■ Scientific Justification

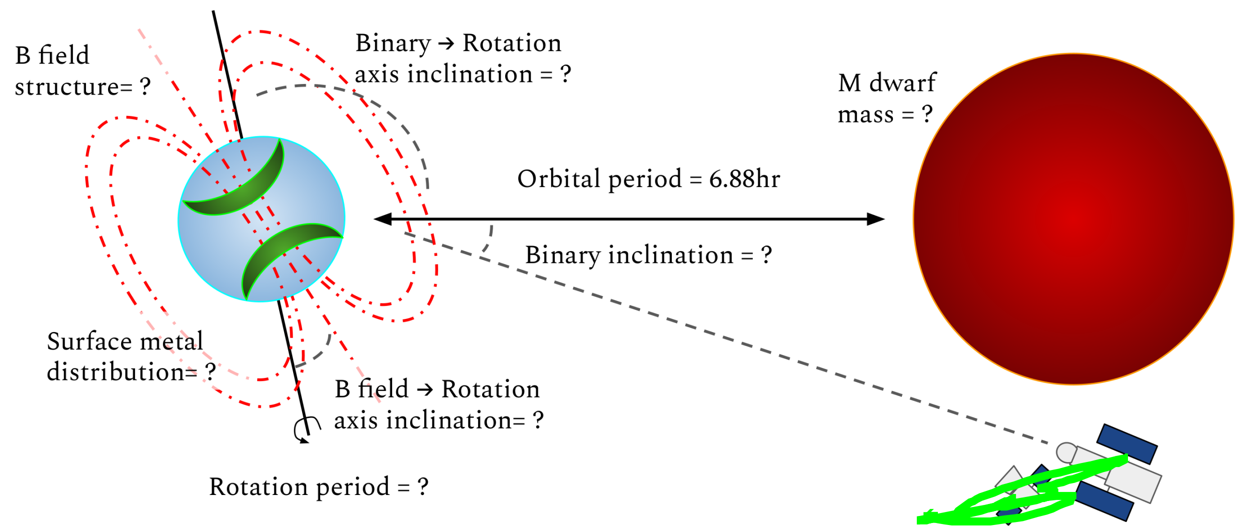

Figure 1: Schematic of the CC Cet binary system (not to scale), a white dwarf accreting magnetically channelled stellar wind from an M dwarf companion. Our proposed *HST* observations will enable measurements of all of the unknown parameters labelled as "?", including the spin period of the white dwarf, inclination of the system, and aurora-like distribution of metals on the white dwarf surface.

The analysis of the first *Gaia*-based, volume limited sample of Cataclysmic Variables (CVs) revealed that one-third of the systems contain magnetic white dwarfs (Pala et al., 2020). However, magnetic fields are exceedingly rare among their detached progenitor systems, the Post Common Envelope Binaries (PCEBs). Since this conundrum was first identified (*Where Are the Magnetic White Dwarfs with Detached, Nondegenerate Companions?*, Liebert et al. 2005), fewer than twenty magnetic white dwarfs in close, detached binaries have been discovered. All of the known examples are relatively cool ($\lesssim 10000$ K) and old ($\gtrsim 1$ Gyr). Most proposed mechanisms for the formation of magnetic fields in white dwarfs occur before or during evolution through the giant stages, so there should be a. a lot more magnetic white dwarfs in PCEBs in general, to match the distribution in CVs, and b. a continuous spread in ages among the magnetic binaries.

Using two short *HST* observations, we have identified the first PCEB with a hot (25000 K) and young (≈ 13 Myr) magnetic white dwarf. Here we propose to characterise the physical properties of this remarkable system in detail with deeper *HST* spectroscopy.

CC Cet is a PCEB consisting of a low-mass white dwarf and an M-4.5 companion (Saffer et al., 1993). Figure 1 shows a schematic of the system, as well as the unknown parameters that our program will quantify. Two spectra of CC Cet were obtained with the Cosmic Origins Spectrograph (COS) onboard *HST* in 2018 August and 2019 January. The spectra show multiple deep absorption lines from C III, Si III and Si IV in addition to the broad H I Lyman α line characteristic of hydrogen atmosphere white dwarfs.

To our great surprise, we found that the metal absorption lines are Zeeman split, demonstrating the presence of a magnetic field. Figure 2 shows the Si IV lines in the two *HST* spectra, clearly Zeeman-split in comparison with a non-magnetic object. Similar splitting is seen in C III and Si III line features. The splitting at each line is consistent with a magnetic field of ≈700 kG.

The high surface gravity of white dwarfs causes them to chemically stratify on very short timescales, leaving pure hydrogen or helium atmospheres. The metals seen in CC Cet must therefore be currently accreting from an external source, in this case the stellar wind of the companion (Debes, 2006).

The Zeeman-splitting was not the only remarkable feature of the absorption lines. We also found that the lines are velocity broadened well beyond the instrumental broadening. We measure a $v \sin i$ of $\approx 40\,\mathrm{km\,s^{-1}}$, implying a rotation period of ≈ 30 minutes, depending on the inclination. This is much faster than either the ∼day long orbital periods of single white dwarfs or of the 6.88 hour binary orbital period of CC Cet: The white has been spun up to a much greater extent than if tidal forces alone are acting.

Furthermore, the line profiles in the two COS spectra are subtlety different, with changes both to the magnitude of the Zeeman-splitting and the line strength, implying a different mean magnetic field and mean metal abundance over the observed hemisphere respectively. The line variations imply that the magnetic dipole is offset from the rotation axis, and that the M dwarf wind is not accreting uniformly onto the white dwarf surface, but is instead being channelled down the magnetic field lines onto the magnetic poles of the white dwarf. Inhomogeneous accretion of stellar wind governed by magnetic field is essentially the same process that produces the Aurora on Earth — at CC Cet, we are seeing aurora on a star!

The inhomogeneous accretion leads to two tantalizing observational consequences. Firstly, the uneven distribution of metals may result in changes in the total net flux of the white dwarf as it rotates. Sufficiently high-precision photometry may therefore detect the rotation of the white dwarf, solving the unknown in our measurement of $v \sin i$ and providing the rotation inclination. To this end, we have ensured that CC Cet will be observed at 2 minute cadence by *TESS* in Sector 31, providing the sub-percent level photometry required to detect the spin period (the system was previously observed in Sector 4 but at only 30 minute cadence, too long to search for the white dwarf spin). We now turn to *HST* for the second observational opportunity: A map of the surface metal distribution and magnetic field configuration of the CC Cet white dwarf, as well as a complete solution for the masses and orbital inclination of the binary system.

Using the same set-up as the previous COS observations, we will observe CC Cet for 5 orbits, for a total exposure time of roughly 9000 s covering ten or more rotations. Using the rotation period and ephermeris measured from the *TESS* light curve, we will extract phase-series spectra using the COSTOOLS routines.

The phase-resolved spectra will provide a measure of the mean magnetic field strength and mean metal abundance of the facing hemisphere as a function of rotation phase. With

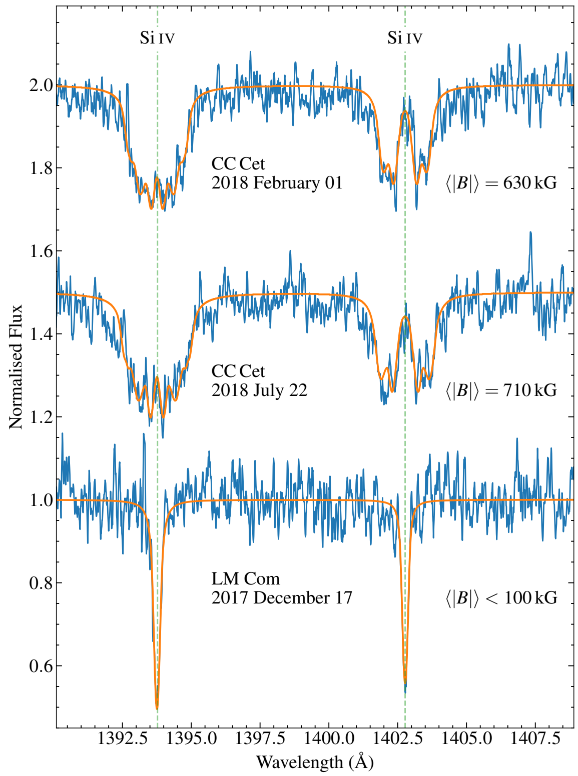

Figure 2: Silicon Si IV lines in the two *HST*/COS spectra of CC Cet, along with a spectrum of LM Com, another PCEB with a similar $T_{\rm eff}$ and $\log g$. The difference between the Zeeman-split lines in CC Cet and the non-magnetic LM Com is readily apparent. The orange line shows the best-fit magnetic model to the lines, and the dashed vertical lines show the rest wavelengths. The date and best-fit mean field modulus are given under each spectrum. The absorption lines of CC Cet are heavily Doppler-broadened, implying that the white dwarf is rapidly rotating, and the strength and splitting of the lines vary between the spectra, demonstrating that the metals are unevenly distributed across the white dwarf surface.

the B field measurements, we will be able to determine the global strength and structure of the magnetic field, as well as its offset from the spin axis. The changes in metal abundance will provide the relative coverage of the white dwarf surface as a function of rotation phase. Combining the two, we will create a map of the white dwarf surface showing the coverage of its stellar aurora.

The total time-on-target of the observations (including portions of the orbit in Earth's shadow) will be approximately 8 hours, covering the full 6.8 hour binary period of CC Cet. We will therefore be able to measure the radial velocity of the white dwarf across the entire orbit. The velocity curve of the companion has been well characterised by Saffer et al. (1993), so we will then have the velocity ratio and hence the mass ratio of the system. Model atmosphere fits to the white dwarf spectrum have tightly constrained the white dwarf mass, and thus these measurements will return the mass of the M dwarf companion and orbital inclination of the system. A difference between the spin axis of the white dwarf and the binary plane could indicate that the white dwarf has been torqued by the magnetic field, providing a clue as to how the white dwarf has been spun up.

In summary, our observations will fully characterise this fascinating and thus-far unique binary system, filling in all of the unknown parameters in Figure 1:

- The *TESS* data will measure the rotation period of the white dwarf. As $v \sin i$ is known, this will also provide the rotation inclination.

- COS spectra will measure the change in Zeeman-splitting and strength of the metal absorption lines as a function of phase. This will provide the magnetic field structure and surface metal distribution.
- The radial velocity curve of the absorption lines will provide the M dwarf mass and binary inclination.

Secondary science: Flares: Although existing optical data (and the original COS observations) indicate that the M dwarf in CC Cet is relatively quiet, there is a reasonable chance that it will flare during the observation. ~~Multi-wavelength observations of flares (in this case FUV with COS and o~~ptical with *TESS*) are rare, and provide insight into the physics of flare generation and their link with particle emission (France et al., 2020). Thus the serendipitous detection of a flare would be exciting secondary science from this dataset. To maximise the science return from a flare we will request *Swift* TOO time to monitor the star during the COS observations, adding U-band and X-ray photometry to the dataset.

References

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Description of the Observations

We will observe CC Cet for 5 consecutive orbits using the G130M grating with a central wavelength of 1291 Å. Based on the previous COS observations we conservatively estimate an exposure time per orbit of 1800s, for a total of 9000 s. Using a white dwarf model atmosphere spectrum fit to CC Cet, we used the ETC to predict achieving a S/N of 30 in $\approx$900 s around the key Si IV 1400 Å lines, allowing us to resolve $\approx$ten phases of line variation. The observations will span roughly 8 hours, covering the entire 6.8 hour binary period and thus allowing a measurement of the full radial velocity curve of the white dwarf. The radial velocity of the two existing spectra is different by $\approx 80\,\mathrm{km\,s^{-1}}$, so measuring the full curve is well within the resolution capabilities of COS. The target has already passed Bright Object Protection analysis for the previous COS observations.

Special Requirements

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Coordinated Observations

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Justify Duplications

CC Cet has already been observed twice using the setup requested here. As described in the science justification, these observations showed that the target is variable, so further spectra are required to improve the signal-to-noise ratio and characterise the variation.