New Clues to the Evolution of Dwarf Carbon Stars From Their Variability and X-Ray Emission

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Abstract

As main-sequence stars with C > O, 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, C 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, 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).

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. As carbon-enriched material dredged up into the atmosphere of the AGB star then accretes onto its main-sequence companion, that carbon preferentially binds with oxygen to form CO, and as C/O exceeds unity on the dwarf, the excess carbon is free 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 dC star, G77-61. As dCs are main-sequence stars, 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 carbon. 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 (Hofner & 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 gigayear timescales, 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 days (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, 3.21, 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 inferring 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 stars (CEMP-s; 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 accretion (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944). 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 yr, 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 days (Corradi et al. 2011). Here, we see direct evidence of the common-envelope phase and the expelled envelope in the form of the nebula. Margon et al. (2018) found a dC without these clear signs of a common-envelope phase to have a period of 2.92 days using multiepoch photometric surveys.

Recently, Roulston et al. (2021) published 34 new dC periods, and Whitehouse et al. (2021) found five new dC periods. Remarkably, 95% of this combined sample of dCs have $P < 10$ days (with the shortest being from Roulston et al. 2021 with a period of only 3.2 hr). We note that both the Roulston et al. (2021) and Whitehouse et al. (2021) samples used photometric surveys that are optimized for finding the types of short periods seen in their dC samples. Known dC periods range up $\sim 11$ yr, which would require long-term photometric, spectroscopic, or astrometric observations to detect and confirm. However, it is clear that dCs can go through a common-envelope phase, 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 dC stars 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 dC stars’ likely population and hence age, we show a Toomre diagram (Carney et al. 1988) for a sample of dCs in Figure 1. We used the Green (2013) Sloan Digital Sky Survey (SDSS) sample of C stars, matching to Gaia Early Data Release 3 (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 R.A. and decl.; and (3) absolute $M_\odot > 5$. We measured the dC radial velocities from the $H_\alpha$ 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, dC stars’ activity may not correlate simply with age, because they are not single stars and therefore do not evolve independently. Indeed, dC stars 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 ($\lesssim 10$ hr) rotation periods. If dC stars gain most of their carbon-rich mass through wind Roche-lobe overflow (WRLOF; Mohamed & Podsia³dowski 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., Kosovichev 2013), which normally yield observable $H_\alpha$ and/or X-ray emission. Since M dwarfs show activity lifetimes of $\sim 1$–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 better-studied Ba and CEMP-s stars can accrete before reaching critical rotation. They found that in order for these stars, and by similarity dC stars, 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.

Green et al. (2019b) thus aimed to study the activity and rejuvenation of dC stars 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 $H_\alpha$ 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, dC stars populate the saturated regime where $\log(L_{\alpha}/L_{\text{bol}}) \sim -3.3$ (e.g., Wright et al. 2011), indicating short rotation periods. However, with the higher 10 MK plasma temperatures, only half of the dCs remain in the saturated regime, with periods weakly constrained to $< 20$ days. 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 dC stars 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 dC stars.

### 2. Sample Selection

We compiled our parent sample of dC stars 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; York et al. 2000). 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 Data Release 8.
Selected dC stars in our sample. For each, we list the coordinate positions and parallaxes from Gaia EDR3.

- SBSS 1310
- LAMOST J124055.15
- HE 1205-0417
- LAMOST J054640.48

The left panel represents the thin and thick disks. As dCs must be in binaries, and some are known to be short-period binaries, their radial velocities may be inflated.

M dwarfs are in the same way as in Green et al. (2019b), 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 parent sample consists of 944 dCs, where we ensured that each is indeed a dC by verifying that each C star had $M_G > 5$ mag from Gaia EDR3 (Gaia Collaboration et al. 2021) while having a significant parallax of $\varpi / \varpi_{\text{err}} > 3$. We expect to publish this large parent sample, along with detailed spectral energy distribution (SED) fit parameters, in an upcoming paper.

We then selected the nearest five dC stars to make our final Chandra 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 selected dC in the same way as in Green et al. (2019b) by using a LEDF for each dC and the sedkit Python package (Filippazzo et al. 2015). Figure 2 shows a color–magnitude diagram (CMD) for a sample of chemically enhanced stars, including dCs. From this, we can see that the five dCs in this sample are all clearly dwarfs having $M_G > 8$. Additionally, we examined the available spectra for the five dCs selected here, all of which show strong C2 and CN bands.

The reddest stars in this CMD correspond to the lowest mass dC stars. These dCs will likely have accreted a substantial fraction (see Miszalski et al. 2013 and the discussion at the end of this paper) of their current mass, and may have even been brown dwarfs before the onset of the accretion that turned them into dCs (see Majidi et al. 2021 for a discussion on a similar topic).

### 3. X-Ray Observations and Analysis

All of our Chandra observations were taken with the Advanced CCD Imaging Spectrometer (ACIS-S) using the S3 chip (backside-illuminated CCD) between 2019 September and 2021 December (Chandra proposals 21200072 and 22200008; PI: P. Green). Exposure times, proposed based on optical magnitudes, ranged from 9.83 to 36.78 ks, with one dC (LSPM...
from the dustmaps Python package (Green 2018); resulting line-of-sight column density ($N_{\text{H}}$) values are listed in Table 2.

Table 2 lists the ObsIDs, the observation properties, and the X-ray source properties for each dC star. The calculated net count rate for each ObsID is given, with the $1\sigma$ 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 $1\sigma$ 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 dC stars without detections, we list the $3\sigma$ upper limits.

### 3.1. Individual Spectral Fits

For the dC stars 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 $N_{\text{H}} = 9.6 \times 10^{21} \text{ cm}^{-2}$). This column density is consistent with the negligible Bayestar17 expected line-of-sight column density of $N_{\text{H}} = 3 \times 10^{19} \text{ cm}^{-2}$.

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 based on X-ray-selected stellar samples observed with Chandra from, e.g., the Chandra Cosmic Evolution Survey (Wright et al. 2010).

#### 3.1.2. J0435

Our requested 100 ksec was split by Chandra mission planners into seven separate observations of J0435. 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 $1\sigma$ errors. All of the fits result in a column density three orders of magnitude higher than the expected line-of-sight column density from the Bayestar17 dust map ($N_{\text{H}} = 6.3 \times 10^{19} \text{ cm}^{-2}$), which suggests the presence of material around J0435 (see Section 4). 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 seven observations with one model. For this fit, we used the same APEC and WABS models as before, but all seven observations are fit with the same plasma temperature and column density, allowing only the normalization to vary between each observation.
| Object   | ObsID   | Obs-Date       | Exposure (ks) | Net Count Rate (cnt ks⁻¹) | N_H (10^{22} cm⁻²) | T_X (MK) | F_X_cobs (10^{38} erg cm⁻² s⁻¹) | F_X (10^{38} erg cm⁻² s⁻¹) | L_X (10^{36} erg s⁻¹) |
|----------|---------|----------------|---------------|---------------------------|---------------------|----------|---------------------------------|---------------------------|-----------------------|
| J0435    | 22298   | 2019-09-15     | 10.12         | 2.61_{-0.27}^{+0.33}           | 6.3_{-1.1}^{+0.7}   | 2        | 230_{-23}^{+32}                  | 246_{-41}^{+64}         | 48_{-8.0}^{+12} |
|          |         |                |               |                           |                     | 10       | 31.6_{-2.4}                      | 32.3_{-0.8}^{+5.3}      | 6.3_{-1.0}^{+1.4}   |
|          |         |                |               |                           |                     | 2        | 319_{-42}                        | 341_{-45}^{+60}         | 66_{-9.0}^{+12} |
|          |         |                |               |                           |                     | 10       | 36.0_{-6.5}                      | 36.8_{-7.4}^{+4.4}      | 7.1_{-1.0}^{+1.2}   |
|          |         |                |               |                           |                     | 2        | 299_{-31}                        | 317_{-39}^{+57}         | 62_{-10}^{+27} |
|          |         |                |               |                           |                     | 10       | 33_{-19}                         | 34.5_{-2.2}^{+6.2}      | 6.7_{-1.2}^{+1.1}   |
|          |         |                |               |                           |                     | 2        | 428_{-190}                       | 458_{-134}^{+38}        | 88_{-28}^{+92} |
|          |         |                |               |                           |                     | 10       | 42.5_{-12.0}                     | 43.3_{-13.0}^{+3.6}     | 8.4_{-2.5}^{+12} |
|          |         |                |               |                           |                     | 2        | 37_{-11}                         | 397_{-51}^{+88}         | 77_{-10}^{+21} |
|          |         |                |               |                           |                     | 10       | 41.8_{-4.4}                      | 42.7_{-3.5}^{+6.9}      | 8.3_{-1.3}^{+1.1}   |
|          |         |                |               |                           |                     | 2        | 424_{-36}                        | 454_{-60}^{+40}         | 88_{-12}^{+92} |
|          |         |                |               |                           |                     | 10       | 47.8_{-6.3}                      | 48.9_{-6.5}^{+9.5}      | 9.5_{-1.3}^{+1.1}   |
|          |         |                |               |                           |                     | 2        | 472_{-61}                        | 505_{-89}^{+58}         | 98_{-13}^{+71} |
|          |         |                |               |                           |                     | 10       | 46.6_{-6.0}                      | 47.7_{-6.2}^{+8.4}      | 9.2_{-1.2}^{+1.1}   |
| J0546    | 22299   | 2020-01-09     | 34.80         | <0.20                     | 7.5_{-1.6}^{+1.7}   | 2        | <18                             | <24                      | <7.2                 |
|          |         |                |               |                           |                     | 10       | <2.5                            | <2.8                     | 0.9                  |
| HE1205   | 22300   | 2020-04-04     | 24.23         | <0.44                     | 8.3_{-1.1}^{+1.4}   | 2        | <47                             | <51                      | <14                  |
| J1240    | 22301   | 2019-09-19     | 36.78         | <0.34                     | 6.3_{-1.5}^{+1.7}   | 2        | <31                             | <32                      | <10                  |
|          |         |                |               |                           |                     | 10       | <4.2                            | <4.3                     | <1.3                 |
| SBSS1310 | 22302   | 2020-01-25     | 14.90         | 1.96_{-0.19}^{+0.24}      | 3.0_{-0.8}^{+1.8}   | 2        | 203_{-23}^{+66}                 | 210_{-33}^{+45}         | 40.7_{-6.4}^{+9.5} |

Note: 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 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.

The simultaneous fit results in a column density of \( N_H = 1.77 \pm 0.30 \times 10^{22} \text{ cm}^{-2} \) and a plasma temperature of \( T_X = 14.2 \pm 2.9 \text{ MK} \). 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.

### 3.2. X-Ray Variability

Since coronal activity is by nature variable, we searched for signs of X-ray variability in the dC stars 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\(^9\) 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, 0, 6, and 0 for the ObsIDs 22298, 23376, 24305, 24306, 24893, 24896, and 26242, respectively. The ObsIDs with variability index equal to 6 are considered definitely variable; a variability index equal to 2 is considered probably not variable, and a variability index of 0 is considered definitely not variable.

One possible explanation for this changing variability index may lie with the source of the X-ray emission in dC stars, which is believed to be from coronal emission associated with rotation and magnetic activity. Stellar flares are associated with magnetic activity and magnetic reconnection (Pettersen 1989), where most of the flare coronal emission is in 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 the lifetime of the flare. These flares could be the source of the differing levels of variability between the J0435 observations. To check for flares from J0435, we searched the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) light curve but found no detected flare events in the full-frame images. However, given that for cool stars the flare duration is of an order of one hour (Howard et al. 2019), the 30 minute cadence of this light curve may not resolve any flares outside of single point outliers.

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. The 1σ error bars are shown for each, with the shaded region showing the average 1σ error across all seven observations. Within these errors, we find no detectable variability in the source flux of J0435.

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\(^9\) [https://cxc.cfa.harvard.edu/ciao/shelp/glvary.html](https://cxc.cfa.harvard.edu/ciao/shelp/glvary.html)
Figure 3. Best-fitting spectral model for SBSS13010. The left panel (a) shows the observed source spectrum in black 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, with the 1σ, 2σ, and 3σ contours shown as the solid, dashed, and dotted lines, respectively. These contours were calculated by varying the plasma temperature and column density over a grid and calculating the confidence with a χ² statistic using the Sherpa package (Freeman et al. 2001). 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.

| ObsID  | \(N_{H\text{,fit}}\) (10^{22} \text{ cm}^{-2}) | \(T_{X\text{,fit}}\) (MK) |
|--------|---------------------------------|------------------|
| 22298  | 1.43 ± 0.13                     | 33 ± 1.0         |
| 23376  | 2.07 ± 0.25                     | 9.1 ± 1.3        |
| 24305  | 1.26 ± 0.18                     | 10.1 ± 1.3      |
| 24306  | 3.41 ± 0.44                     | 6.7 ± 1.4       |
| 24893  | 1.48 ± 0.32                     | 13.9 ± 1.8      |
| 24896  | 1.48 ± 0.28                     | 13.6 ± 1.4      |
| 26242  | 1.77 ± 0.63                     | 18.4 ± 1.5      |

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.

### 3.3. Rotation–Activity Relationship

In main-sequence stars, X-ray emission, and often chromospheric Hα 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 \(R_o = P_{\text{rot}}/\tau\) (Noyes et al. 1984), which relates the rotation period to the convective turnover time (τ), has been shown to correlate with activity and saturates for rapid rotators at the level of \(\log(L_\alpha/L_{bol}) \approx -3.3\) for \(R_o \gtrsim 0.13\) (Micela et al. 1985; Wright et al. 2011).

In Green et al. (2019b), all six of the observed dCs were detected with Chandra, with \(\log(L_\alpha/L_{bol})\) ranging from −4.5 to −3.2, depending on the assumed model plasma temperature. These values place the dC stars 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, SBSS13101, 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 Data Release 5 (ZTF DR5; Bellm et al. 2019; Graham et al. 2019; Masci 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 & Ivezic (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% (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 day−1 from an observational alias, such as 0.5 day−1 or 0.333 day−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 day. 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 7 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% 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 dC stars in Green et al. (2019b) and this work, we can now place dCs on an activity–rotation diagram. Figure 8 shows the updated Figure 3 of Green et al. (2019b), but we now show the true position of the five dC stars 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 and 10 MK
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 dC stars in the current study were selected to investigate if dCs, regardless of Hα emission or a spectroscopically detectable WD, show signs of spin-up and chromospheric rejuvenation. Indeed, we find that the two dC stars 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 days, 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 $R_\odot$ (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 dC stars in this paper, and in Green et al. (2019b), must have experienced a common-envelope phase and the associated inspiral 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 star should have a rotation period commensurate with post-common-envelope binaries (PCEBs), i.e., $P \approx 1$ day. Thus, the X-ray detections in Green et al. (2019b) and in this work do indeed trace short-period rotation of dC stars; however, the cause of this dC spin-up is more likely associated with common-envelope spiral-in, and 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 dC stars in the current study were selected to investigate if dCs, regardless of Hα emission or a spectroscopically detectable WD, show signs of spin-up and chromospheric rejuvenation. Indeed, we find that the two dC stars 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 days, 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 $R_\odot$ (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 dC stars in this paper, and in Green et al. (2019b), must have experienced a common-envelope phase and the associated inspiral 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 star should have a rotation period commensurate with post-common-envelope binaries (PCEBs), i.e., $P \approx 1$ day. Thus, the X-ray detections in Green et al. (2019b) and in this work do indeed trace short-period rotation of dC stars; however, the cause of this dC spin-up is more likely associated with common-envelope spiral-in, and

![Figure 5](image_url)  
**Figure 5.** Fit values of the model column density ($N_H$) and plasma temperature ($T_X$) for the dC star 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 seven observations. The black contours represent the 1, 2, and 3σ regions for the combined fit. The expected column density at the distance of J0435 from the three-dimensional optical/IR dust maps of Green et al. (2019a) ($N_H = 6.3 \times 10^{20} \text{ cm}^{-2}$) is more than two orders of magnitude lower than the values shown here from X-ray fitting.

![Figure 6](image_url)  
**Figure 6.** Unabsorbed model flux for each ObsID of the dC star 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 seven observations, with the gray shaded region showing the mean error of the observations. We find no signs of variability in the source flux of J0435. Note that all the ObsIDs for J0435 span some 28 months, but several are clustered within a few days so we plot by ObsID here, which does not map to MJDs (listed in Table 2).

| ObsID  | $F_{X,\text{obs}}$ $\left[10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}\right]$ | $F_X$ $\left[10^{-28} \text{ erg s}^{-1}\right]$ | $L_X$ $\left[10^{-28} \text{ erg s}^{-1}\right]$ |
|-------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 22298 | 23.8 $^{+1.4}_{-1.3}$                        | 170 $^{+19}_{-18}$                            | 32.9 $^{+6.1}_{-6.1}$                          |
| 23376 | 23.1 $^{+1.0}_{-1.0}$                        | 165 $^{+23}_{-23}$                            | 31.9 $^{+4.5}_{-4.5}$                          |
| 24305 | 21.5 $^{+2.3}_{-2.3}$                        | 154 $^{+31}_{-31}$                            | 29.8 $^{+6.0}_{-6.0}$                          |
| 24306 | 24.9 $^{+2.3}_{-2.3}$                        | 178 $^{+35}_{-35}$                            | 34.5 $^{+6.2}_{-6.2}$                          |
| 24893 | 26.7 $^{+2.7}_{-2.7}$                        | 191 $^{+46}_{-46}$                            | 37.0 $^{+6.1}_{-6.1}$                          |
| 24896 | 30.6 $^{+2.1}_{-2.1}$                        | 219 $^{+29}_{-29}$                            | 42.4 $^{+5.8}_{-5.8}$                          |
| 26242 | 27.4 $^{+1.6}_{-1.6}$                        | 196 $^{+34}_{-34}$                            | 37.9 $^{+6.4}_{-6.4}$                          |

Note. Combined model fits for each ObsID of J0435. For each observation, the observed source flux, unabsorbed flux, and luminosity are listed. For each value the 1σ errors are shown.
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 dC stars in which the orbital period is on the order of years. For example, the three dCs from Harris et al. (2018, with astrometric periods of 1.23, 3.21, 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 ($N_H = 1.77 \times 10^{22}$ 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 ($N_H = 6.3 \times 10^{19}$ 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 dC stars 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 $\sim 10^{-7} - 10^{-5} M_{\odot}$ yr$^{-1}$ (Höfner & Olofsson 2018). This should result in extended shells of dust around nascent dC systems. In addition, those dC stars 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 star, having a photometric period of 1.16 days (Corradi et al. 2011; Miszalski et al. 2013). As the WD companion to the newly minted dC cools, the planetary nebula should similarly fade (on typical timescales of $\sim 10^4$ yr), but may leave detectable signs of circumbinary dust and gas around the dC star. Given that dC main-sequence lifetimes can exceed planetary nebula lifetimes by a factor of $\sim 10^5$, it is perhaps a surprise that even one dC star is known within a cataloged planetary nebula.

We compiled the 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 Panoramic Survey Telescope and Rapid Response System (Pan-STARRS1 survey; Chambers et al. 2016; Flewelling et al. 2020; Magnier et al. 2016a, 2016b, 2016c; Waters 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 Wide-field Infrared Survey Explorer (WISE) surveys, respectively. We also cross-matched to the Galaxy Evolution Explorer (GALEX) Direct Data Releases 6/7 (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 2384.0 s. The exposure was split into
Figure 8. 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 dC stars 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 locations on the diagram, assuming both 2 MK and 10 MK 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 dC stars with new X-ray detections reported in this paper, J0435 and SBSS1310, as well as the 3σ upper limits for the three nondetections. The rotation period for SBSS1310 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 13.4 MK (Section 3.1.2). It is clear that for either 2 MK and 10 MK models, most dC stars are found in the saturated regime of active stars.

Figure 9 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 $R_V = 3.1$, to calculate the extinction in the observed bands. The fit results in a dC temperature of $4026 \, \pm \, 78 \, \text{K}$ and dC radius of $0.87 \, \pm \, 0.09 \, R_\odot$. This best-fit model is shown as the solid red line in Figure 9, with the shaded red region representing the $1\sigma$ 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 $\text{[Fe/H]} = -4.0$ and $\alpha = 0.4$, normalized to the Gaia EDR3 distance and fit radius. Figure 9 also shows two blackbodies for a WD of 7000 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

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10 We obtained FUV images in both filters to account for the SBC red leak.

11 https://www.stsci.edu/hst/instrumentation/wfc3/data-analysis/photometric-calibration/uvis-encircled-energy.

12 https://www.stsci.edu/hst/instrumentation/acs/data-analysis/aperture-corrections.
consistent with the fit dC temperature and a cool WD companion. From Figure 9, 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 \( M_\odot \)), assuming that there have been no accretion episodes since.

Circumbinary and circumstellar dust around J0435 should reemit 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 1\( \sigma \) uncertainties of the blackbody fit, supporting the nondetection 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 dC stars were detected with Chandra and consistent with saturated X-ray activity, their pilot sample was biased to enhance detection probability, targeting dC stars showing H\( \alpha \) emission, a known tracer of coronal activity.

Following up on successful detection of those dC stars, our sample in this paper aimed to study a more representative sample, targeting the five nearest-known dCs regardless of H\( \alpha \) 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 \( \log(L_x/L_{bol}) \), finding that both of those dC stars fall in the saturated regime. For the three nondetections, we place 3\( \sigma \) upper-level constraints on the X-ray flux.

For the dC J0435, we have seven individual Chandra observations, with a total of 289 counts. This allowed us to fit the X-ray spectrum, placing constraints on the plasma temperature (\( T_x = 14.2 \) MK) and column density (\( N_H = 1.77 \times 10^{22} \) 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 common-envelope material would be expected to have been cleared from the system, especially given the time since the common envelope inferred from the estimated cooling age. There could be the remains of the AGB wind, the common envelope, 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 multwavelength studies of J0435.

While our results here are consistent with Green et al. (2019b), recent works have shown that the previous interpretation of dC X-ray activity, as primarily due to accretion spin-up, may not be complete. Roulston et al. (2021) and Whitehouse et al. (2021) recently found 40 dC stars with photometric periods, with 95% having $P < 10$ days. These dC stars must have been engulfed in a common envelope during their former giant companion’s TP-AGB phase. This would have caused a spiral-in of the dC, after which tidal spin–orbit synchronization would lead to the observed short dC rotation periods. It appears that, compared to accretion-induced spin-up, as originally postulated by Green et al. (2019b), these spin–orbit-induced short rotation periods are more likely the source of the increased coronal activity as traced by the X-ray emission.

An interesting comparison to make is to the symbiotic stars (Davidson et al. 1976; 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 dC stars, this accretion disk results in X-ray emission, with thermal bremsstrahlung models of $\sim 100$ 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; Danekar et al. 2021), compared to the approximate $\sim 10$ 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 dC stars. 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 star. If the initial orbital period is too short, the system risks entering a common-envelope 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 Bondi–Hoyle–Lyttleton (BHL) accretion, or WRLOF may not effectively shrink the orbit to begin a common envelope, 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 star, 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 dC stars. 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 dC stars 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 dC stars must accrete enough carbon-rich material before the common-envelope phase, but after the third dredge-up has polluted the AGB companion, via WRLOF (Mohamed & Podsiadlowski 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 toward the secondary star (the proto-dC). This results in accretion rates which can be significantly higher than those in the BHL 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 (Chen et al. 2018; Saladino et al. 2018), driving these systems toward the short periods that have been found for dC stars.

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 dC stars 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)$_2$ $\sim 1/3$ to (C/O)$_2$ $> 1$ 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 star must happen during this short time, which supports the WRLOF scenario, as a dC may accrete 0.35 $M_\odot$ in only $10^3$–$10^4$ yr (for the above AGB mass loss rates of $10^{-7}$–$10^{-5}$ $M_\odot$ yr$^{-1}$; Höfner & Oflofsion 2018) via WRLOF with accretion efficiencies as high as $\sim 50\%$ (Abate et al. 2013).

Systems in which the dC star has not experienced a common-envelope phase (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 dC stars 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.

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