■ Scientific Justification

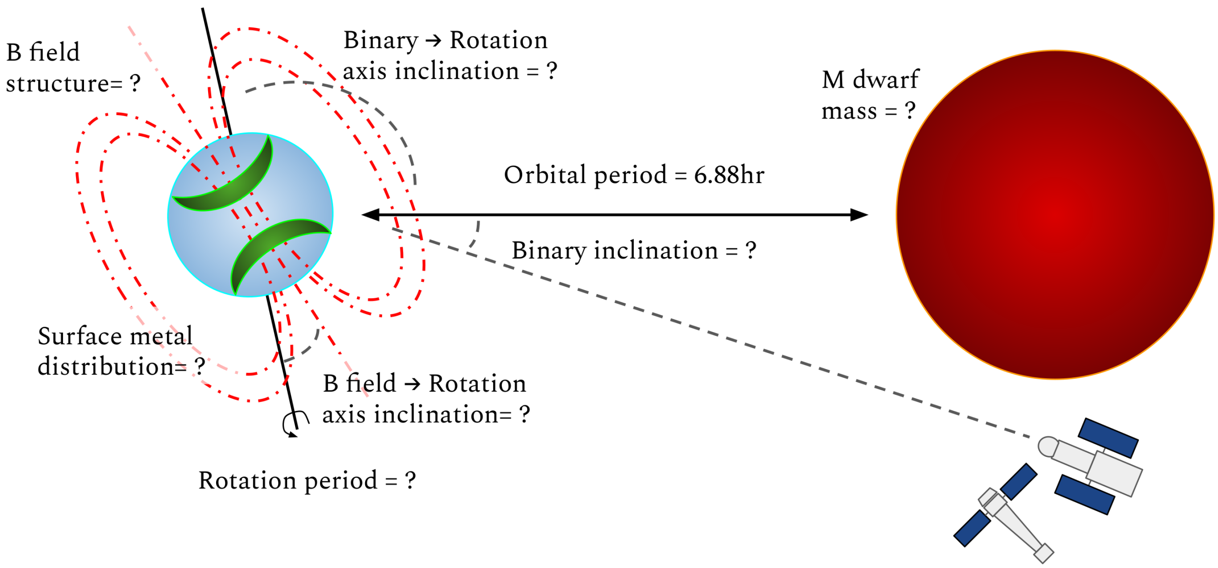

Figure 1: Schematic of the CC Cet binary system (not to scale), a white dwarf accreting magnetically channelled stellar wind from an M dwarf companion. Our proposed *HST* and *XMM* observations will enable measurements of all of the unknown parameters labelled as "?", including the spin period of the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

The absent stars: 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 progenitor systems, close, detached white dwarf-M dwarf binaries known as 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 (Parsons et al., 2021). All of the known examples are relatively cool ($\lesssim 10000\,K$) and old ($\gtrsim 1$ Gyr), and have likely gone through at least one period of mass transfer, i.e. they are not true "Pre-CVs". 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. Many 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.

From two short *HST* observations, Wilson et al. (2021) 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 and *XMM-Newton* X-ray measurements.

CC Cet is a PCEB consisting of a low-mass white dwarf and an M4.5V companion (Saffer et al., 1993). Figure 1 shows a schematic of the system, highlighting 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. 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).

Surprisingly, the metal absorption lines are Zeeman split, demonstrating the presence of a magnetic field. Figure 2 (Wilson et al., 2021) 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 $\approx$700 kG. As CC Cet is not predicted to start mass transfer via Roche Lobe overflow for ≈ 10 Gyr, it is therefore the first unambiguous magnetic Pre-CV found.

The Zeeman-splitting is not the only remarkable feature of the absorption lines, as they are also velocity broadened well beyond the instrumental broadening. Wilson et al. (2021) measure a $v \sin i$ of $\approx$40 km s^{-1}, implying a rotation period of $\approx$ 2000 s depending on the inclination. This is much faster than either the $\sim$day long orbital periods of single white dwarfs or of the 6.88 hour binary orbital period of CC Cet, implying that the white dwarf 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 subtly 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 axis of 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 field lines onto the magnetic poles of the white dwarf.

New observations: The relatively low S/N and unknown phase coverage of the existing spectra preclude a precise measurement of the white dwarf rotation period or further characterisation of the magnetic field. We therefore request additional, deeper COS observations to measure the rotation period, produce a map of the surface metal distribution and magnetic field configuration, and find 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 rotation cycles. Using the Costools routines we will extract time-series spectra and measure the variation of the absorption lines with time to **establish the white dwarf spin period**. The spectra will then be phase-folded onto the spin period and combined into $\approx$10 phase-bins. **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.**

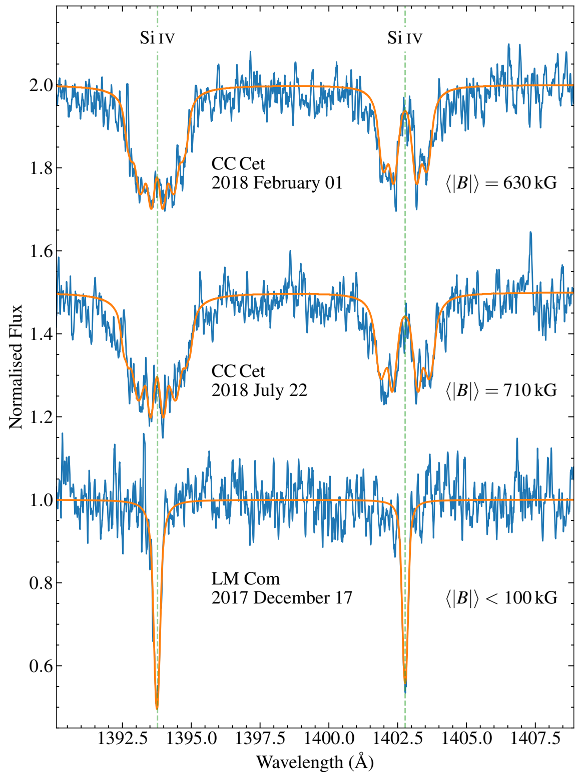

Figure 2: Silicon Si IV lines in the two *HST*/COS spectra of CC Cet, along with a spectrum of LM Com, another PCEB with a similar T_{eff} and $\log g$. The difference between the Zeeman-split lines in CC Cet and the non-magnetic LM Com is readily apparent. The orange line shows the best-fit magnetic 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.

With the magnetic 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 metal accretion topology.

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.

X-ray observations: X-ray emission induced by accretion is a common feature of magnetic CVs (e.g. Lopes de Oliveira et al., 2020). Despite having much lower accretion rates, accretion induced X-ray emission has been detected from some PCEBs (e.g QS Vir, Matranga et al., 2012) and even at single white dwarfs (Cunningham et al., 2022). A short (7 ks) *XMM*-

Newton observation of CC Cet obtained along with one of the *HST* spectra gave a hint of a detection of the system in both pn and MOS detectors, indicating an X-ray luminosity at, *or exceeding,* the well-established saturated value for coronal emission of $L_X/L_{bol} = 10^{-3}$. For CC Cet, this saturated X-ray luminosity is 1.5×10^{28} erg s^{-1}.

Deeper observations will measure the X-ray emission as a function of phase, potentially providing an independent measure of the mass accretion rate over the facing side and further constraining the surface metal distribution and magnetic field structure. A measure of the wind accretion rate would be particularly powerful, and would also help constrain the wind accretion efficiency.

We request 100 ks of *XMM* time, entirely overlapping the *HST* observations to precisely phase the data and search for multi-wavelength flares and wind accretion X-rays.

Secondary science: Flares: Although existing optical data indicate that the M dwarf in CC Cet is relatively quiet (only one flare is seen in four Sectors of *TESS* observations), there is still a reasonable chance that it will flare during the observation as even "quiet" M dwarfs flare regularly in the ultraviolet (France et al., 2020). The serendipitous detection of a flare would be exciting secondary science from this dataset, especially with simultaneous X-ray observations. 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 photometry to the dataset. Multi-wavelength observations of flares are rare, and provide insight into the physics of flare generation and their link with particle emission.

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

- With time-series spectra we will measure the rotation period of the white dwarf. As v sin i is known, this will also provide the rotation inclination.
- Phase-folding those spectra will reveal the change in Zeeman-splitting and strength of the metal absorption lines as a function of phase. This will provide constraints on the magnetic field structure and relative surface metal coverage.
- The radial velocity curve of the absorption lines will provide the M dwarf mass and binary inclination.
- X-ray data will independently measure the accretion rate as a function of phase and provide the opportunity to detect multi-wavelength flares.

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 ≈ 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

None

Coordinated Observations

We will observe CC Cet for 100 ks with *XMM-Newton*-EPIC, entirely overlapping the *HST* observations in time. The simultaneous observations will allow observations of multi-wavelength flares and precise phasing of the X-ray data to the white dwarf rotation period, whilst the longer overall exposure time will increase the S/N of the relatively faint X-ray emission.

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, and further spectra are required to improve the signal-to-noise ratio and characterise the variation.