The Time-Domain Spectroscopic Survey: Radial Velocity Variability in Dwarf Carbon Stars

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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 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.

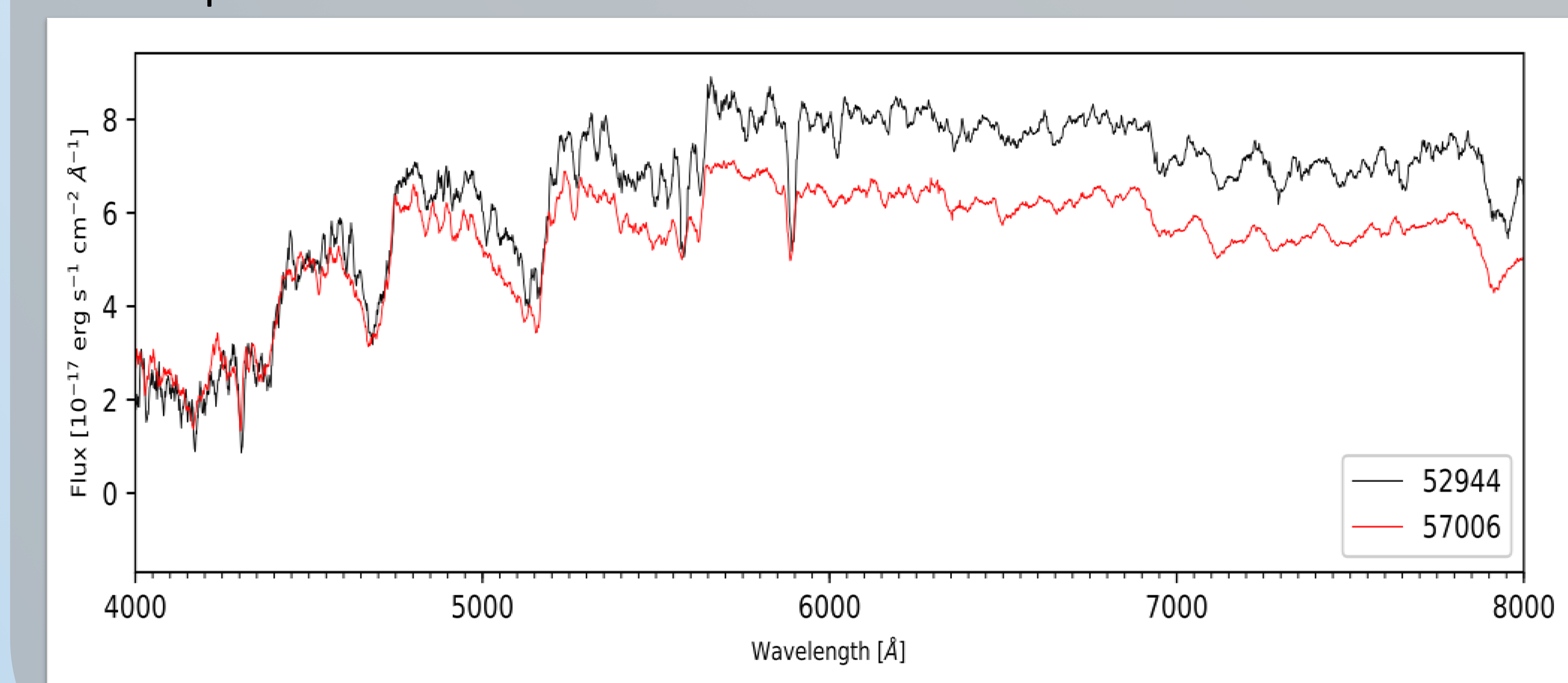


Figure 1. (above) – Example of a dC star spectrum. Plotted are two epochs for the same dC, showing the strong C_2 bandheads.

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, 241 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% levels of five dC properties: r magnitude, g-r color, total proper motion, ΔMJD, and Gaia DR2 parallax. Within this 5-space, we choose the closest unique control star for each dC.

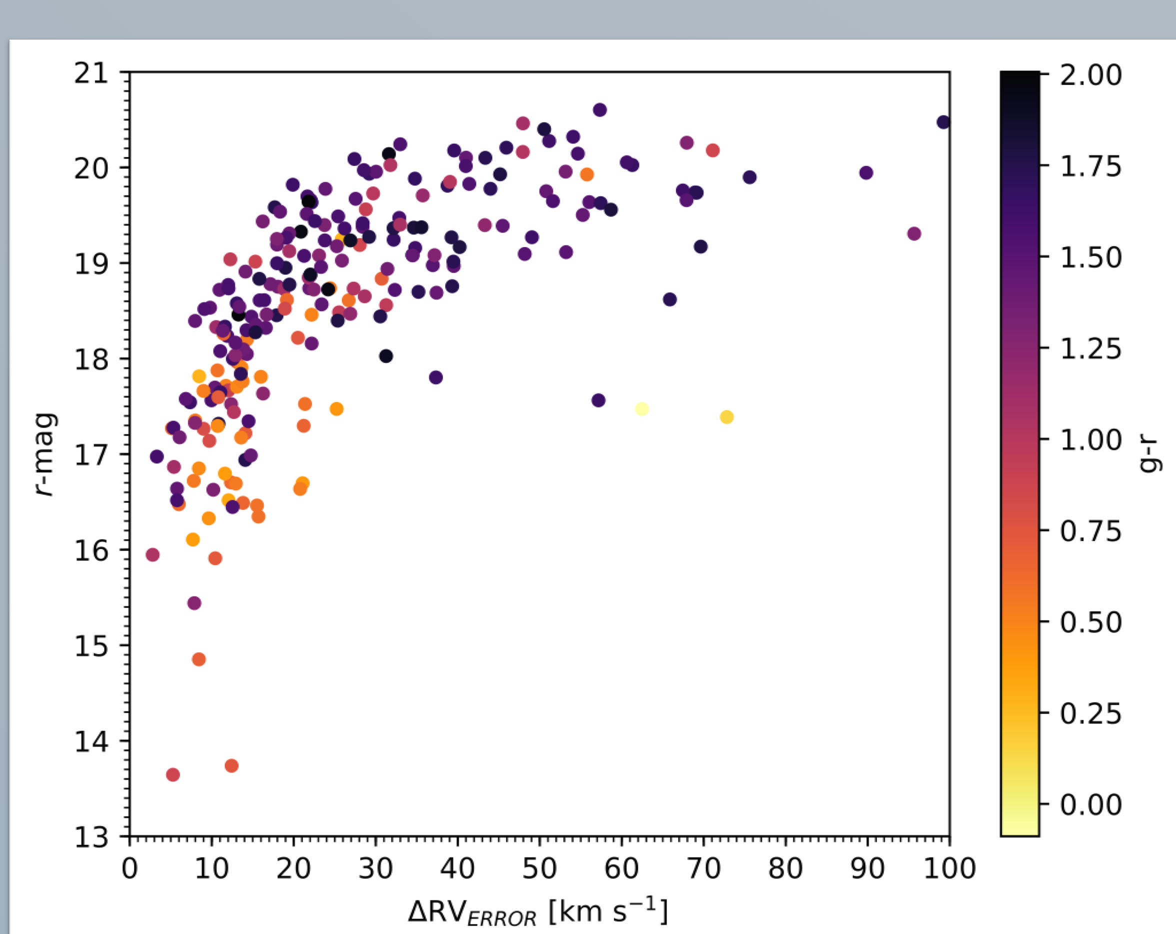


Figure 2. (left) – Optical *r*-band magnitude plotted against the radial velocity variation (ΔRV) errors obtained when directly comparing two epochs of dC stars in our sample. Larger errors are found for fainter stars, as expected, since these tend to have poor spectroscopic *S/N* (see Fig3.) Optical $g-r$ color is denoted for each object by color.

For the majority of objects, the errors on our measurements are between 10-40 $km\ s^{-1}$

ΔRV Measurements & Analysis

We measured radial velocity variations (ΔRV) by cross-correlating epochs using IRAF FXCOR (Tonry & Davis 1979). Each spectrum and cross-correlation 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 differ at the 99.8% level, supporting the hypothesis dCs are in binary systems that have undergone mass transfer, which can be seen in Fig.3.

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). Both requires a narrow and a wide component, but the latter is much wider for dCs, confirming that the dCs have more systems with high ΔRVs, indicative of close binary systems.

Indeed, several dCs display large ΔRV values (≥ 100 $km\ s^{-1}$), indicative of close binary orbits. We are targeting these for follow-up spectroscopy to determine their orbital parameters.

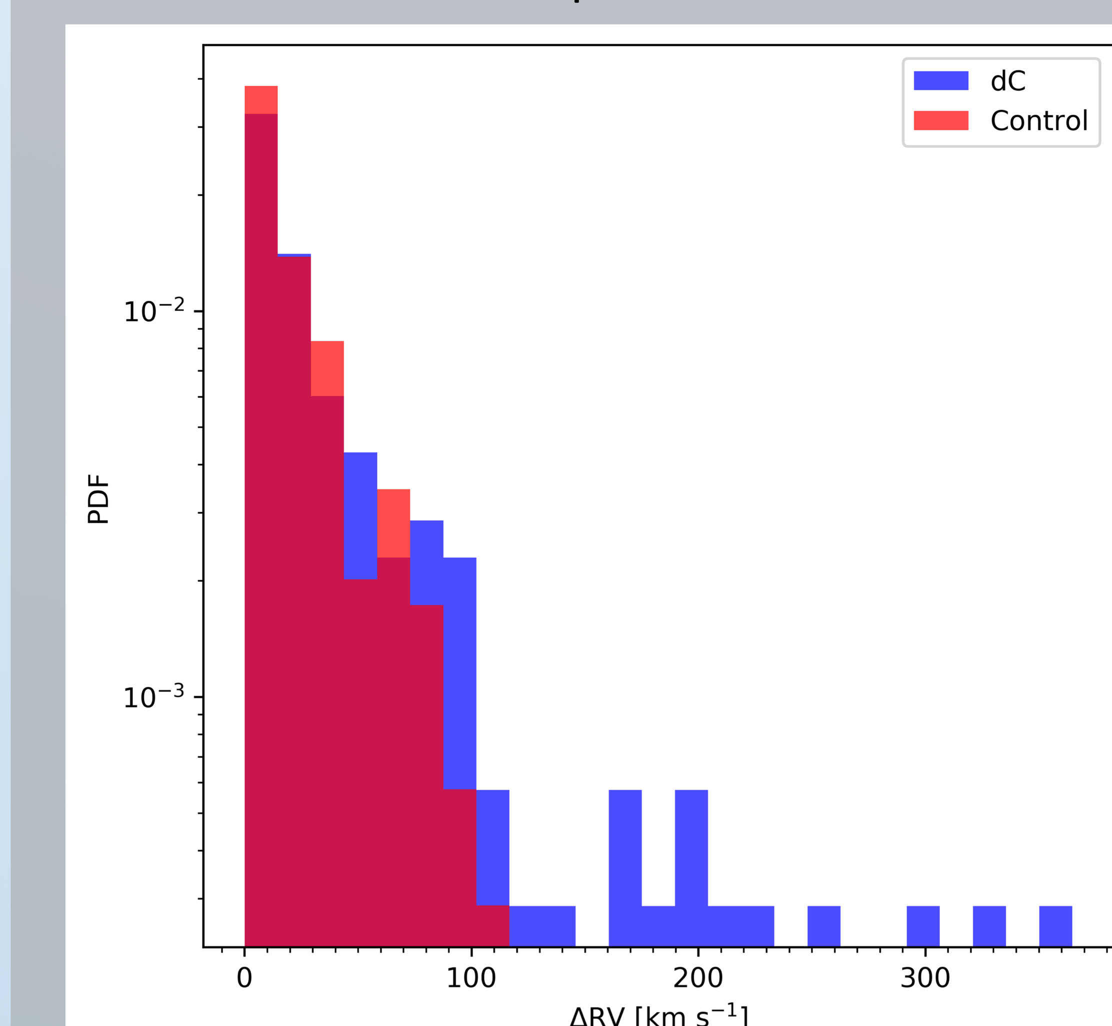


Figure 3. (left) – Normalized ΔRV histogram for both of the finalized dC and control samples. This histogram shows the wider flaring of the base for the dC sample, suggesting the dCs are more likely in the close binaries that we are sensitive to. Gaussian fits show the dCs have a wider distribution ($\sigma_{dC} \sim 60\ km\ s^{-1}$ and $\sigma_{Contorl} \sim 30\ km\ s^{-1}$)

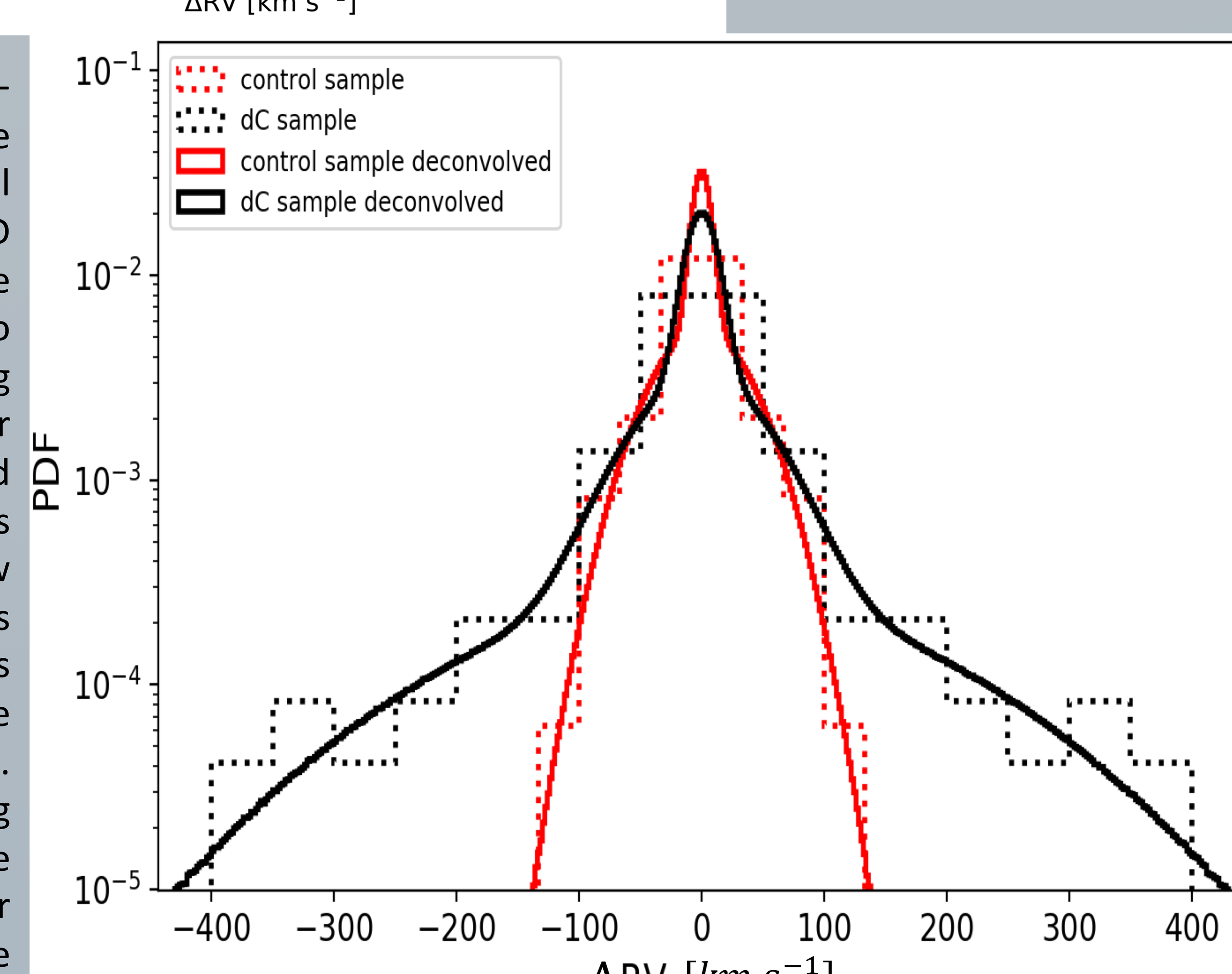


Figure 4. (right) – Results of XD for the dC and control samples. This XD method uses the errors and helps to infer the underlying ΔRV distribution for both the dCs and control stars. This figure shows how the dC distribution is wider and then flairs out compared to the control sample. Again, confirming the dCs are in close binaries that our method is sensitive to.

Orbital Separation Simulations & Future Work

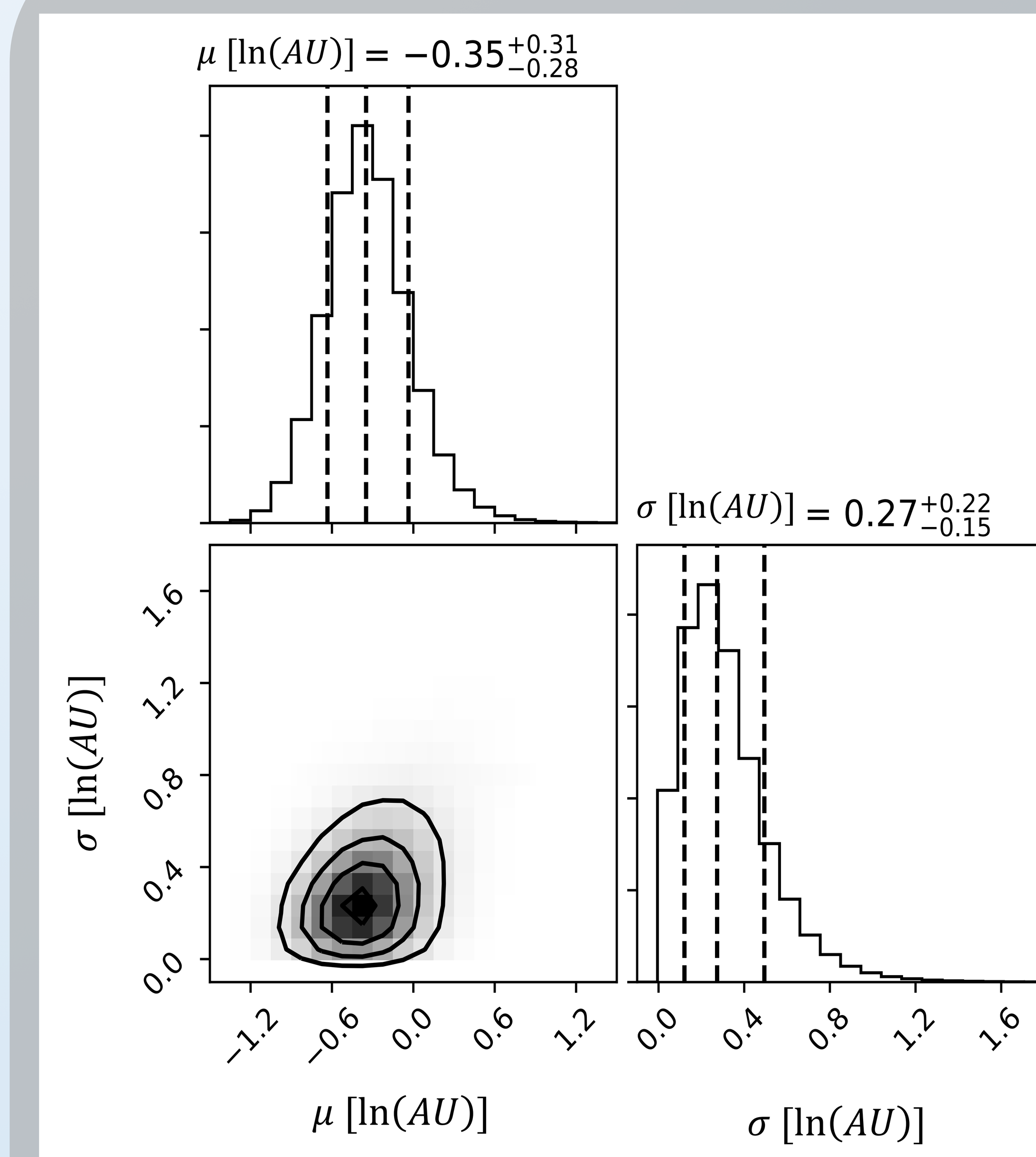
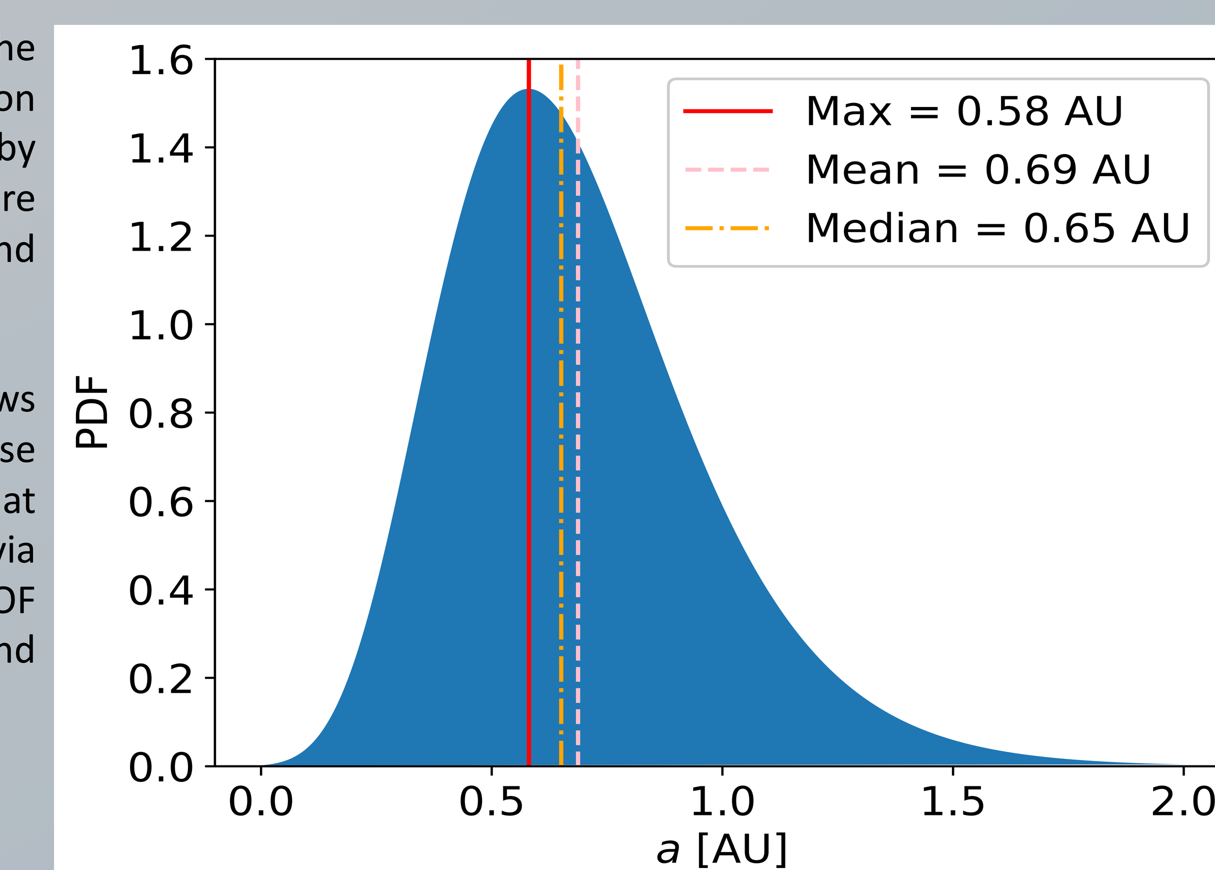


Figure 5. (left) – Contour plot of our two parameter model with marginalized posteriors for each parameter. This early draft model assumes a circularized orbit, with SDSS epochs at the maximum RV difference. This reduces our model for ΔRV to a function of $M_{dC}, M_{WD}, \sin i$, and a. With few current constraints for dCs, we assign a dC mass distribution uniform from 0.1 to 1.0 $M_{\odot}$. For MWDs, use a Gaussian distribution used by Maoz+ (2012). We also assumed the dC-WD separation distribution is. lognormal, following Raghavan+ (2010) for close binary systems..

Figure 6. (right) – The dC-WD separation distribution as found by our MCMC. Marked are the peak, mean, and median of the PDF.

This distribution shows the dCs are in close binary systems that have likely interacted via a combination of RLOF and AGD-wind accretion.



We've modeled the binary orbital separation distribution by using a MCMC parameter estimation method. We assumed a simple circularized orbit with given mass and $\sin i$ PDFs. The resulting best parameters for the lognormal separation PDF can been seen in Fig.5 and the corresponding PDF in Fig.6.

This distribution shows the dCs are in close binary systems that have likely interacted via a combination of RLOF and AGB-wind accretion.

However, we want to point out the assumptions used so far will have an effect on the separation distribution. We need to constrain the dC masses, which is one of the goals of future work being done by exploring X-ray luminosities and SED fitting in an attempt to constrain the dC masses (see Poster #118, Paul Green+).

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