The Time-Domain Spectroscopic Survey: Orbital Separations of Dwarf Carbon Stars

B.R. Roulston[1], P. J. Green[2], J.J. Ruan[3], C. L. MacLeod[2], S.F. Anderson[4], C. Badenes[5] & the TDSS & SDSS-IV Teams

([1]BU, [2]CfA, [3]McGill, [4]U.Wa, [5]U. Pitt) – Contact: **roulstbr@bu.edu**

What are Dwarf Carbon (dC) stars?

Carbon (C) stars were long thought to all be AGB stars, since only they can dredge carbon into their atmospheres from shell helium flashes. Yet main sequence dwarf carbon (dC) stars, discovered by their high proper motions indeed show carbon molecular bands. They are thought to have gained C/O>1 extrinsically as post mass transfer binary systems, where a former AGB companion has since faded to a white dwarf. The dC stars are likely the progenitors of the CH, Ba, and CEMP-s stars, but determining this requires demonstrating a high binary frequency for dCs. Below are 2 epochs of spectroscopy studied for radial velocity variability in our SDSS dC sample.

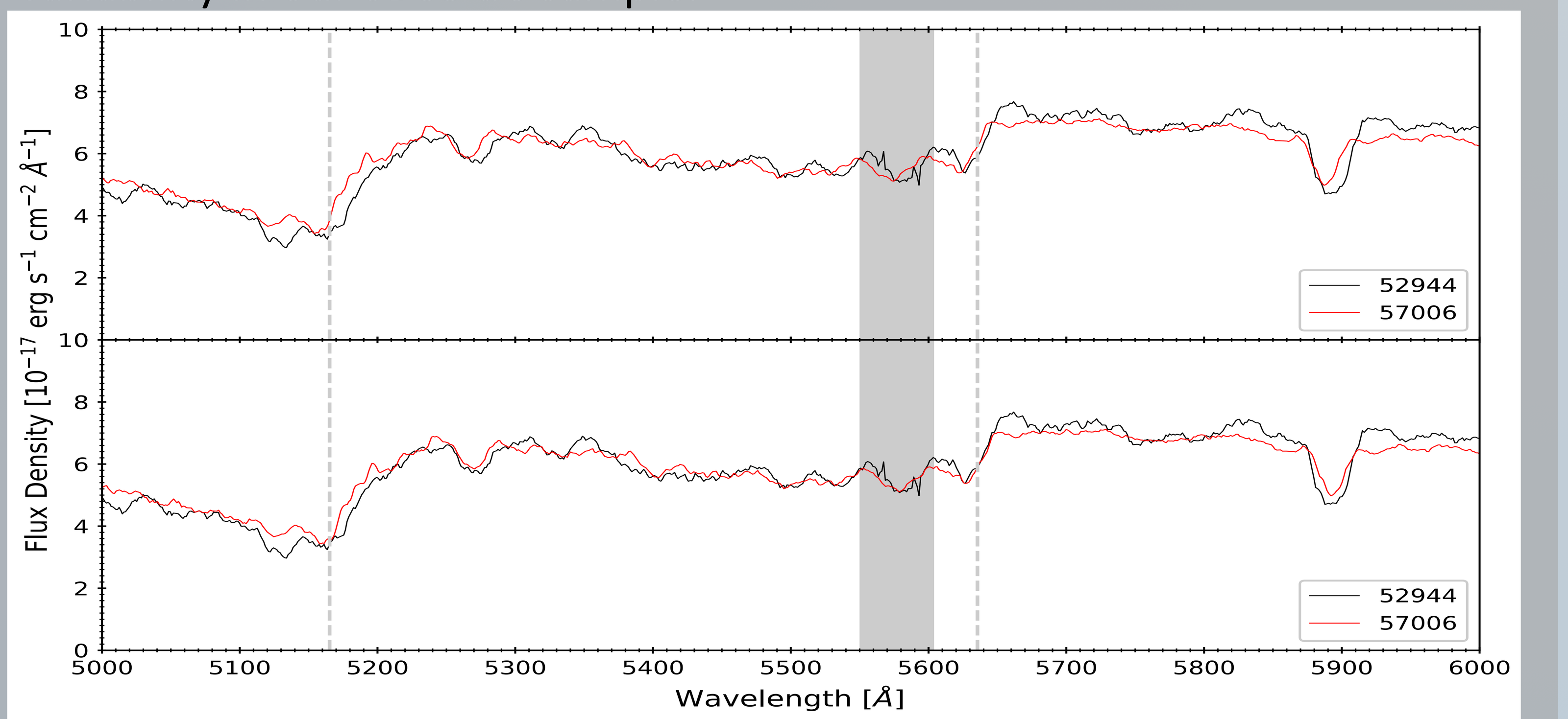


Figure 1. (above) – Example of a dC star spectrum. Plotted are two epochs for the same dC, showing the strong C_2 bandheads. Bottom spectrum has been shifted by the measured ΔRV. Gray band is region of strong night sky lines where the flux calibration may be contaminated.

Dwarf Carbon Star Sample

The SDSS-IV Time Domain Spectroscopic Survey (TDSS; Morganson+2015) has a program of repeat Few Epoch Spectroscopy (FES; MacLeod+2017) including 829 unique dC stars from Green+2013 and Si+2014. From this sample, 240 dC stars with more than one epoch of SDSS spectroscopy (up to 06-30-2017) were selected.

As part of the statistical analysis of this work, a control sample of stars was also selected from the SDSS. This control sample was selected from within the 2%-98% range of four dC properties: r magnitude, g-r color, total proper motion, and Gaia DR2 parallax. Within this 4-space, we choose the closest unique control star for each dC.

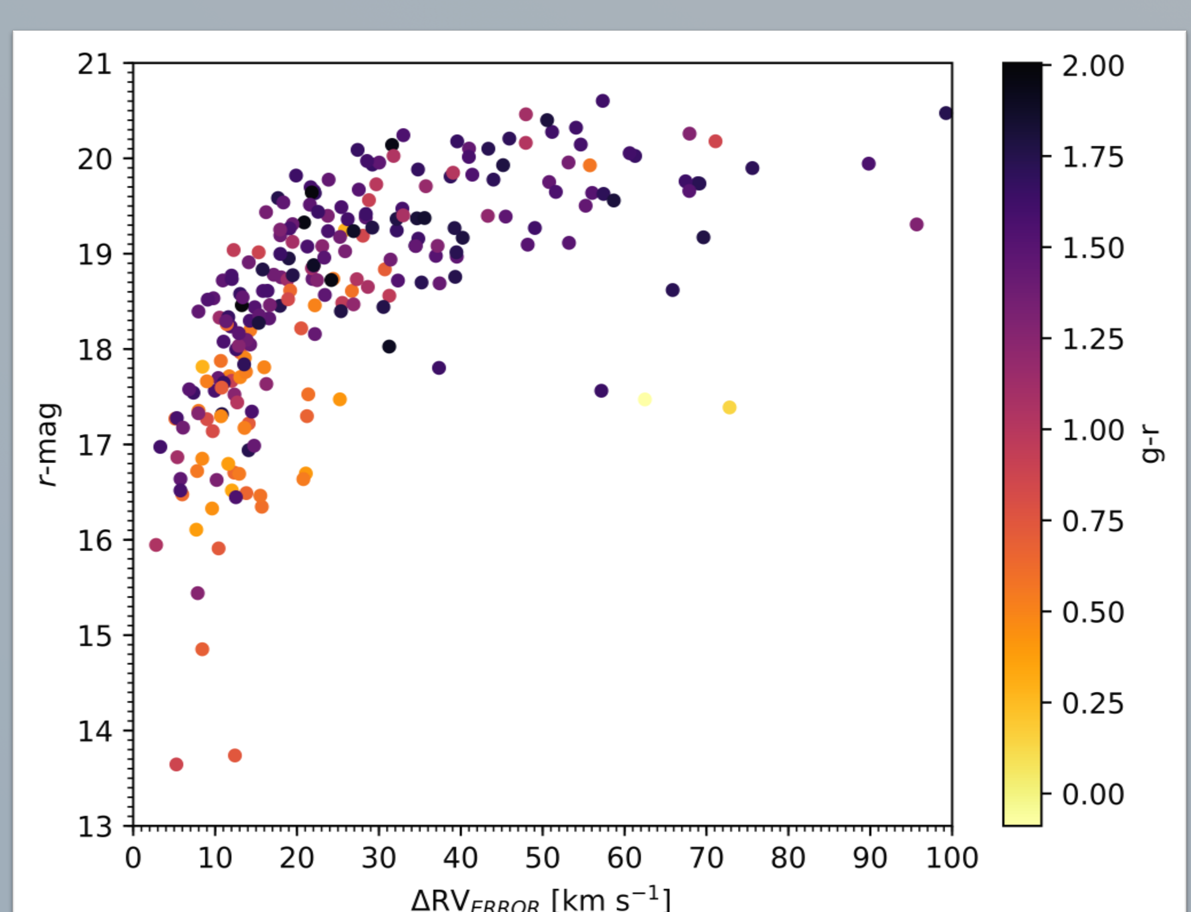


Figure 2. (left) – Optical *r*-band magnitude plotted against the radial velocity variation (ΔRV) errors obtained when directly comparing two epochs of dC stars in our sample. Larger errors are found for fainter stars, as expected, since these tend to have poor spectroscopic *S/N*. Optical *g* – *r* color is denoted for each object by color.

ΔRV Measurements & Analysis

We measured radial velocity variations (ΔRV) by cross-correlating epochs using IRAF FXCOR (Tonry & Davis 1979). Each spectrum and cross-correlation function was visually inspected for quality. To contrast ΔRV distributions from dC and control samples, we used a standard two sample Anderson-Darling (Scholz & Stephens 1987) test. The distributions, which can be seen in Fig. 3, differ at the 99.8% level, supporting the hypothesis dCs are in binary systems that have undergone mass transfer.

Since the AD test ignores the errors on the ΔRV measurements, we have used the extreme deconvolution (XD) method of Jo Bovy+ (2011) to deconvolve the underlying ΔRV distributions (Fig.4). The dC distribution is best modeled by a mixture of two Gaussians while the control is best modeled by one Gaussian. Therefore after controlling for errors, the dC distribution still has large ΔRV systems that represent the closest binary systems.

Indeed, several dCs display large ΔRV values (≥ 100 $km\ s^{-1}$), indicative of close binary orbits. We have been approved for dedicated follow-up spectroscopy with the MMT 6.5m to determine their orbital parameters.

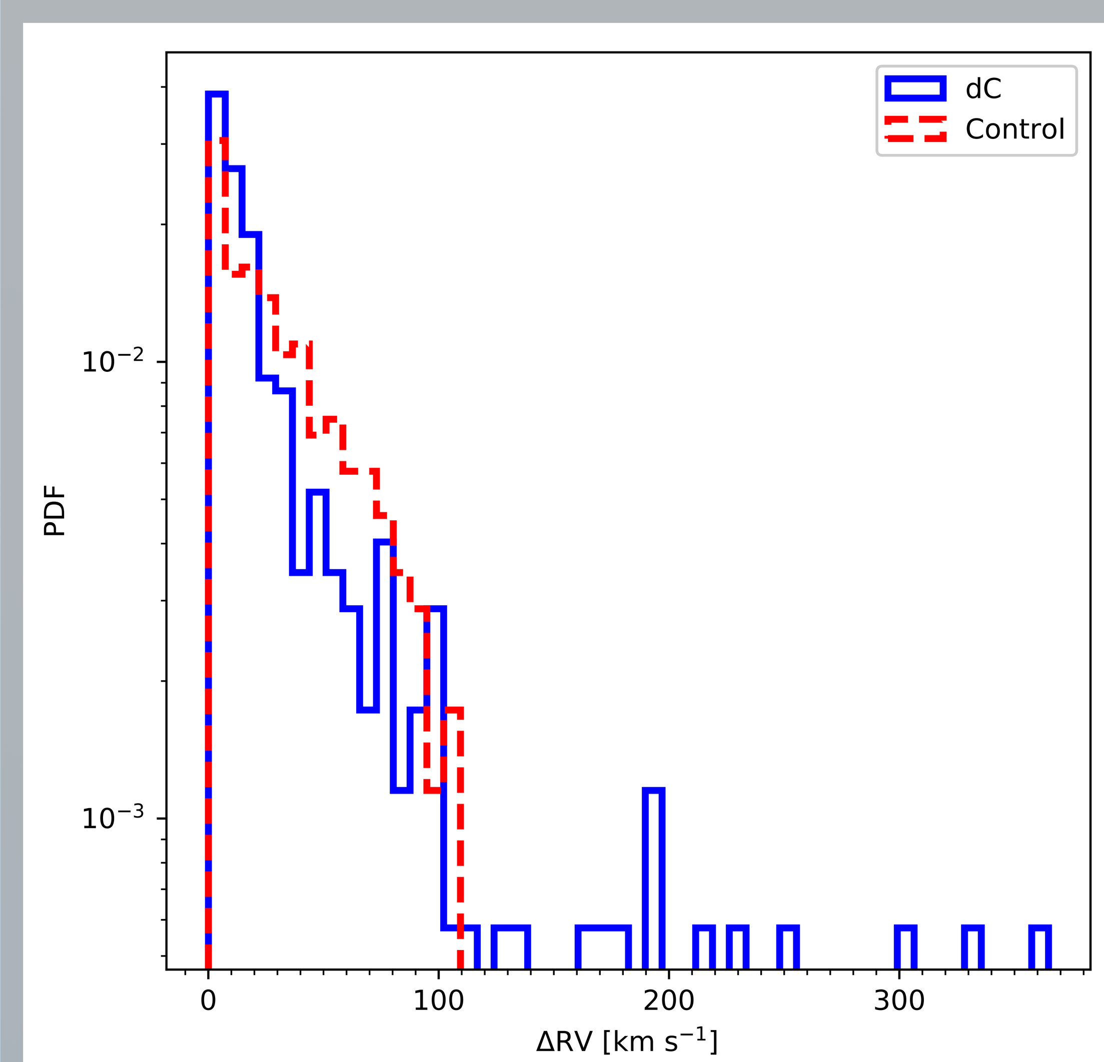
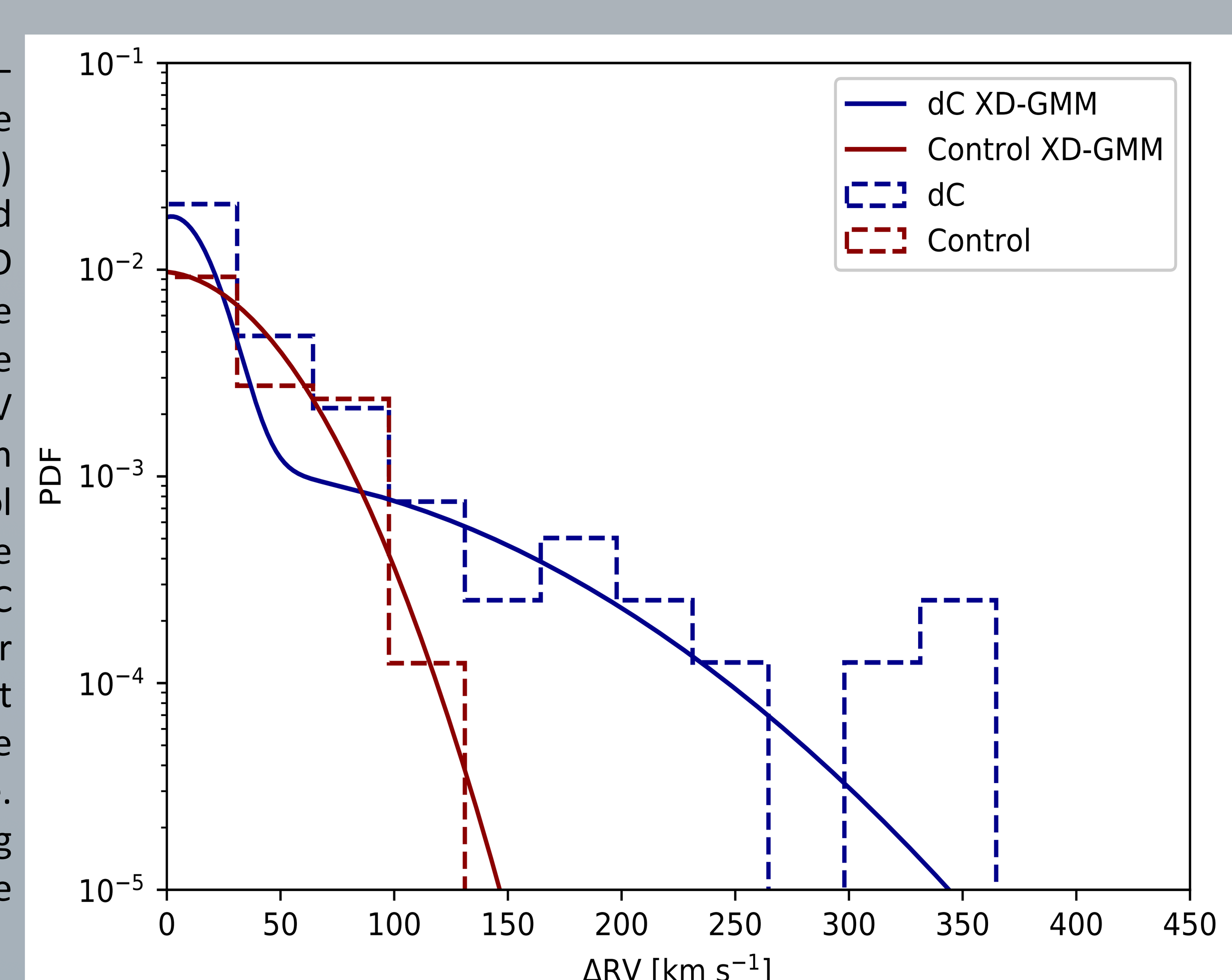
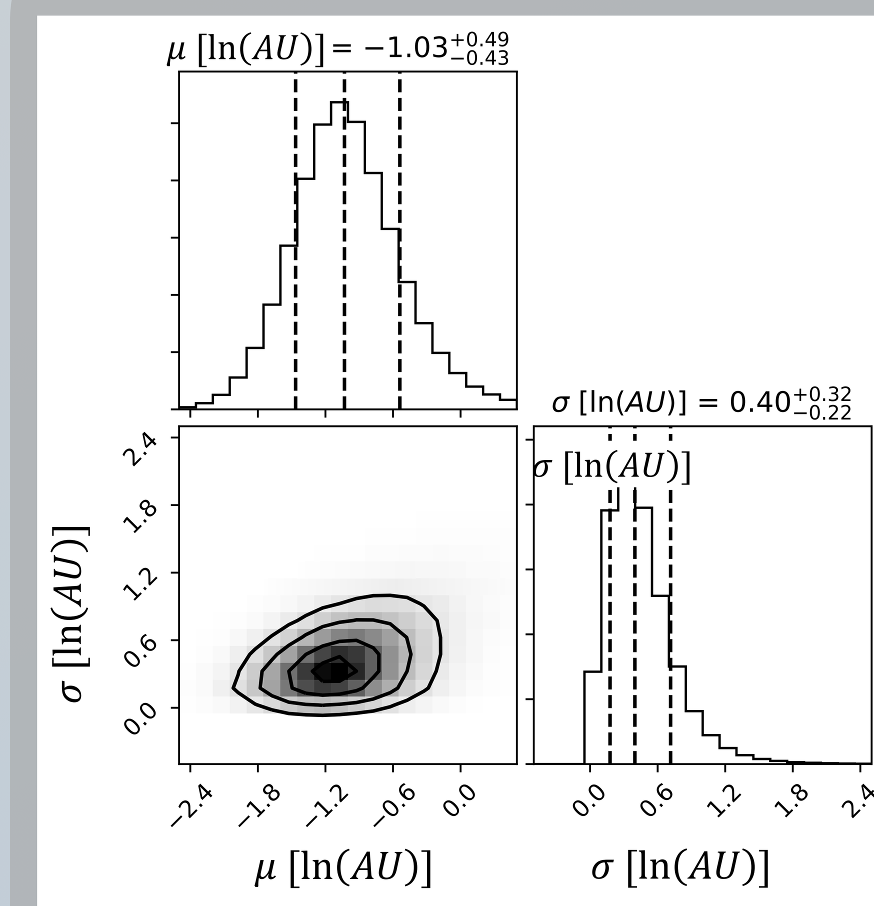


Figure 3. (left) – Normalized ΔRV histogram for both of the finalized dC and control samples. This histogram shows the wider flaring of the base for the dC sample, suggesting the dCs are more likely in the close binaries to which our survey is sensitive. Simple single Gaussian fits (not shown in the figure) show the dCs have a wider distribution ($\sigma_{dC} \sim 60\ km\ s^{-1}$ and $\sigma_{Control} \sim 30\ km\ s^{-1}$)

Figure 4. (right) – Results of Extreme Deconvolution (XD) for the dC and control samples. XD incorporates the errors to infer the underlying ΔRV distribution for both the dCs and control stars. This figure shows how the dC distribution is wider and flares out compared to the control sample. Again, confirming the dCs are in close binaries.



Orbital Separation Simulations

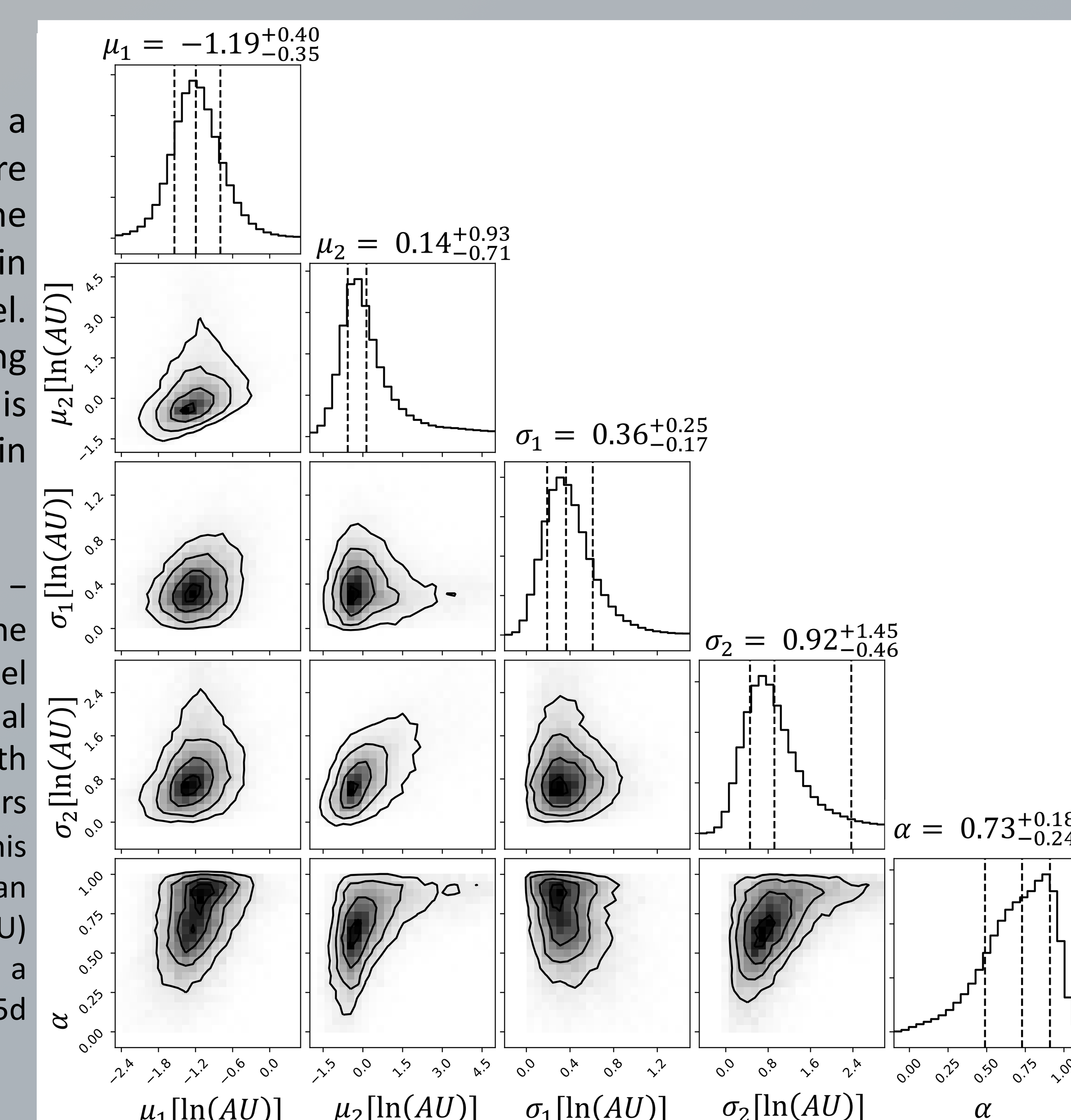


For our orbital separation simulations we assume that the dC-WD separation distribution is lognormal, following Raghavan+ (2010) for close binary systems. This model also assumes a circularized orbit, with SDSS epochs at the maximum RV difference. This reduces our model for ΔRV to a function of M_{dC}, M_{WD}, $\sin i$, and α. With few current constraints for dCs, we assign a dC mass distribution uniform from 0.1 to 1.0 $M_{\odot}$. For M_{WD} , use the Gaussian distribution from Maoz+ (2012).

Figure 5. (left) – Contour plot of our log-normal model with marginalized posteriors for both μ and σ, the mean and standard deviation of the logarithmic separation distribution. This results in a mean separation of (0.39AU) which corresponds to a mean period of 79-100d for the dC mass range.

We also test a bimodal mixture model which has the same assumptions in the unimodal model. The added mixing parameter (α) is constrained to be in the range [0,1].

Figure 6. (right) – Contour plot of the bimodal mixture model of log-normal distributions with marginalized posteriors for each parameter. This results in a mean separation of (0.71AU) which corresponds to a mean period of 300-415d for the dC mass range.



We model both a unimodal and bimodal separation distribution using MCMC methods (assuming a base log-normal distribution). From the mixing parameter α, we see the bimodal model has a strong component that resembles that of the unimodal model, with a weaker component that consists of larger separations.

The total bimodal distribution results in a mean separation of 0.71 AU, which results in a period range of 300–415 days for the mean period across the assumed dC mass range.

This distribution shows that dCs consist of close binary systems that have likely interacted via a combination of RLOF and AGB-wind accretion. The 3x larger final expected TDSS sample of dCs with multi-epoch spectroscopy should afford even stronger constraints in the future.

References

Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018
Green, P. 2013, ApJ, 765, 12
Jo Bovy, Hogg, D. W., & Roweis, S. T. 2011, Annals of Applied Statistics, 5
Maoz, D., Badenes, C. & Bickerton, S.J. 2012, ApJ, 751, 143.
Morganson, E., Green, P. J., Anderson, S. F., et al. 2015, ApJ, 806, 244
Raghavan, D., McAlister, H. A., Henry, T. J., et al. 2010, ApJS, 190, 1
Scholz, F. W., & Stephens, M. A. 1987, Journal of the American Statistical Association
Si, J., Luo, A., Li, Y., et al. 2014, Science China Physics, Mechanics, and Astronomy, 57, 176
Tonry, J., & Davis, M. 1979, AJ, 84, 1511

This work has been submitted to ApJ for publication. A preprint can be found on the ArXiv or by following the QR code to the right.

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