Distances of Dwarf Carbon Stars

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Abstract

Parallaxes are presented for a sample of 20 nearby dwarf carbon stars. The inferred luminosities cover almost two orders of magnitude. Their absolute magnitudes and tangential velocities confirm prior expectations that some originate in the Galactic disk, although more than half of this sample are halo stars. Three stars are found to be astrometric binaries, and orbital elements are determined; their semimajor axes are 1–3 au, consistent with the size of an AGB mass-transfer donor star.

Key words: astrometry – parallaxes – proper motions – stars: carbon – stars: distances

Supporting material: machine-readable tables

1. Introduction

Distances, absolute magnitudes, and luminosities for the dwarf carbon (dC) stars are uncertain. They tend to be faint, and at sufficiently large distances, so their parallaxes are not easy to measure. To date, only three have published parallaxes (Dahn et al. 1977; Harris et al. 1998); those three have similar colors and absolute magnitudes. However, properties of the many dC stars discovered in recent years (Margon et al. 2002; Downes et al. 2004; Green 2013) suggest that they are likely to have a broad range of physical properties, and expectations about their origin (Green & Margon 1994) suggest that they are likely to be produced in both disk and halo populations with a range of metallicities and absolute magnitudes. This paper presents parallaxes for an expanded sample of dC stars, with a goal of investigating the range of absolute magnitudes over which these stars extend.

2. Data

2.1. Sample

The sample of 20 dC stars in this paper consists of 13 targets taken from the Sloan Digital Sky Survey (SDSS; Fukugita et al. 1996; Gunn et al. 1998, 2006; York et al. 2000) and seven targets from other papers in the literature. Three have parallaxes published previously (Harris et al. 1998), and here we give an improved parallax for two of them (LHS 1075 and CLS 96), and an entirely new parallax for the third (G77-61). These targets were chosen to be definite dwarfs (as opposed to giant carbon stars) based on their significant proper motions. They were selected to be “nearby” (with distances likely to be within 300 pc) so as to have significant parallaxes; criteria used to select the sample included large proper motion, bright apparent magnitude for a candidate’s color, and a range of colors and band strengths so as to include a variety of types of stars. The sample does not include any of the warm, CH-like stars from the SDSS, because the estimated distances for even the brightest were >500 pc, too distant to obtain a meaningful parallax measurement.

Images have been taken with the U.S. Naval Observatory’s (USNO) 1.55 m Strand Astrometric Reflecting Telescope in Flagstaff, AZ. Descriptions of the telescope, the CCD cameras and filters used here, and the observing and processing procedures are given by Monet et al. (1992) and Dahn et al. (2017). The astrometric results are given in Table 1. Column (1) gives the identifying number in the 2MASS Point Source Catalog (Skrutskie et al. 2006). The 2MASS J number provides an unambiguous link to SIMBAD where many alternate names and much additional information can be found. Column (2) gives alternate names, usually the name by which the star was first identified as a carbon star. Columns (5) and (6) indicate the camera and filter employed for each parallax determination, while Columns (7), (8), and (9) give the number of acceptable CCD frames (observations), the number of separate nights on which those observations were obtained, and the number of reference stars employed in astrometric solutions, respectively. Columns (10) and (11) give the years observed and total epoch range, respectively. The derived relative parallax and its mean (standard) uncertainty are given in Column (12) (throughout this work, we refer to the trigonometric parallax angle as $\pi$). The relative total proper motion and its uncertainty follow in Column (13), and the position angle of the proper motion is given in Column (14). The error in the position angle reflects the uncertainty in the orientation of the CCD in its dewar, and of the dewar on the telescope. The derived absolute parallax and its uncertainty are presented in Column (15), and the calculated tangential velocities and their uncertainties are given in Column (16).

Many of the 20 stars in this paper are near the faint limit for this observing program and require long exposure times and good seeing. As a consequence, we have obtained fewer observations than desired, some with lower signal-to-noise ratios than desired, and the resulting parallax values have larger errors than desired. Nevertheless, the parallaxes are significant for all stars: the fractional error in parallax has a median value of 9%, and ranges from 3% in the best case to 23% in the worst case.

* Deceased.
### Table 1
Astrometric Results

| 2MASS J (1) | Alternate Names (2) | R.A.* (J2000.0) (3) | Decl.* (4) | Cam. (5) | Filt. (6) | Nf (7) | Nn (8) | Ns (9) |
|-------------|---------------------|--------------------|-----------|----------|---------|-------|-------|-------|
| 00260048−1918519 | LHS1075 (LP765-18) | 00 26 00.2 | −19 18 52 | TEK2K | A2−1 | 148 | 129 | 7 |
| 01202853−0836307 | SDSS J012028.55−083630.8 | 01 20 28.5 | −08 36 31 | EEV24 | I−2 | 112 | 92 | 10 |
| 01215031+0113024 | LP578-45 (NLTT4523) | 01 21 50.3 | +01 13 03 | TEK2K | I−2 | 145 | 144 | 8 |
| 03323808+0157599 | G77-61 (LHS1555) | 03 32 38.1 | +01 58 00 | EEV24 | A2−1 | 117 | 71 | 13 |
| 07425720+4659186 | LSPM J0742+4659 | 07 42 57.2 | +46 59 18 | EEV24 | I−2 | 277 | 145 | 12 |
| 08180742+2234290 | SDSS J081807.45+223429.6 | 08 18 07.4 | +22 34 29 | EEV24 | I−2 | 127 | 106 | 20 |
| 08345114+0740088 | SDSS J083451.15+074008.8 | 08 34 51.2 | +07 40 09 | EEV24 | A2−1 | 37 | 30 | 17 |
| 09332463−0031445 | HE 0930−0018 | 09 33 24.6 | −00 31 45 | TEK2K | A2−1 | 100 | 97 | 14 |
| 10549214−3402259 | CLS31 | 10 54 29.4 | −34 02 26 | EEV24 | I−2 | 63 | 61 | 9 |
| 11034878+5559373 | SDSS J110348.86+555937.2 | 11 03 48.9 | +55 59 37 | TEK2K | I−2 | 204 | 186 | 7 |
| 13533300−0040395 | SDSS J135333.01−004039.4 | 13 53 33.1 | −00 40 40 | TEK2K | I−2 | 222 | 198 | 11 |
| 14531880+6004209 | SDSS J145318.83+600421.0 | 14 53 18.8 | +60 04 21 | EEV24 | I−2 | 111 | 93 | 9 |
| 14572597+2341257 | SDSS J145725.86+234125.5 | 14 57 25.9 | +23 41 26 | EEV24 | I−2 | 44 | 41 | 21 |
| 15270276+4345172 | SDSS J152702.74+434517.3 | 15 27 02.8 | +43 45 17 | TEK2K | I−2 | 287 | 231 | 15 |
| 15480927+3227247 | SDSS J154809.22+322724.9 | 15 48 09.2 | +32 27 25 | TEK2K | I−2 | 115 | 96 | 15 |
| 15523734+2927591 | LP328-57 (CLS96) | 15 52 37.4 | +29 27 59 | TEK2K | A2−1 | 242 | 183 | 10 |
| 16232838+4237538 | LP225-12 (NLTT42660) | 16 22 32.9 | +42 37 54 | TEK2K | I−2 | 293 | 231 | 8 |
| 16313278+3535285 | SDSS J163132.78+353528.5 | 16 31 32.8 | +35 35 29 | EEV24 | I−2 | 147 | 106 | 17 |
| 21051653+2514486 | LSR J2105+2514 | 21 05 16.5 | +25 14 49 | TEK2K | I−2 | 165 | 146 | 15 |
| 21493784−1138285 | LP754-48 (NLTT55182) | 21 49 37.8 | −11 38 29 | TEK2K | A2−1 | 277 | 227 | 6 |

**Notes.**
* Coordinates are from the 2MASS catalog.
* Estimated Galactic population membership (see Section 3): (1) disk, (2) halo, (3) intermediate, (4) contradictory.
* Notes on individual objects. (1) Hints of a possible very low amplitude perturbation not confirmed. (2) No evidence seen corresponding to the 245-day radial velocity period reported by Dearborn et al. (1986). (3) Tabulated astrometry after removal of the perturbation discussed in Section 2.4 below. (4) This is the common proper motion companion to 2MASS J14572616+2341227 (LSPM J1457+2341S) for which π_{abs} = 5.77 ± 1.48 mas was reported in Dahn et al. (2017). These additional observations further support the physical nature of the pair. The weighted mean astrometric results for the pair are reported above. Kirkpatrick et al. (2016) reported evidence for a third component based on the ALLWISE motion survey.

(This table is available in its entirety in machine-readable form.)

### 2.3. Photometry

Photometry of most of the target stars and their surrounding reference stars was obtained with the USNO 1.0 and 1.55 m telescopes using Johnson–Cousins BVI filters. These data were used in the astrometric processing above to correct for differential color refraction (DCR). For those fields lacking BVI photometry, gri data from the SDSS database were transformed to BVI using the relations of Ivezić et al. (2007) and then used for the DCR corrections. Photometric data for the 20 dC target stars is given in Table 2 including JHK₅ from 2MASS.
Note.

Table 2
Photometric Results

| Parameter | LSPM J0742+4659 | LP225-12 | LP758-43 |
|-----------|-----------------|----------|----------|
| Period (year) | 1.23 ± 0.01 | 3.21 ± 0.01 | 11.35 ± 0.15 |
| $a^2$ (mas) | 5.83 ± 0.54 | 14.21 ± 0.41 | 22.09 ± 0.14 |
| $i$ (deg) | 150 ± 4 | 72 ± 2 | 63.3 ± 1.0 |
| $e$ | 0.3 ± 0.2 | 0.3 ± 0.2 | 0.1 ± 0.1 |
| $\omega$ (deg) | 132 ± 20 | 270 ± 15 | 350 ± 20 |
| $\Omega$ (deg) | 154 ± 5 | 128.5 ± 0.5 | 282 ± 3 |
| $T_0$ | 2014.1 ± 0.1 | 2006.5 ± 0.5 | 2011.0 ± 0.5 |

Note.

Table 3
Orbits of New Astronomical dC Binaries

Note.

2.4. Binary Orbits

Three stars in this sample, LSPM J0742+4659, LP225-12, and LP758-43, were found to have significant systematic astrometric residuals from the default solution for parallax and proper motion, indicating a periodic perturbation from an unseen binary companion. A solution for the orbit of the photocenter (iterating between the parallax solution with the orbit removed, and the orbit solution with the parallax and proper motion removed) was carried out. The results for the parallax and proper motion are given in Table 1, and those for the orbital motion are given in Table 3, which are plotted in Figures 1 through 3. The eccentricity for all three orbits is quite small and, within the observational errors, is consistent with zero. A fourth target G77-61 has been found to be a spectroscopic binary (Dearborn et al. 1986), but we have not yet detected any significant signature of the orbit in the astrometric data. Another example of a dC spectroscopic binary was found among the SDSS carbon stars (Margon et al. 2018). It is notable for its short orbital period of 2.9 day, much shorter than that of G77-61 and the three new systems reported here. This short period implies a different orbital evolution during the mass-transfer process. Other spectroscopic binaries are being found in a new survey of dC stars (L. J. Whitehouse et al. 2018, in preparation).

3. Discussion

Studies by McClure and others (McClure & Woodsworth 1990; McClure 1997) have shown that the subgiant CH, giant CH, and giant Ba stars are all binaries, most with periods 400–4000 days and with eccentricities smaller than for normal binaries. These facts indicate a previous phase of orbital dissipation during mass transfer from an AGB companion, likely during wind accretion from the companion.

The orbits of the three dC binaries in this paper are consistent with this picture. The three binaries have periods 450–4100 days, and their eccentricities are small. Using the parallaxes in Table 1, the amplitudes of the photocenter orbits in Table 3 are 0.9, 1.6, and 3.1 au. The true orbits will be larger if the secondary star is contributing significant light to the photocenter. Because the data are taken with a red filter (the wide-R A2-1 filter for LP758-43, and I-2 for the other two binaries) and the companions are likely to be white dwarfs, we expect that not much light is contributed by the companions.
These amplitudes are comparable to those for the CH and Ba stars studied by McClure and are similar to the maximum size of the AGB star thought to be the source of the carbon-rich material transferred to the dC star we see now.

The binaries found in this paper are expected to be those with long periods among nearby targets, because they will have the largest apparent (angular) orbits that are easiest to detect astrometrically. It is likely that more binaries with smaller astrometric amplitudes are undetected in our sample. Indeed, the high frequency of binaries being found using radial velocities (L. J. Whitehouse et al. 2018, in preparation) indicates that most or all dC stars are now in binaries with white dwarf companions. Further study, and the determination of their orbits, can confirm this expectation.

Figure 4 shows that the stars in this sample have J − Ks colors redder than oxygen-rich dwarfs and subdwarfs. Presumably, their J-band flux is suppressed by CN absorption, although some contribution from Ks-band brightening from dust emission in a few stars is possible. The subdwarf LHS466, taken from Dahn et al. (2017), has J − Ks = 0.88 measured by 2MASS, suggesting it might be the brightest known dC star. However, its UKIDSS J − Ks = 0.64, corresponding to 0.66 on the 2MASS system, indicates the 2MASS value is spurious or contaminated. Therefore, Figure 4 appears to provide a nearly clean separation of our dC stars.

Using J − Ks colors to separate dC stars from the far more common oxygen-rich dwarfs may provide an important means of identifying a complete sample of dC stars in the solar neighborhood. This step will be necessary to avoid the selection effects in the present discovery of dC stars from SDSS, and thus in the sample in this paper. Therefore, Figure 4 may provide a procedure to utilize Gaia data for an expanded sample to facilitate understanding the true range of properties of these stars.

Figure 5 shows a color-absolute magnitude diagram of the stars in this paper. They cover a range of Mv of 7.9–12.4, and are subluminous by up to 3 mag in Mv. We see that the close agreement of Mv for the first 3 dCs with parallaxes (Harris et al. 1998) was apparently fortuitous. Using the degree of
subluminosity in Figure 5, together with their tangential velocities from Table 1, we can classify each star as probable disk or halo (Column 17 in Table 1). We find four stars are probable disks, 10 stars are probable halos, two stars have intermediate values of subluminosity and velocity, and four stars have contradictory values. This result confirms that the dC stars do have a wide range of properties, with origins in the disk as well as the halo (Farhi et al. 2018).

The first dC star (G77-61) was identified as a dwarf from its parallax as measured by the USNO plate parallax program (Dahn et al. 1977). Forty years later, parallaxes have been measured for only 20 additional dC stars, all by the USNO CCD parallax program, including the 20 presented in this paper. Gaia DR2 will probably have parallax data for most of the stars in this paper (Katz & Brown 2017). The faintest stars may have $G > 20$, fainter than the limit for DR2, and a few are likely to have a binary perturbation detected by Gaia, and will be omitted from DR2 until a later data release. For the stars that are in DR2, the formal error of the DR2 parallaxes is estimated to be 0.1–0.7 mas for the magnitude range of our dC sample. Therefore, DR2 data probably will improve on the conclusions of this paper, other than the topic of binary perturbations that DR2 will not address. Later data releases from Gaia will certainly improve on the distances, the binary characteristics, and the sample size available to understand dC stars.

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Figure 5. $M_V$ vs. $V - I$ for the dwarf carbon stars in this paper (red circles). The three new astrometric dC binaries are noted. Additional data points include late K- and M-dwarf (black circles) and subdwarf stars (blue circles) from Dahn et al. (2017) and Hipparcos. Also plotted are extreme subdwarf (green circles) and ultra subdwarf (green triangle) M stars from Dahn et al. (2017).

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