Chandra Observations of the Nearest Dwarf Carbon Stars

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ABSTRACT

As main-sequence stars with C/O > 1, dwarf carbon (dC) stars are never born alone but inherit carbon-enriched material from a former asymptotic giant branch (AGB) companion. In contrast to M dwarfs in post-mass transfer binaries, C2 and/or CN molecular bands allow dCs to be identified with modest-resolution optical spectroscopy, even after the AGB remnant has cooled beyond detectability. Accretion of substantial material from the AGB stars should spin up the dCs, potentially causing a rejuvenation of activity detectable in X-rays. Indeed, a few dozen dCs have recently been found to have photometric variability with periods under a day. However, most of those are likely post-common-envelope binaries (PCEBs), spin-orbit locked by tidal forces, rather than solely spun-up by accretion. Here, we study the X-ray properties of a sample of the five nearest known dCs with Chandra. Two are detected in X-rays, the only two for which we also detected short-period photometric variability. We suggest that the coronal activity detected so far in dCs is attributable to rapid rotation due to tidal locking in short binary orbits after a common-envelope phase, late in the thermally pulsing (TP) phase of the former C-AGB primary (TP-AGB). As the radius of a TP-AGB star rapidly expands once it reaches the C giant phase, the initial range of orbital periods that can lead to the mass transfer balance necessary to form a short period dC remains a mystery.

Keywords: Carbon stars (199), Chemically peculiar stars (226), Binary stars (154), Close binary stars (254), Common envelope evolution (2154), X-ray stars (1823)

1. INTRODUCTION

Dwarf carbon (dC) stars are main-sequence stars that show molecular absorption bands of C, such as C2, CN, and CH, in their optical spectra. Traditionally, carbon stars were thought to be enhanced intrinsically. Stars on the thermally pulsing (TP) phase of the asymptotic giant branch (AGB) experience shell He flashes. These He flashes cause strong convection in the intershell region, with resulting dredge-up (the third dredge-up; Iben 1974) of He fusion products, namely carbon.

If enough carbon is dredged up into the atmosphere of the AGB star to turn C/O > 1, the carbon preferentially binds with oxygen to form CO, leaving excess carbon to form the aforementioned molecules of C2, CN, and CH.

This traditional explanation for C stars made it surprising when Dahn et al. (1977) found the first dwarf carbon star, G77-61. As dCs are main-sequence stars (hydrogen core fusing), they could not have produced their own carbon, nor could they have experienced the third dredge-up necessary to bring this carbon to their envelopes. G77-61, and the hundreds of dC stars found since, must have been extrinsically enriched with C. Dahn et al. (1977) put forth a few theories for this extrinsic carbon enhancement, with the preferred method being binary mass transfer.
1.1. Binary Formation of dCs

In the mass transfer scenario, the dC progenitor is in a binary system with a more massive star that evolved into a TP-AGB star. This TP-AGB star experienced intrinsic carbon enhancement as described above and became a giant C star itself. During the TP-AGB phase, stars can rapidly expand once C/O > 1, reaching radii of up to 800 R⊙ (Marigo et al. 2017) and can have slow, massive winds with mass loss rates of ~ 10⁻⁷–10⁻⁵ M⊙ yr⁻¹ (Höfner & Olofsson 2018). This large, slow, carbon enhanced wind can be accreted by the dC progenitor, bringing C/O > 1 and forming a dC. The TP-AGB then evolves further, expelling its envelope via a wind, leaving behind the CO core as a white dwarf (WD). The WD then cools over giga-year time scales, usually beyond detection in optical spectra.

Many studies have supported this binary mass transfer hypothesis. The first known dC, G77-61, was found to be a binary via radial velocity monitoring with a period of 245.5 d (Dearborn et al. 1986). Additionally, there have been almost a dozen “smoking gun” systems in which the WD is still visible in the optical spectrum, indicating more recent mass transfer, i.e., a hot WD which has been cooling for a shorter time than in most dCs binaries (Heber et al. 1993; Liebert et al. 1994; Green 2013; Si et al. 2014). Harris et al. (2018) found three dCs to be astrometric binaries with periods of 1.23 yr, 3.21 yr, and 11.35 yr. Both Whitehouse et al. (2018) and Roulston et al. (2019) found radial velocity variations among a large sample of dCs, with the latter finding a binary fraction near unity as would be expected from the mass transfer theory (95%; Roulston et al. 2019). We note for context that the CH, Ba and the carbon-enhanced metal poor (CEMP-s) stars (Lucatello et al. 2005) - mostly giants or subgiants - likely evolved from dC stars, and are better known than dCs only by virtue of their larger luminosities.

It was traditionally thought that accretion of the mass needed for dCs to form would take place via Bondi-Hoyle-Lyttleton (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944) accretion. This was because, if the initial orbital separation was too close during the rapid expansion of the AGB radius during the TP-AGB phase, a common-envelope (Paczynski 1976) would result. On a timescale of 100–1000 yrs, this common-envelope would drastically shrink the orbital period and result in the ejection of the TP-AGB envelope. This envelope ejection would truncate the thermal pulses, and if there had not already been sufficient carbon enhancement, the proto-dC would remain a normal O-rich main-sequence star.

However, there are numerous cases of short-period dCs that have been found. Miszalski et al. (2013) found that the central star of the “Necklace” planetary nebula is in a binary with a dC companion, with an orbital period of 1.16 d (Corradi et al. 2011). Here, we see direct evidence of the common-envelope and the expelled envelope in the form of the nebula. Margon et al. (2018) found a dC without these clear signs of common-envelope to have a period of 2.92 d using multi-epoch photometric surveys.

Roulston et al. (2021) just published 34 new dC periods, and Whitehouse et al. (2021) found 5 new dC periods. Remarkably, 95% of this combined sample of dCs have P < 10 d (with the shortest being from Roulston et al. (2021) with a period of only 3.2 hr). It is clear that dCs can go through a common-envelope, and possibly even a significant fraction do so.

1.2. dC Rotation and Activity

Main-sequence stars are known to “spin down” as their rotation rates, dynamo strengths, and associated activity decrease with age (e.g., Kraft 1967; Skumanich 1972). As dCs are thought to be from older thick disk and halo populations (Green 2013; Farihi et al. 2018), they may be expected to exhibit slower rotation rates and corresponding weaker activity. To demonstrate dCs’ likely population and hence age, we show a Toomre diagram for a sample of dCs in Figure 1. We used the Green (2013) SDSS sample of C stars, matching to Gaia EDR3 (Gaia Collaboration et al. 2021). We selected only those stars with: (1) parallax \( \varpi/\varpi_{\text{err}} > 5 \) (2) proper motion signal-to-noise > 5 in both right ascension and declination and (3) absolute \( M_G > 5 \). We measured the dC radial velocities from the Hα line, and then used the Gaia EDR3 distance and proper motions to calculate the space velocities \( U, V, W \). We mark the transitions between thin and thick disk, and thick disk and halo kinematics. As seen in the figure, the majority of dCs show kinematics consistent with either thick disk or halo populations.

However, dCs’ activity may not correlate simply with age, because they are not single stars and therefore do not evolve independently. Indeed, dCs reveal a population of binary systems in which interaction and mass transfer can be confirmed by simple inspection of their signature optical spectra. Jeffries & Stevens (1996) showed that a slow (10–20 km s⁻¹) AGB wind can spin up a low-mass companion to short (≤ 10 hr) rotation periods. If dC stars gain most of their carbon-rich mass through wind-Roche Lobe Overflow (WRLOF; Mohamed & Podsadiłowski 2007), which focuses the wind into the orbital plane, it is possible that this may cause dCs to spin up to even shorter periods. Rapid rotation in stars with convective envelopes drives a magnetic dynamo, so this spin-up rejuvenation may result in enhanced chromospheric and coronal activity (e.g., Kovtun 2013), which normally yield observable Hα and/or X-ray emission. Since M dwarfs show activity lifetimes of ~ 1–5 Gyr (West et al. 2008), dCs may remain active after mass transfer for similar timescales. Additionally, Matrozis et al. (2017) modeled the maximum amount of mass the progenitors of the more well studied Ba and CEMP-s stars can accrete before reaching critical rotation. They found the in order for these stars, and by similarity dCs, to accrete enough material to change their surface abundances there must be angular momentum loss from the freshly spun-up accretor. They suggest one possible method of angular momentum loss is through enhanced magnetic braking from the increased differential rotation of the accretor envelope.
Figure 1. Toomre diagram for dCs showing the UVW kinematics with the dCs shown as red scatter points (the cyan points are periodic dCs from Roulston et al. 2021). The radial velocity for each dC was measured from the Hα line. Distances and proper motions were taken from Gaia EDR3. The marked dashed and dotted lines represent, respectively, the divisions between thin and thick disks, and thick disk and halo kinematics \( V_{\text{tot.}} = 70, 180 \text{ km s}^{-1} \); Bensby et al. 2005; Reddy et al. 2006; Nissen & Schuster 2009). A sample of SDSS K and M dwarfs are shown as the background heatmap, with darker colors showing regions with a higher density of K and M dwarfs. These normal (C/O < 1) stars are more representative of the thin and thick disk. dCs must be in binary systems, and likely short period binary systems. These short periods correspond to large radial velocity variations which may inflate the dC UVW velocities. We therefore also inflate the K and M dwarfs UVW space velocities with similar velocities using the RV models of Roulston et al. (2019). The left panel (a) shows the uninflated UVW space velocities for the K and M dwarfs, while the right panel (b) shows the inflated UVW velocities. Even when the K and M dwarfs are inflated with larger velocities to match the dCs, they do not match the same UVW kinematics as the dCs, pointing to dCs truly originating from thick disk or halo populations.

Green et al. (2019b) thus aimed to study the activity and rejuvenation of dCs using Chandra. Their sample was constructed to observe the dCs that were most likely to be detected based on optical spectroscopy, i.e., those with either Hα emission or showing a composite dC+WD spectrum. They detected all six members of their observed sample; however, their sources lacked enough counts to robustly fit a model to the source spectrum. Nonetheless, they fit two models appropriate for coronally active stars, with differing plasma temperatures of 2 MK and 10 MK. Green et al. (2019b) found that when assuming the lower 2 MK plasma temperature, dCs populate the saturated regime where \( \log \left( \frac{L_x}{L_{\text{bol}}} \right) \sim -3.3 \) (e.g., Wright et al. 2011), indicating short rotation periods. However, with the higher 10MK plasma temperatures, only half of the dCs remain in the saturated regime, with periods weakly constrained to < 20 d. While there were no rotation periods available in Green et al. (2019b), they argued that their saturated X-ray activity indicated rapid rotation rates that were indicative of dC spin up from mass transfer.

Green et al. (2019b) end their discussion with the caveat that their sample is not representative of dCs in general since they explicitly observed those dCs with optical signs of activity. They argue that observations of a sample of the closest dCs, without requiring signs of activity, is critical to understanding the dC rotation-activity relationship. Here, we have targeted such a sample, observing the five closest known dCs.

2. SAMPLE SELECTION

We compiled our parent sample of dCs from the current literature. The largest contributor (747 dCs, 79%) is the Green (2013) sample of carbon stars from the Sloan Digital Sky Survey (SDSS; Blanton et al. 2017). We also selected a smaller number of dCs from Si et al. (2014), who found 96 new dCs using a label propagation algorithm from SDSS DR8, and Li et al. (2018) who selected carbon stars from the Large Sky Area Multi-Object Fiber Spectroscopic Telescope survey (LAMOST; Cui et al. 2012) using a machine learning approach. Our resulting final sample consists of 944 dCs, where we ensured that each is indeed a dC by verifying that each C star had \( M_G > 5 \text{ mag from Gaia Early Data Release 3} \) (Gaia EDR3; Gaia Collaboration et al. 2021) while having a significant parallax of \( \varpi / \varpi_{\text{err}} > 10 \).

We then selected the five closest dCs to make our final sample. Our selected sample can be found in Table 1 with their corresponding Gaia EDR3 properties. In addition, we have estimated the bolometric luminosities for each dC in the
exposures (ObsIDs). None of our observations use a grating and all were taken in VFAINT ACIS mode; observation details can be found in Table 2.

We reprocessed the Chandra event lists for all ObsIDs with the CIAO (ver 4.13.0) chandra_repro script and CALDB (4.9.5). This reprocessing ensures we have used the most recent calibrations for our data, including corrections for afterglows, bad pixels, charge transfer inefficiency, and time-dependent gain corrections. We searched each ObsID for each target near the expected Gaia EDR3 position, detecting sources for two of our five targets, J0435 and SDSS1310. We detected J0435 in all five ObsIDs, with all detections being within 1′′ of the expected Gaia EDR3 position. SDSS1310 was detected within 0.3′′ of the Gaia EDR3 position. A detection was counted if there were multiple neighboring pixels, within 5′′ of the expected source, that had at least one X-ray count.

We estimated source properties in the 0.3–8.0 keV energy range using the CIAO srcflux tool for the two dCs with detections. For both detections, we used a circular aperture of 5′′ for the source region and an annular aperture with an inner radius of 5′′ and outer radius of 15′′ for the background region. Both of these regions were centered on the detected position of the dC. We accounted for Milky Way dust extinction by using the 3-dimensional Bayestar17 (Green et al. 2018) dust maps from the dustmaps Python package (Green 2018); resulting line of sight column density ($N_H$) values are listed in Table 2.

Table 2 lists the ObsIDs for each dC, the observation properties, and the X-ray source properties for each dC. The calculated net count rate for each ObsID is given, with the $3\sigma$ upper and lower error limits. For the three dCs with no detections, the $3\sigma$ upper limits are given. Following Green et al. (2019b), we derived two X-ray flux estimates, using both a 2 MK and a 10 MK optically thin plasma (APEC; Smith et al. 2001) with absorption modeled using WABS (Morrison & McCammon 1983). We list the $3\sigma$ upper and lower limits for the two dCs with detections for the net count rate, observed flux, unabsorbed flux, and X-ray luminosity. For the three dCs without detections, we list the $3\sigma$ upper limits.

### 3.1. Individual Spectral Fits

For the dCs SBSS1310 and J0435, we have also fit individual spectral models for each observation. These individual fits use the same APEC and WABS models as before, but now fitting the plasma temperature, column density, and a normalization as free parameters.

#### 3.1.1. SBSS1310

The best fitting model for SBSS1310 consists of a 12.1 MK plasma temperature with a low column density ($3\sigma$ upper limit of $N_H = 9.6 \times 10^{22}$ cm$^{-2}$). This column density is consistent with the negligible Bayestar17 expected line of sight column density of $N_H = 3 \times 10^{19}$ cm$^{-2}$.
Table 1. Parallaxes, Distances and Bolometric Luminosities

| Object     | R.A.     | Decl.    | \(\varpi\) | Distance | \(M_G\) | \(\log (L_{bol}/L_\odot)\) |
|------------|----------|----------|------------|----------|---------|-----------------------------|
| LSPM J0435+3401 (J0435) | 04h35m26.31s | +34d01m35.54s | 7.819 ± 0.019 | 127.19 ± 0.21 | 8.18 | -1.27 ± 0.01 |
| LAMOST J054640.48+351014.0 (J0546) | 05h46m40.51s | +35d10m13.23s | 6.126 ± 0.035 | 162.05 ± 0.62 | 9.03 | -1.54 ± 0.01 |
| HE 1205-0417 (HE1205) | 12h07m51.75s | -04d34m41.55s | 6.52 ± 0.12 | 153 ± 2 | 8.90 | -1.43 ± 0.01 |
| LAMOST J124055.15+485114.2 (J1240) | 12h40m55.17s | +48d51m14.14s | 5.57 ± 0.15 | 179 ± 3 | 8.93 | -1.55 ± 0.02 |
| SBSS 1310+561 (SBSS1310) | 13h12m42.27s | +55d55m54.84s | 9.538 ± 0.023 | 104.48 ± 0.17 | 9.10 | -1.51 ± 0.01 |

Note—Selected dCs in our sample. For each, we list the coordinate positions and parallaxes from Gaia (Gaia Collaboration et al. 2021). We take the distance for each dC from Bailer-Jones et al. (2021), which were used to calculate the absolute Gaia G band magnitude. Additionally, for each dC, we include the bolometric luminosity as calculated from our SED fits. Here, we adopt the solar bolometric luminosity of \(\log (L_\odot/\text{erg s}^{-1}) = 33.583\).

Table 2. Chandra X-ray Observations

| Object | ObsID | Obs-Date   | Exposure | Net Count Rate | \(N_H\) | \(T_X\) | \(F_X\) | \(L_X\) |
|--------|-------|------------|----------|----------------|--------|--------|--------|--------|
|        |       |            | [ks]     | [cnt ks^{-1}]  | \([10^{19} \text{ cm}^{-2}]\) | \([\text{MK}]\) | \([10^{-15} \text{ erg cm}^{-2} \text{s}^{-1}]\) | \([10^{28} \text{ erg s}^{-1}]\) |
| J0435  | 22298 | 2019-09-15 | 10.12    | 2.61^{+0.33}_{-0.27} | 6.3^{+0.7}_{-1.1} | 2 | 230^{+57}_{-38} | 46^{+12}_{-8.9} |
|        |       |            |          |                |       |        |        |        |
|        |       |            |          |                |       |        |        |        |
|        |       |            |          |                |       |        |        |        |
|        |       |            |          |                |       |        |        |        |
|        |       |            |          |                |       |        |        |        |
| J0546  | 22299 | 2020-01-09 | 34.80    | <0.20          | 7.5^{+1.5}_{-0.6} | 2 | <18 | <24 | <7.2 |
|        |       |            |          |                |       |        |        |        |
|        |       |            |          |                |       |        |        |        |
|        |       |            |          |                |       |        |        |        |
|        |       |            |          |                |       |        |        |        |
| HE1205| 22300 | 2020-04-04 | 24.23    | <0.44          | 8.4^{+1.3}_{-1.2} | 2 | <47 | <51 | <14  |
|        |       |            |          |                |       |        |        |        |
|        |       |            |          |                |       |        |        |        |
|        |       |            |          |                |       |        |        |        |
| J1240  | 22301 | 2019-09-19 | 36.78    | <0.34          | 6.3^{+0.8}_{-1.2} | 2 | <31 | <32 | <10  |
|        |       |            |          |                |       |        |        |        |
|        |       |            |          |                |       |        |        |        |
|        |       |            |          |                |       |        |        |        |
| SBSS1310| 22302 | 2020-01-25 | 14.90    | 1.98^{+0.24}_{-0.19} | 3.0^{+1.8}_{-1.7} | 2 | 203^{+47}_{-32} | 210^{+49}_{-33} | 40.7^{+9.5}_{-6.4} |
|        |       |            |          |                |       |        |        |        |
|        |       |            |          |                |       |        |        |        |

Note—Chandra observations of the nearest dCs. The ObsID, date, and exposure time are listed for each individual observation. For the dCs with detections (J0435, SBSS1310), the net count rate is shown. For each detected exposure, we use the column density \((N_H)\) from Green et al. (2019a) and assume two different plasma temperatures of 2 MK and 10 MK. For each assumed plasma temperature, the observed source flux, unabsorbed source flux, and source luminosity are calculated in the 0.3–8.0 keV range. The 1σ errors for each property are shown. For dCs without a detection, the 3σ upper limits are shown assuming the same set of plasma temperatures.
Figure 3. Best fitting spectral model for SBSS13010. The left panel, (a), shows the observed source spectrum in black scatter points with the associated errors. The best fitting model is shown as the solid red line. The right panel, (b), shows the contours for the plasma temperature and column density. The 1σ, 2σ, 3σ contours are shown as the solid, dashed and dotted lines respectively. The best fit parameters are shown as the blue marker, with the 1σ errors. The Bayestar17 expected line of sight column density is shown as the red dashed line for reference.
Figure 3 shows the best fit spectral model for SBSS1310. The left panel shows the observed source spectrum with the associated errors and the best fitting model. The right panel shows the error contours for the fit parameters, with the best fit parameters shown as the blue marker. The Bayestar17 expected line of sight column density is shown as the red dashed line for reference. The resulting model is consistent with the expected negligible column density, and with the assumed 10 MK plasma temperature from (Green et al. 2019b). Green et al. (2019b) assumed this 10 MK plasma temperature from (Green et al. 2019b). The colored scatter points show the best fitting parameters for the individual fits, with their errors. The simultaneous fit parameters are consistent within the errors with each of the individual fits and show that J0435 must have a higher intervening column density than expected from the Bayestar17 dust maps.

| Table 3. J0435 Individual Model Fits |
|-------------------------------------|
| ObsID | $N_H,\text{fit}$ | $T_X,\text{fit}$ |
|-------|----------------|----------------|
|       | [$10^{22}$ cm$^{-2}$] | [MK] |
| 22298 | $1.43^{+0.33}_{-0.32}$ | $33^{+11}_{-5.0}$ |
| 23376 | $2.07^{+0.25}_{-0.13}$ | $91^{+1.3}_{-3.3}$ |
| 24305 | $1.26^{+0.30}_{-0.18}$ | $101^{+1.8}_{-1.3}$ |
| 24893 | $1.48^{+0.14}_{-0.32}$ | $13.9^{+1.8}_{-1.2}$ |
| 24896 | $1.48^{+0.22}_{-0.28}$ | $13.6^{+1.4}_{-1.4}$ |

Note—Individual model fits for each ObsID of J0435. Each model uses the same model, but is fit independently. The 1σ errors for each fit parameter are shown.

We carried out five separate observations of J0435 with Chandra. As with SBSS1310, we fit each observation with a spectral model with plasma temperature and column density as free parameters. For each ObsID, the resulting plasma temperature and column density are listed in Table 3 with their 3σ errors. All of the fits result in a column density three orders of magnitude higher than the expected line of sight column density from Bayestar17 dust map ($N_H = 6.3 \times 10^{19}$ cm$^{-2}$). The fit plasma temperatures are consistent with the higher assumed values of the 10 MK models.

In addition to the individual fits, we simultaneously fit all five observations with one model. For this fit, we used the same APEC and WABS models as before, but all five observation are fit with the same plasma temperature and column density, allowing only the normalization to vary between each observation.

The simultaneous fit results in a column density of $N_H = 1.69 \pm 0.27 \times 10^{22}$ cm$^{-2}$ and a plasma temperature of $T_X = 13.4 \pm 2.4$ MK. Figure 4 shows both the individual and simultaneous fits for J0435. For each observation, the observed source spectrum is shown, with the best fitting individual model shown as a dashed blue line. The best fit simultaneous model is shown as the red solid line. The bottom panel shows the combined source spectrum, with the total simultaneous fit model.

Figure 5 shows the resulting best fit parameters for J0435. The colored scatter points show the best fitting parameters for the individual fits, with their errors. The simultaneous fit parameters are consistent within the errors with each of the individual fits and show that J0435 must have a higher intervening column density than expected from the Bayestar17 dust maps.

### 3.2. X-ray Variability

Since coronal activity is by nature variable, we searched for signs of X-ray variability in the dCs observed to date. We used the CIAO implementation of the Gregory-Loredo variability algorithm (Gregory & Loredo 1992) glvary. We tested all available ObsIDs for dCs in both the Green et al. (2019b) sample and this work. We found that none of the dCs in Green et al. (2019b) show significantly variable count rates, with all having a variability index of 0 or 1.

From this work, we found that SBSS1310 has a variability index of 2 and is considered not variable. For J0435, the variability indices are 6, 2, 0, 0, 6 for the ObsIDs 22298, 23376, 24305, 24893, and 24896 respectively. The first and last ObsID are considered definitely variable; the second ObsID (23376) is considered probably not variable, and the two ObsID with variability indexes of 0 are considered definitely not variable.

One possible explanation for this changing variability index may lie with the source of the X-ray emission in dCs, which is believed to be from coronal emission associated with rotation and magnetic activity. Stellar flares are associated with magnetic activity and magnetic reconnection (Petersen 1989), where most of the flare coronal emission is in...
Figure 4. *Chandra* count rate spectrum in the range 0.3–8.0 keV for J0435. Each of the five individual ObsIDs is shown, respectively, in the upper five panels. Each of the individual observations is fit separately with the same model. The resulting fit for each is shown as the blue dashed line in each panel, with the fit parameters shown in the panel. The combined spectrum of all five observations is shown in the bottom (last) panel. We fit all five observations simultaneously, forcing the same column density and plasma temperature, but leave the model normalization free to be fit for each observation. The resulting simultaneous fit is shown as the solid red line in each panel.
X-rays. As dCs show X-ray emission and are thought to have rejuvenated activity, we expect dCs to flare at similar rates as active M dwarfs. As flares are transient, stochastic events, the resulting X-ray emission will also be transient and stochastic. If J0435 has an active corona, we should observe some continuous level of X-ray emission. During a flare however, the X-ray emission should increase with a lifetime of the flare. These flares could be the source of the differing levels of variability between the J0435 observations.

We searched the TESS (Ricker et al. 2015) light-curve for J0435 for flares, finding one flare event, supporting that J0435 not only has rejuvenated magnetic activity, but that this magnetic activity is driving flares. Figure 7 shows the TESS light-curve of J0435. Following the method of Shibayama et al. (2013) we calculate the flare energy, assuming a flare temperature of 9000 ± 500 K G"unther et al. (2020). We find the flare energy to be $(1.52 \pm 0.32) \times 10^{36}$ erg. This is a very energetic flare that would be classified as a superflare (Shibayama et al. 2013). While most dCs have fallen in a TESS full-frame image, most are too faint to provide quality light-curves.

Additionally, for J0435, we used the best simultaneous fit model parameters to calculate the observed flux, unabsorbed flux, and source luminosity in the 0.3–8.0 keV range for each ObsID. These values are listed in Table 4 with their 1σ upper and lower limits. Figure 6 shows the unabsorbed model flux for each ObsID of the dC J0435. The individual observations are shown as the color scatter points with their respective 1σ errors. The red scatter point is the best fit for the combined set of all five observations. The black contours represent the 1, 2, and 3σ regions for the combined fit. The red dashed line is the expected column density at the distance of J0435 from Green et al. (2019a).

Figure 5. Fit values of the model column density ($N_H$) and plasma temperature ($T_X$) for the dC J0435. The individual observations are shown as the color scatter points with their respective 1σ errors. The red scatter point is the best fit for the combined set of all five observations. The black contours represent the 1, 2, and 3σ regions for the combined fit. The red dashed line is the expected column density at the distance of J0435 from Green et al. (2019a).

Figure 6. Unabsorbed model flux for each ObsID of the dC J0435. For each ObsID, the flux is calculated using the combined fit model parameters (see Figures 4 and 5). The dashed black line is the mean of the five observations, with the grey shaded region showing the mean error of the observations. We find no signs of variability in the source flux of J0435. The shaded region showing the average 1σ error across all five observations. Within these errors, we find no detectable variability in the source flux of J0435.

3.3. Rotation-Activity Relationship

In main-sequence stars, X-ray emission, and often chromospheric H\alpha emission, is associated with coronal activity due to magnetic activity. This activity is thought to be produced by an αΩ dynamo (Parker 1955) which requires a differentially rotating convective envelope and a solidly rotating radiative core. However, it has been found that even late-type, fully convective stars show magnetic activity associated with rotation (Wright et al. 2018). The Rossby number $Ro = P_{rot}/\tau$ (Noyes et al. 1984), which relates the rotation period to the convective turnover time ($\tau$), has been shown to correlate with activity and saturates for rapid rotators at the level of $\log (L_x/L_{bol}) \approx -3.3$ for $Ro \lesssim 0.13$ (Micela et al. 1985; Wright et al. 2011).

In Green et al. (2019b), all six of the observed dCs were detected with Chandra, with $\log (L_x/L_{bol})$ ranging from −4.5 to −3.2, depending on the assumed model plasma temperature. These values place the dCs in the saturated regime for stellar rotation; however, at the time, no rotation periods were known for these stars. The recent studies by Roulston et al. (2021) and Whitehouse et al. (2021) have found many new periods for dC stars, including five of the six in the Green et al. (2019b) sample. One of the detections in this work, SBSS1310, is in both Roulston et al. (2021) and Whitehouse
et al. (2021). However, J0435 does not have a known rotation period in the literature.

We searched the light-curve of J0435 in the Zwicky Transient Facility DR5 (ZTF; Bellm et al. 2019; Masci et al. 2019; Graham et al. 2019), for periodic signals. We used similar methods as detailed in Roulston et al. (2021), explained briefly here. We used an outlier removal procedure to clean the raw light-curve, before searching for periodic signals using a Lomb-Scargle periodogram (LS; Lomb 1976; Scargle 1982). While there were no significant peaks in the individual ZTF light curves, we used the multiband periodogram from (VanderPlas & Ivezić 2015) to search for shared variability in both the $g$ and $r$ bands. To consider a peak in the power spectrum as significant, we used the $5\sigma$ (five times the mean power) limit as well as the 0.1% false-alarm probability (FAP) limit (see Greiss et al. 2014 and Hermes et al. 2015 for more details). Additionally, we required that the peak frequency must be separated by at least 0.005 d$^{-1}$ from an observational alias, such as 0.5 d$^{-1}$ or 0.333 d$^{-1}$.

The highest peak in the combined ZTF power spectrum for J0435 meets both of these requirements, so we take the period to be 0.1719 ± 0.0016 d. We do note the caveat that this period is assumed to be both the rotation period and orbital period under the assumption that in a close binary system, we would expect a synchronized (Hurley et al. 2002), low eccentricity orbit. Figure 8 shows the ZTF light-curve for J0435 folded on the highest found significant peak. The best fitting single sinusoidal model to the data is shown for each band as the solid red line, with the residuals below. The bottom panel shows the power spectrum, and the power needed to reach our 5$\sigma$ or 0.1% FAP limits. J0435 also has a light curve in the Catalina Real-Time Transient Survey (Drake et al. 2009), but including this light curve in the multiband periodogram results in the same period and significance as the ZTF only analysis. Since the Catalina data have much larger errors, we do not include them in our multiband analysis.

With the newly found periods for the dCs in Green et al. (2019b) and this work, we can now place dCs on an activity-rotation diagram. Figure 9 shows the updated Figure 3 of Green et al. (2019b), but we now show the true position of the five dCs in that sample with their rotation periods (the one dC from that sample without a rotation period is still shown with horizontal lines). We additionally place the two new X-ray detected dCs from this work, SBSS1310 and J0435, on this diagram. For SBSS1310 we include both the 2 MK and 10 MK model values, both placing SBSS1310 in the saturated regime. For J0435, we use the simultaneous fit model, making it the best-constrained dC of both samples. J0435 is clearly in the saturated regime with a short rotation period ($P = 0.1719$ d) and $\log (L_x / L_{bol}) = -2.76$.

The dC sample of Green et al. (2019b) was chosen because its stars were expected to show X-ray activity due to being either composite spectroscopic binaries of the dC+DA type, or showing signs of chromospheric activity with H$_\alpha$ emission. This suggested that dCs have experienced spin-up from the angular momentum of the accreted material during mass transfer. As dCs are believed to be from older thick disk and halo populations (Green 2013; Farihi et al. 2018), we should expect them to have spun-down from magnetic braking and angular momentum loss through magnetized winds (Kraft 1967; Matt et al. 2015; Garraffo et al. 2018); therefore, any signs of short rotation periods would be indicators of mass transfer spin-up. Indeed, the location of the dCs from Green et al. (2019b) in the rotation-activity diagram indicated short rotation periods, which have now been confirmed by Roulston et al. (2021) and Whitehouse et al. (2021).

The dCs in the current study were selected to investigate if dCs, regardless of H$_\alpha$ emission or a spectroscopically detectable WD, show signs of spin-up and chromospheric rejuvenation. Indeed, we find that the two dCs with X-ray detections in this work are both in the saturated activity regime with short rotation periods.
However, the recent works of Roulston et al. (2021) and Whitehouse et al. (2021), where a large number of new dC periods were found, complicate the interpretation of activity as resulting only from accretion-induced spin-up (Green et al. 2019b). Remarkably, 95% of the new dC periods are under 10 d, with nine having been confirmed to have the same photometric (likely rotational) period and orbital period. Since dCs form via mass transfer from evolved TP-AGB stars and TP-AGB stars can reach radii of 800 R_⊙ (3.7 au) as they experience successively stronger thermal pulses (Marigo et al. 2017), these short period dC stars must have experienced a common-envelope phase (Paczynski 1976; Ivanova et al. 2013). Therefore, the dCs in this paper, and in Green et al. (2019b), must have experienced a common-envelope and the associated spiral-in to these short periods. This spiral-in results in the circularization and subsequent synchronization of the binary (Hurley et al. 2002), and therefore the resulting final dC should have a rotation period commensurate with post-common-envelope binaries (PCEBs), i.e. P~ 1 d. Thus, the X-ray detections in Green et al. (2019b) and in this work do indeed trace short period rotation of dCs; however, the cause of this dC spin-up is more likely associated with common-envelope spiral-in, and subsequent spin-orbit locking in the binary system with the remnant WD, and not necessarily angular momentum gain from accreting carbon-rich material. A more appropriate Chandra sample to probe accretion-induced spin-up would be to target dCs in which the orbital period is on the order of years. For example, the 3 dCs from Harris et al. (2018) (with astrometric periods of 1.23 yr, 3.21 yr, and 11.35 yr) should have avoided a common-envelope phase, and therefore, the rotation period should only have been affected by accretion.

4. J0435 SPECTRAL ENERGY DISTRIBUTION

The significant column density (N_H = 1.69 × 10^{22} cm^{-2}) from the spectral fit of J0435 indicates the presence of substantial material along our line of sight. However, the expected intervening column density from the Bayestar17 dust maps (N_H = 6.3 × 10^{19} cm^{-2}) suggest negligible amounts of dust in the direction and distance of J0435. This suggests that there may be either substantial circumbinary or circumstellar material around J0435.

The mass transfer process to form dCs requires the accretion of carbon-rich material from a former TP-AGB companion (which now as a WD, has cooled beyond detection). The carbon-rich dust expelled by these TP-AGB stars has large opacity to optical and infrared photons, driving high radiation pressure and therefore large mass loss rates of ~ 10^{-7} –
Figure 9. Updated activity-rotation figure from Green et al. (2019b). For context, the activity and rotation for normal (C/O < 1) main-sequence stars are shown in the background. The logarithm of X-ray to bolometric luminosity is plotted against rotation period for the normal dwarf stars from the samples of: Wright et al. (2011), Stelzer et al. (2016), and Wright et al. (2018). We show the dCs from the Green et al. (2019b) Chandra sample and use the recently found rotation periods from Roulston et al. (2021) and Whitehouse et al. (2021) to place those dCs at their true location on the diagram, assuming both 2MK and 10MK APEC plasma models for X-ray emission. The X-ray detected dC J1548 from the Green et al. (2019b) sample does not have a rotation period and so is marked by horizontal dashed lines. Finally, we show the two dCs with new X-ray detections reported in this paper, J0435 and SBSS1310, as well as the 3σ upper limits for the three non-detections. The rotation period for SBS1310 comes from Roulston et al. (2021), and the rotation period for J0435 is from this paper. For J0435, we use the simultaneous best-fit X-ray model of 13.4MK (section 3.1.2). It is clear that for either 2MK and 10MK models, most dCs are found in the saturated regime of active stars.

$10^{-5} \text{M}_\odot \text{yr}^{-1}$ (Höfner & Olofsson 2018). This should result in extended shells of dust around nascent dC systems. In addition, those dCs that experience a common-envelope phase will eject the envelope of the TP-AGB star resulting in a planetary nebula. This seems to be observed in the Necklace Nebula where the central source was found to be a binary with a dC, having a photometric period of 1.16 d (Corradi et al. 2011; Miszalski et al. 2013). As the WD companion to the newly minted dC cools, the planetary nebula should similarly fade, but may leave detectable signs of circumbinary dust and gas.

We compiled the spectral energy distribution (SED) of J0435 using a variety of catalog observations. In the optical, we cross-matched to Gaia EDR3 (Gaia Collaboration et al. 2021) and the Pan-STARRS1 survey (Chambers et al. 2016; Magnier et al. 2020a; Waters et al. 2020; Magnier et al. 2020b,c; Flewelling et al. 2020). In the near-infrared and mid-infrared, we cross-matched to the Two Micron All-Sky Survey (2MASS; Skrutskie et al. 2006) and WISE surveys respectively. We also cross-matched to the GALEX GR6/7 (Martin et al. 2005) finding only a near-ultraviolet (NUV, 130–180 nm) detection for J0435.

We obtained deeper NUV and far-ultraviolet (FUV) observations of J0435 using the Wide Field Camera 3 (WFC) and Advanced Camera for Surveys (ACS) detectors on the Hubble Space Telescope (HST). We obtained NUV images with WFC3 using the F225W filter, across one full orbit with a total exposure time of 2384.0s. The exposure was split into four equal exposures of 596.0s and dithered using the WFC3-UVIS-DITHER-BOX pattern, with point spacing of 0.173″ and line spacing of 0.112″. We obtained FUV images with the Solar Blind Channel (SBC) on the ACS us-
and the flux from a 4000 measured NUV (F225W) magnitude is counts using the provided encircled energy fractions. For both the NUV and FUV images, we correct the aperture and 0.5 HST observations. We performed simple aperture photom-
tions to update the coordinates of J0435 to the time of the HST observations. We performed simple aperture photometry using a circular aperture (with radius 0.8'' and 0.2'' for the NUV/FUV images respectfully) for the source and an annulus (with inner and outer radii of 2'' and 4'' for the NUV and 0.5'' and 4.5'' for the FUV) for the background region. For both the NUV and FUV images, we correct the aperture counts using the provided encircled energy fractions. The measured NUV (F225W) magnitude is 22.224 ± 0.003, and the measured FUV (1400Å–1650Å) magnitude is extremely faint, at 29.04 ± 0.95.

Figure 10 shows the SED of J0435 with the catalog and new HST fluxes. We fit a blackbody model to the SED of J0435, excluding the HST and GALEX FUV/NUV fluxes. We corrected for the expected extinction by using the Bayestar17 dust maps (Green et al. 2018). We used the extinction law from Cardelli et al. (1989), assuming RV = 3.1, to calculate the extinction in the observed bands. The fit results in a dC temperature of 4026 K ± 78 K and dC radius of 0.48 R⊙ ± 0.15 R⊙. This best-fit model is shown as the solid red line in Figure 10, with the shaded red region representing the 1σ uncertainty region from this fit. Also shown (as the solid purple line) is a 4000 K BT-Settl model atmosphere (Allard et al. 2011) with [Fe/H] = −4.0 and α = 0.4, normalized to the Gaia EDR3 distance and fit radius (again with the shaded purple region showing the 1σ uncertainty). Figure 10 also shows two blackbodies for a WD of 7000 K and 5500 K. For both WD blackbodies, we show the combined dC blackbody and dC BT-Settl model atmosphere as dashed lines.

The dC blackbody model fit reproduces the observed dC SED moderately well, with the BT-Settl model atmosphere matching more closely in the UV region. Our measured HST NUV flux is consistent with that of the GALEX NUV flux, and the flux from a 4000 K main-sequence BT-Settl model. Although our HST flux has a fairly large uncertainty, it is consistent with the fit dC temperature and a cool WD companion. From Figure 10, it is clear the WD must be cooler than 7000 K or we would have observed a slightly higher NUV flux, and our FUV detection should have been much stronger. If we use our FUV flux as an upper limit of the WD flux contribution, we find the WD is likely around 5500 K implying a cooling age (therefore the time since mass transfer to the dC) of approximately 3.5 Gyr (using a standard WD mass of 0.6 M⊙), assuming that there have been no accretion episodes since.

Circumbinary and circumstellar dust around J0435 should re-emit absorbed radiation in the mid-infrared. This should be visible as a bump in the infrared region of the SED. While there does appear to be a slight bump in the SED of J0435 in the 2MASS fluxes, it is within the 1σ uncertainties of the blackbody fit, supporting the non-detection of a dusty disk in the SED of J0435. Additionally, the SED is well fit using the negligible extinction from the Bayestar17 dustmaps, pointing again to a lack of dust along the line of sight to J0435.

5. DISCUSSION

Green et al. (2019b) sought to determine if dCs, while expected to be of older thick disk and halo populations (Green 2013; Farihi et al. 2018), may still show signs of coronal activity due to rapid rotation induced by an increase in angular momentum from mass transfer. While they did indeed find that all of their observed dCs were detected with Chandra and consistent with saturated X-ray activity, their pilot sample was biased to enhance detection probability, targeting dCs showing Hα emission, a known tracer of coronal activity.

Following up on successful detection of those dCs, our sample in this paper aimed to study a more representative sample, targeting the five nearest known dCs regardless of Hα emission. Of the five dCs targeted, we detect X-ray emission in two. We use the same assumed 2 MK and 10 MK plasma temperature models to calculate log (L_x/L_Hα) finding that both of those dCs fall in the saturated regime. For the three non-detections, we place 3σ upper level constraints on the X-ray flux.

For the dC J0435, we have five individual Chandra observations, with a total of 214 counts. This allowed us to fit the X-ray spectrum, placing constraints on the plasma temperature (T_X = 13.4 MK) and column density (N_H = 1.69 × 10^{22} cm^{-2}). The column density suggests a large amount of material surrounding J0435, but the lack of a mid-infrared excess in the SED, and the good SED fit without the need for a larger extinction correction, suggests that the material around J0435 may be gas with very little dust. The material may indeed be the remnants of the TP-AGB wind or common-envelope ejecta. This explanation is problematic, however, as the CE material would be expected to should have been cleared from the system, especially given the time since the CE inferred from the estimated cooling age. There could be the remains of the AGB wind, the CE, or an accretion disk that was in the form of dust but has been heated above the sublimation temperature by the strong X-ray activity found in J0435. The origin of this anomalous column density and low reddening motivates further multi-wavelength studies of J0435.

While our results here are consistent with Green et al. (2019b), recent works have shown that the previous interpre-

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2 We obtained FUV images in both filters to account for the SBC red leak.
3 https://www.stsci.edu/hst/instrumentation/wfc3/data-analysis/photometric-calibration/uvis-encircled-energy
4 https://www.stsci.edu/hst/instrumentation/acs/data-analysis/aperture-corrections
Figure 10. Spectral energy distribution for the dC J0435. The SED was compiled from Gaia EDR3 and Pan-STARRS1 in the optical, GALEX in the NUV, 2MASS in the near-infrared, WISE in the mid-infrared, and new HST observations in the NUV/FUV regions. The best fitting blackbody model is shown as the solid red line and consists of a 4026 K ± 78 K dC with a radius of 0.48 R⊙ ± 0.15 R⊙. The red shaded region shows the 1σ uncertainty of this best-fit model. The bottom panel shows the observed flux divided by the expected flux from the best-fit blackbody for each observation; error bars represent the blackbody fit errors added in quadrature to the photometric flux uncertainties. Also shown is a BT-Settl model atmosphere (Allard et al. 2011) with [Fe/H]=−4.0 and α = 0.4, normalized to the Gaia EDR3 distance and fit radius (again with the shaded purple region showing the 1σ uncertainty). The black dashed and dotted-dashed lines show two blackbodies of a 7000 K and 5500 K respectively meant to describe the WD. For each WD model, the combined dC blackbody and combined BT-Settl models are shown. The new HST fluxes are consistent with a 4000 K main-sequence star combined with a cool WD. The FUV flux places a weak constraint of approximately 5500 K on the WD companion. In addition, there appears to be a slight increase in the near-infrared flux as compared to the best-fit blackbody, but within the 1σ uncertainty region.

An interesting comparison to make is to the symbiotic stars (Allen 1984; Luna et al. 2013). Symbiotic stars consist of a compact object in a bound orbit around a red giant and accreting from its wind. They are known to have orbital periods ranging from hundreds of days to thousands of days (Mikołajewska 2012). The accretion in symbiotics is believed to take place via wind accretion or a form of WRLOF (Luna et al. 2018), both of which likely form an accretion disk around the compact object. In symbiotics with a WD, which are analogous to dCs, this accretion disk results in X-ray emission, with thermal bremsstrahlung models of ~ 100 MK (Chernyakova et al. 2005; Tueller et al. 2005; Mukai et al. 2007; Smith et al. 2008; Kennea et al. 2009; Luna et al. 2013, 2018; Danehkar et al. 2021), compared to the approximate ~ 10 MK we find for the dCs with X-ray detections. This supports our conclusion that the observed X-ray emission in dCs is indeed from coronal activity and not from accretion onto the WD companion.
The question remains though of how the initial properties of both the binary and the individual stars affect the formation of dCs. The evolution of the TP-AGB star, and the subsequent third dredge-up events, are affected by both the initial mass and metallicity of the star (Kalirai et al. 2014); this includes the final C/O of the TP-AGB envelope, controlling the C budget available to enhance the proto-dC. If the initial orbital period is too short, the system risks entering a CE phase either during the red giant branch or during the AGB phase before the third dredge-up can enhance the AGB to C/O $> 1$. If the initial orbital period is too long, then mass transfer may only take place via BHL accretion, or WRLOF may not effectively shrink the orbit to begin a CE, which would then cause the binary to spiral in to the observed short periods. Therefore, the initial orbital and stellar properties that can result in a dC, and more strictly short period dCs, must inhabit a parameter space more stringent than traditional (C/O $< 1$) WD+MS PCEBs, although they remain unknown.

Roulston et al. (2021) examined whether main-sequence companions to TP-AGB stars can accrete enough mass during the common-envelope phase to form dCs. They found that the common-envelope efficiency must be low to account for the known short period orbits of dCs, which is consistent with the more well known normal (C/O $< 1$) WD+MS PCEBs (Zorotovic et al. 2010; Toonen & Nelemans 2013; Camacho et al. 2014). Furthermore, they also found that dCs cannot accrete enough carbon rich material during the common-envelope phase, at least on the approximately 100 yr common-envelope timescale assumed. They suggest that the dCs must accrete enough carbon rich material before the common-envelope, but after the third dredge-up has polluted the AGB companion, via WRLOF (Mohamed & Podsadловый 2007). In WRLOF, the primary (in the case of dCs, this would be a TP-AGB star) does not completely fill its Roche-Lobe, and the primary wind is focused in the orbital plane towards the secondary star (the proto-dC). This results in accretion rates which can be significantly higher than those in the Bondi-Hoyle-Lyttleton prescription, in some cases as high as 50% (Abate et al. 2013; Saladino et al. 2018, 2019; Saladino & Pols 2019). It has also been shown that WRLOF can efficiently tighten the orbit (Saladino et al. 2018; Chen et al. 2018), driving these systems toward the short periods that have been found for dCs.

The WRLOF formalism for forming dCs requires a balance of initial orbital period, progenitor TP-AGB mass and metallicity, and progenitor dC mass and metallicity (and likely other parameters as well). It has been suggested that dCs may be predominantly found in low metallicity populations, as the amount of carbon excess needed to be accreted to make C/O $> 1$ is less in a low metallicity star. The prototype dC G77-61 is extremely metal deficient with [Fe/H] $\sim -4$ (Plez & Cohen 2005). The mass of the dC progenitor (and C/O of the accreted mass) will also change how much material must be accreted. Miszalski et al. (2013) estimated that to shift a secondary from (C/O)$_f \sim 1/3$ to (C/O)$_f > 1$ would require the accretion of $\Delta M_2 = 0.03 - 0.35 M_\odot$ for a secondary with a mass $M_2 = 1.0 - 0.4 M_\odot$. The TP-AGB phase can last from 1 Myr up to 3.5 Myr (Kalirai et al. 2014), while the C-AGB phase itself only lasts up to $\sim 0.42$ Myr for an initial mass of $2.60 M_\odot$. Mass transfer to the dC must happen during this short time, which supports the WRLOF scenario, as a dC may accrete $0.35 M_\odot$ in only $10^7 - 10^8$ yrs (for the above AGB mass loss rates of $10^{-7} - 10^{-5} M_\odot$ yr$^{-1}$, Höfner & Olofsson 2018) via WRLOF with accretion efficiencies as high as $\sim 50\%$ (Abate et al. 2013).

Systems in which the dC has not experienced a common-envelope (such as the dCs with orbital periods of a year or more (Harris et al. 2018), may be the best candidates yet for testing if the accretion of carbon-rich material can cause the rejuvenation of dCs via spin-up to short rotation periods. Additionally, future simulations of WRLOF and common-envelope evolution in progenitor dC systems, coupled with the observed dC space density and fraction of dCs with short orbital periods, may allow the first insight into the initial conditions needed for dC formation.

**Facility:** CXO (ACIS-S), HST (WFC3, ACS), 2MASS, Gaia, WISE, TESS

**Software:** Astropy (Astropy Collaboration et al. 2013, 2018), CIAO (Fruscione et al. 2006), Matplotlib (Hunter 2007), Numpy (Harris et al. 2020), Scipy (Virtanen et al. 2020), TOPCAT (Taylor 2005)

The scientific results reported in this article are based on observations made by the Chandra X-ray Observatory, and data obtained from the Chandra Data Archive. This research has made use of software provided by the Chandra X-ray Center (CXC) in the application packages CIAO and Sherpa.

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