bands as strong as the ^{13}C-rich "J" stars (as does LHS 1075, Lloyd-Evans 1992). PG 0824+289, from which a synthetic WD spectrum has been subtracted, has an intermediate isotope ratio.

5. PG 0824+289

PG 0824+289 was reported by Heber et al. (1993) to be a double-lined spectroscopic binary consisting of a hot DA white dwarf and a dwarf carbon star. From their low-resolution spectra, Heber et al. have estimated the temperature and absolute magnitude of the WD to be $T_{\rm eff} = 40{,}000$ K and $M_V = +9.2$, yielding a distance via photometric parallax of 120 pc. From the relative fluxes of the two components, the dC is estimated to have $M_V = +10.4$.

Strong, variable Balmer line emission in PG 0824+289 reported by Heber et al. suggests that the system may be a close binary, with the emission due to reprocessing of intense ionizing flux from the DA by the photosphere of the dC. Analogous binaries with M rather than dC companions are known, with periods from a few hours to a few days (deKool & Ritter 1993). The emission spectrum of the cool star varies strongly with binary phase in such systems (e.g., Thorstensen et al. 1978).

On 1993 April 25, we obtained one low-resolution spectrum of PG 0824+289, displayed in Figure 4. Clearly visible are the C_2 band heads at λ4737 and λ5165, while the λ5636 band head is not evident. A strong CN band is seen at λ7876, a spectral range not previously published. The Na I doublet is also quite strong.

The Balmer emission reported by Heber et al. varied between spectra taken several months apart, and Hα and Hβ

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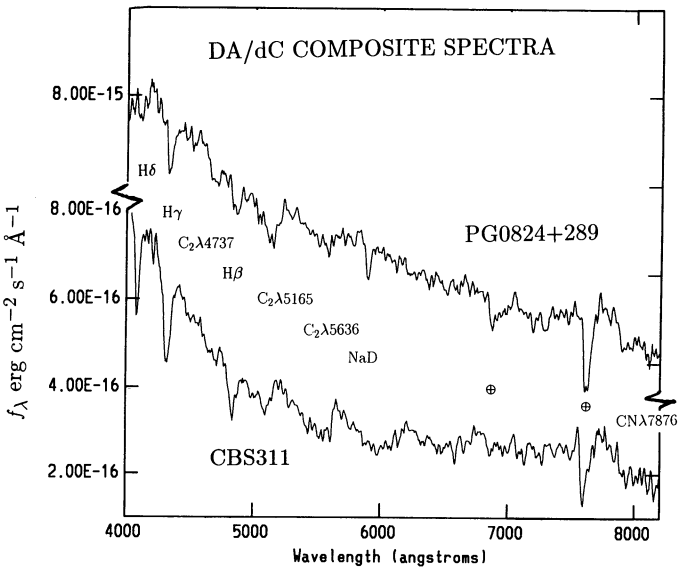

FIG. 4.—Spectra of the two known composite DA + dC stars. Clearly visible in this MMT low (20 Å) resolution spectrum of PG 0824+289 are the C_2 bandheads at $\lambda4737$ and $\lambda5165$. The $\lambda5636$ bandhead is not visible, while the CN bands near $\lambda6200$ and $\lambda7876$ are evident. The Na I lines are also quite strong. Balmer emission can be seen in the reversed line cores at Hβ and Hγ, while there is no sign of Hα in either emission or absorption. CBS 311 shows no Balmer emission at all. The dC has strong CN bands at $\lambda5730$ and $\lambda7876$. The $\lambda6191$ spectral feature noted by Green et al. (1992) in high proper motion dC stars is also visible here.

varied in phase with each other, Hα remaining the stronger emission line by a factor of several. In our (single) low-resolution spectrum, Balmer emission can just be seen in the reversed line cores at Hβ and Hγ, but there is no sign of Hα in either emission or absorption.

5.1. *Neighbor Star*

The status of PG 0824+289 as a close binary system was called into question by the discovery (Margon et al. 1992) that the system is spatially resolved. Elongated images are evident on both the Palomar Sky Survey and archival Lick astrograph plate material. CCD imagery with the Kitt Peak 2.1 m and Gunn *g*, *r*, *i* filters showed two objects of similar *i* magnitude, but quite different color, separated by 3.″3 at position angle 120° (Fig. 5). The two objects differ by 3.0 mag in the *g* band, 1.8 mag in the *r* band, and 0.9 mag in the *i* band, with the easternmost object clearly the cooler one.

Many spectrograph slits are by default oriented east–west, accidentally quite close to the alignment of the two components of this system. We investigate here whether the composite nature of spectra so far published for PG 0824+289 might be due to this unfortunate coincidence.

We consider three possibilities for the resolved objects: (1) A chance projection of a WD near a distant carbon giant. The latter on occasion show Balmer line emission. However, since both types of objects have very low surface densities at the relevant apparent magnitudes, any such superposition seems to be of extremely low probability. (2) A WD and dC in an

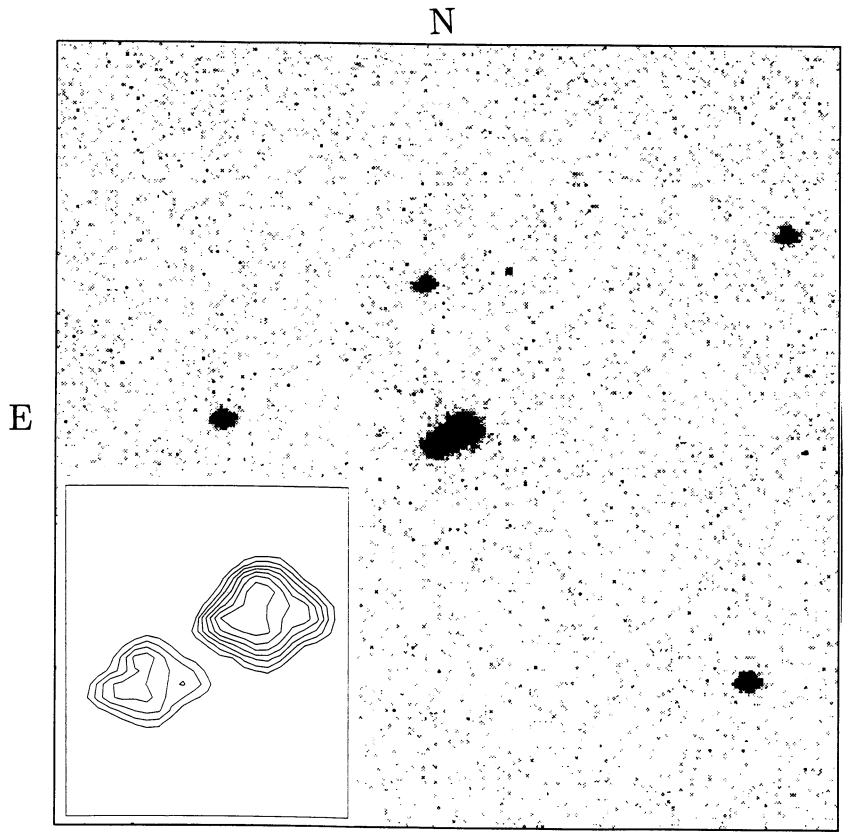

FIG. 5.—A Gunn *i* image of PG 0824+289 obtained at the KPNO 2.1 m on 1992 October 17 and kindly made available to us by John Hoessel. North is up, with east to the left. The two objects visible here differ by 3.0 mag in the *g* band, 1.8 mag the *r* band, and 0.9 mag in the *i* band, with the easternmost object clearly the cooler one. They are separated by 3.″3 at position angle 120°. The inset shows a contour map of PG 0824+289 with seven contour levels between 25% and 100% of peak (log) flux.

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unresolved pair, with a cool neighbor star of a third spectral type. The cool star could be an active M dwarf, whose flares could contribute to the observed Balmer line emission while the continuum remained too low to affect substantially the composite spectrum of PG 0824+289. Either slight changes in slit alignment or variability in the M dwarf emission could thus result in the large apparent changes in the Balmer line equivalent width reported by Heber et al. (1993). (3) A spatially resolved, physical DA/dC pair. This latter possibility would challenge the preferred (MTB) explanation for dC's, since at a distance of 120 pc, the projected separation of the pair implies a true separation of at least 400 AU, so that any recent significant mass transfer is implausible. Which, if any, of these possibilities is correct?

While observing PG 0824+289 at KPNO and MMT, we took care to eliminate possible contamination of either star with the other by orienting the spectrograph slits at position angle 30°. Figure 6 shows a low (20 Å) resolution spectrum of the easternmost, red star. Based on the strength of TiO, CaH, and MgH bands, and confirmed by a higher resolution spectrum taken on 1993 April 26, our classification is an ordinary M3 or M4 dwarf, with no Balmer emission evident. Our spectra of the west, bluer star are indeed composite, showing that the DA/dC system is in fact spatially unresolved, and that, fortuitously, none of the features originally attributed to the DA/dC system arises from the nearby M dwarf.

Although all spectra were taken through 1".5 slits, their observed relative fluxes repeatably suggest that the red star is fainter in the V band by ≈ 3 mag, and in the B band by ≈ 4 mag. Given the (Greenstein) $v = 14.22$ for PG 0824+289 (Green et al. 1986), the implied V mag for an M3–M4 star places it at a distance of 150–230 pc. Considering the uncertainty in this photometry, this distance is not inconsistent with the distance of 120 pc derived by Heber et al. for PG 0824+289. It is also intriguing that our measured radial velocity of -58 ± 22 for the neighboring M dwarf (measured once on 1993 April 26 using a GV template) is consistent with its membership in the PG 0824+289 system. It is possible that angular momentum transfer to the M dwarf in past interaction as a triple system may have significantly decreased the orbital separation, but the inferred projected separation of 400 AU precludes any current physical significance for the association.

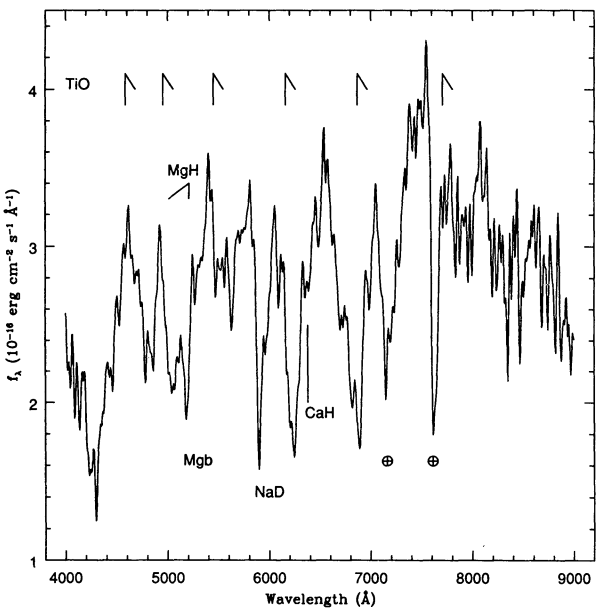

FIG. 6.—MMT low (20 Å) resolution spectrum of the faint star near PG 0824+289, using a spectrograph slit oriented at position angle 30° to avoid contamination from the nearby companion. Based on the strength of TiO, CaH, and MgH bands, and confirmed by a higher resolution spectrum taken on April 26, our classification is an ordinary M3 or M4 dwarf, with no Balmer emission.

5.2. *EUV Reprocessing or Chromospheric Activity?*

Neither the strength nor the variability of Balmer line emission as observed in PG 0824+289 by Heber et al. (1993) are necessarily the result of reprocessing by the dC atmosphere of UV photons from the white dwarf. Hα equivalent widths of 1–5 Å are found in rapidly rotating late-type (dKe and dMe) stars when their equatorial velocity exceeds about 5 km s^{-1} (e.g., Stauffer & Hartmann 1986; Bopp & Fekel 1977). By subtracting a 40,000 K dwarf model from our spectrum of the PG 0824+289 composite, we measure the equivalent width of Hβ from the dC to be about 2 Å. Thus the carbon dwarf in PG 0824+289 could be the first example of a "dCe."

Active late-type dwarfs rotate on timescales of days (e.g., Doyle 1987), and the rotation of long-lived chromospheric plages can mimic the periodic Balmer emission variability characteristic of close binary UV reprocessing systems. The ironclad signature of active flare stars, however, is short-term (≈ 1 hr timescale) variability, with flares in Hα of equivalent width 10 Å quite typical. Well-studied interacting WD + MS binaries also may display Balmer emission variability corresponding to orbital periods ranging from an hour to several days (e.g., Saffer et al. 1993; de Kool & Ritter 1993). We compared Hβ equivalent widths between KPNO spectra obtained over four nights. The mean Hβ equivalent width we measure in the DA/dC spectra is 0.5 ± 0.1 Å, and there is no evidence for greater than 2 σ variability in equivalent width on any timescale. However, the lack of Balmer line variability on day timescales is not necessarily inconsistent with orbital variation in the UV reprocessing scenario to a close binary.

We now attempt to be somewhat more quantitative in contrasting the two scenarios of EUV reprocessing in a close binary or chromospheric activity in the dC. Since significant mass transfer has probably occurred, we assume a low-eccentricity orbit and use our limit $\Delta RV \leq 15$ km s^{-1}, along with reasonable mass estimates for the DA and dC (0.6 $M_\odot$ and 0.4 $M_\odot$, respectively, based on the absolute magnitudes of the two components) to derive a lower limit to the semimajor axis of $a \gtrsim 16 \sin^4 i$ AU. For typical inclination angles, this limit is two orders of magnitude larger than the separations of close white dwarf + red dwarf binaries where EUV reprocessing appears to influence the spectrum.

We now compare the portion of the DA luminosity intercepted by the dC with the total Hα luminosity from that half of the dC which faces the DA. A fit to the white dwarf data of Lang (1980) yields

$$\log \frac{L_{\rm DA}}{L_\odot} = 4.17 \log T_{\rm eff} - 19.66 ,$$

so that $L_{\rm DA} \approx 0.34\ L_\odot$. The fraction of this luminosity intercepted by the dC is $R_{\rm dc}^2/4a^2$. The absolute magnitude of the dC from Heber et al. implies a radius $R_{\rm dC} \approx 0.5\ R_\odot$. The DA luminosity intercepted by the dC is thus

$$L_{\rm DA}^{\rm (dC)} \approx (6.9 \times 10^{24} \sin^{-4} i) \text{ ergs s}^{-1} .$$

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We estimate a lower limit to the observed Hα flux from the dC by assuming the Hα equivalent width to be about 3 times that which we observe at Hβ (also supported by the spectra of Heber et al. 1993). From this flux we derive $L_{H\alpha} \approx 5 \times 10^{28}$ ergs s^{-1}. Then the ratio of the inferred Hα luminosity to intercepted DA luminosity is $L_{H\alpha}/L_{DA}^{(dC)} \approx 3500 \sin^4 i$. For EUV reprocessing to be the cause of the Balmer line emission, this ratio should certainly be less than unity, considering that only a fraction of $L_{DA}^{(dC)}$ is converted into Balmer emission line flux. To have $L_{H\alpha}/L_{DA}^{(dC)} \lesssim 1$, we estimate that $i \lesssim 7°$.

The coincidence of this constraint with that derived by comparison of our upper limit to ΔRV with known K velocities of close WD + MS binaries is serendipitous. However, this exercise shows that given the current data, Balmer emission intrinsic to the dC is a strong possibility. Strong constraints on inclination angle and period (be it orbital or rotational) would be invaluable to our understanding of this system.

As the referee has pointed out, although chromospheric activity fades with age, the dCe scenario is not incompatible with the minimum age of the PG 0824+289 system. Activity lifetimes in late-type dwarf/X-ray emitting stars may be up to a few Gyr (e.g., Fleming et al. 1988), which is more than sufficient for a 2 $M_\odot$ star to evolve through an AGB C star to a DA phase. Furthermore, we must consider the possibility that mass transfer spins up the secondary to prolong or even induce chromospheric activity. However, if the binary is close, tidal locking of rotation and revolution will occur very quickly, and the resulting rapid rotation could also induce activity in the dC. Since PG 0824+289 is both a known *ROSAT* EUV and soft X-ray source, it is possible that a substantial fraction of the *ROSAT* flux is due to a dCe component.

5.3. *Space Motion of* PG 0824+289

The proper-motion measurement of the DA/dC PG 0824+289 cited in Heber et al. (1993) was made from photographic plates where its close neighbor star is not well resolved. Since the astrometric centroiding was performed on different plate/filter combinations for the measured epochs, and since the stars are of very different colors, even their very small reported motion is probably imprecise. We can use our new RV measurements to constrain the space motion of PG 0824+289; if we take the proper motion to be anything from zero up to the value presented in Heber et al., the space velocity relative to the local standard of rest remains about 40 km s^{-1}, and V about 20 km s^{-1}. The important result is that PG 0824+289 is kinematically a disk star.

6. CBS 311

CBS 311 was first cataloged in the objective prism survey of Sanduleak & Pesch (1989), and more recently as a UV-excess object in the Second Byuryakan Survey (Stepanian, Lipovetsky, & Erastova 1990). Liebert et al. (1993) subsequently found the star to have a composite DA/dC spectrum similar to PG 0824+289. On 1993 April 25, we obtained a low-resolution MMT spectrum of the object, shown in Figure 4, similar to the one presented in Liebert et al.

Liebert et al. estimate $T_{eff} = 31{,}100$ K and $\log g = 7.84$ for the DA, which yields $M_V = +9.72$ and thereby a distance of about 430 pc for the system. By subtracting a WD model with these parameters for the composite spectrum, they obtain $M_V = +10.8$ for the dC, 0.7 mag fainter than the halo dC G77−61. We see no Balmer emission in CBS 311. Unfortunately, our 2 Å resolution has too few narrow features to permit a radial velocity measurement. A red spectrum of similar resolution is therefore of interest.

Since our spectra go further to the red than those of Liebert et al., we merely add that CBS 311 also has strong CN bands at λ5730 and λ7876. The λ6191 spectral feature noted in dC stars with halo kinematics (Paper II) is also seen here. Since the age of the WD from cooling curves is at most about 20 Myr (Winget 1987), this WD is almost certainly Population I. Thus the λ6191 spectral feature, although not ubiquitous in dC's, is probably a useful luminosity indicator for disk systems as well as for halo varieties.

7. DISCUSSION

An impressive array of stellar types are now recognized to owe their peculiar abundances to mass transfer from an AGB companion that has since evolved to a white dwarf. These include Ba II and CH subgiants (Luck & Bond 1991), *s*-process–enriched F and G dwarfs (Tomkin et al. 1989), and S stars without Tc (e.g., Brown et al. 1990; Jorissen & Mayor 1992). The origins of these stars in MTBs appear to link the Ba II and CH star phenomena as two generations (Population I and Population II, respectively) of the same family. The higher neutron exposures and large C/O ratios of the CH giants have led Luck & Bond (1991) to argue instead that the metal-deficient ([Fe/H] < −1) Ba stars are the true Population II analogs of the classical Ba II giants.

CH subgiants (sgCH) are old disk F and G-type stars with $M_V \approx +2$ to $+4$ (beyond the old disk turnoff) and enhanced abundances of carbon and *s*-process elements. Their binarity has yet to be proved. Ba II stars, G and K giants with similar abundance anomalies, are demonstrated post–MTB systems. Smith, Coleman, & Lambert (1993) suggest that when ^{12}C and *s*-process–rich material on the surface of a CH subgiant becomes mixed with normal abundance matter as the star evolves up the giant branch, the C/O ratios and *s*-process enhancements decrease together. This is consistent with a model (Luck & Bond 1991) in which the sgCH stars evolve to become Ba II giants. The lower carbon isotope ratios of the Ba II giants would then be due to the convective mixing on the giant branch of (^{12}C-depleted) material previously processed by the CN cycle on the main sequence.

Similarly to the CH giants, dC's span a wide range of carbon isotope ratios. High $^{12}C/^{13}C$ ratios are consistent with accretion of the nearly pure ^{12}C triple-α products of thermally pulsing AGB stars. Although lower ratios in post–MTB giants have been attributed to the mixing of CN-processed material during the first ascent of the giant branch *after* the mass transfer has taken place (e.g., Smith et al. 1993), this clearly has not taken place in dC's. The ^{13}C in some dwarfs must instead have come from the accretion of low-isotope ratio material from the former giant companion, possibly a ^{13}C-rich J star. R-type carbon giants, which do have low $^{12}C/^{13}C$ ratios, can probably now be ruled out as the donors to the ^{13}C-rich dC's because R stars do not show *s*-process enhancements.

In Paper II, we remarked that a wide absorption band near λ6200, rare in carbon giants, is a common though not ubiquitous feature of dC spectra. Since at the time, the only two dC's studied at sufficient resolution had been found to be ^{13}C-rich, we suggested that the strength of this band might be due to strong ^{13}C in the (0, 2) λ6191 band of C_2. This now appears *not* to be the reason, since at least CLS 96 and CLS 50 have strong bands near λ6200, but are found here to have weak ^{13}C. Neither does this feature correlate well with CN band

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strengths. Its origin must first be identified, but if the feature is sensitive either to gravity or metallicity, it would be of great interest. Regardless of the resolution of this issue, however, the use of the λ6200 feature as a luminosity indicator (Paper II) remains intriguing.

Although *HST* observations are underway, few sgCH, CH, or Ba II giants have shown strong evidence for white dwarf companions in *IUE*. Dwarf carbon stars in general offer a better opportunity to detect the presumed WD companion than do their giant analogs, as the current primary is much fainter and the dC systems are on average closer. Since the timescale for WD cooling beond *IUE* detectability exceeds by a large factor the giant lifetimes of low-mass stars, many post–MTB giants were probably polluted while still on the main sequence (MS). The large difference between low-mass MS and giant lifetimes means that the number of dC's in the galaxy should far exceed the number of post–MTB giants. On the other hand, since for dC's, one star in the MTB has already evolved past the AGB phase while the other remains on the MS, dC's must be in binaries of more extreme initial mass ratios than are the Ba II or CH giants, which decreases the expected number of dC's. The balance between these arguments determines the space densities of the dC's relative to the Ba II and CH giants, but the net result is clear: even the current (very incomplete) sample of only 10 dC's provides strong evidence that the space density of dC's far exceeds that of their giant analogs (Paper II).

Unfortunately, only G77−61 currently has a measured trigonometric parallax, but distances to the DA/dC systems are available by modeling the DA spectra to determine absolute magnitudes and thereby photometric parallaxes for those systems. There are now three dC's (G77−61, PG 0824+289, and CBS 311) with reasonably precise absolute magnitude estimates available, all within about 0.5 mag of $M_V \approx 10.4$. This, together with their strong C_2 bands, makes it clear that enough mass can be transferred to make C/O > 1 without moving the star up to subgiant luminosity as a result. However, it cannot be assumed that the luminosity of the dC has not been altered by the mass transfer event. All three dC's with reliable M_V estimates lie near the mass limit for H-burning in metal-poor stars. At least some dC's may thus be brown dwarfs that have moved up to the MS only as a result of mass accretion. This is not to imply that all dC's should be of similar mass. If they are innocent bystanders in an MTB, there should exist MS examples up to the G turnoff. Indeed, less (or less carbon-rich) mass transfer is required to reach the same C/O ratios in earlier (less convective) dwarfs. However, examples may not be any easier to find, since C_2 and CH molecular bands are harder to detect in warmer stars.

To decipher what sort of AGB star was the mass donor, there is no substitute for accurate C/O, carbon isotope ratios, and abundances of *s*-process elements, Fe, and C + N + O from echelle spectroscopy. The C/O ratios of many CH stars, for instance, are higher than those of the Population I N-type AGB carbon stars. This could be evidence that the CH stars' carbon donor, presumably a thermally pulsing AGB star of an earlier, halo generation, had larger C/O ratios than today's N stars. Strong C_2 bands in the dC's indicate that they too may have very high C/O.

In the case of *halo* dC's, this would be consistent with the correlation between the ratio of the number of carbon to M-type AGB stars in Local Group galaxies (Aaronson, Olszewski, & Hodge 1983), which suggests that AGB stars with C > O are more easily created in low-metallicity environments where O abundance is initially low. The family of post–MTB systems also appears to follow a trend of increasing $^{12}C/^{16}O$ ratio with decreasing [Fe/H]. However, from (incomplete) kinematical evidence, there appear to be both disk and halo dC's, and both show large C/O ratios. Before judging this a contradiction, it is important to know what dC's of each population become as they evolve. At least some of the dC's studied here have masses ($\lesssim 0.4\ M_\odot$) lower than either the Ba II giants (1–3 $M_\odot$) or the sgCH stars, and so cannot be their progenitors. They could, however, be the progenitors of CH giants. Indeed, since late-type dwarfs can be highly convective, they suffer less dilution upon evolution than do more massive dwarfs. Therefore, a late-type dwarf already showing C > O is more likely to retain visible evidence of pecular abundances as it evolves. For earlier types, C/O ratios could easily decrease so that halo dC's could evolve to CH stars, while disk dC's evolve to sgCH and/or Ba II stars.

Higher resolution spectra are also called for over a long temporal baseline to determine the orbital characteristics of dC's for comparison to other post–MTB systems. The eccentricities of CH star orbits are lower than for either S or Ba II stars. Such nearly circular orbits are likely to be the result of Roche lobe overflow, while the higher eccentricity orbits of Ba II giants inspired the wind accretion models of Jorissen & Boffin (1992).

Although a significant fraction of faint WDs have composite spectra indicating a low-mass MS companion (Berg et al. 1992), most of those systems are expected to be very wide, noninteracting binaries (de Kool & Ritter 1993). Comparing the space densities of WD + dM and WD + dC systems of similar orbital properties may eventually reveal the fraction of AGB stars that transfer mass in the carbon star phase, whether that fraction changes with stellar population, and how the transfer takes place.

In conclusion, dC's show enhanced *s*-process abundances and a wide range of carbon isotope ratios. Their radial velocity variability, while poorly constrained in this study, is not inconsistent with the observed orbits of the CH giants. Out of the 10 dC's currently known, three dC systems (two composite spectrum DA/dC's and one single-line spectroscopic binary) are definitely in binary systems with post–AGB stars. The evidence thus suggests that dC's are the MS progenitors of CH giants and/or that CH giants are the high-luminosity tail in a distribution of MTB systems numerically dominated by dC's. Although very difficult for such faint stars, high-resolution echelle spectroscopy can more conclusively resolve the questions of origin and evolution of dC's that remain.

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