■ Rationale for DD Time

The target is a rapidly-rotating white dwarf with a spin period of ≈ 30 min with an M dwarf binary companion in a 6.88 hr orbit. The white dwarf is magnetic and is accreating the stellar wind of the M dwarf inhomogeneously over its surface. This should result in flux variations that may be apparent in TESS 2 min cadence data. Observing simultaneously with HST will allow us to make a phase-resolved map of the white dwarf surface, with variations in the spectra locked to the TESS timing data. The TESS observations will be obtained in Cycle 31 covering 2020 October 22 to 2020 November 18, hence the requirement for DDT time to obtain simultaneous observations.

■ Science Justification

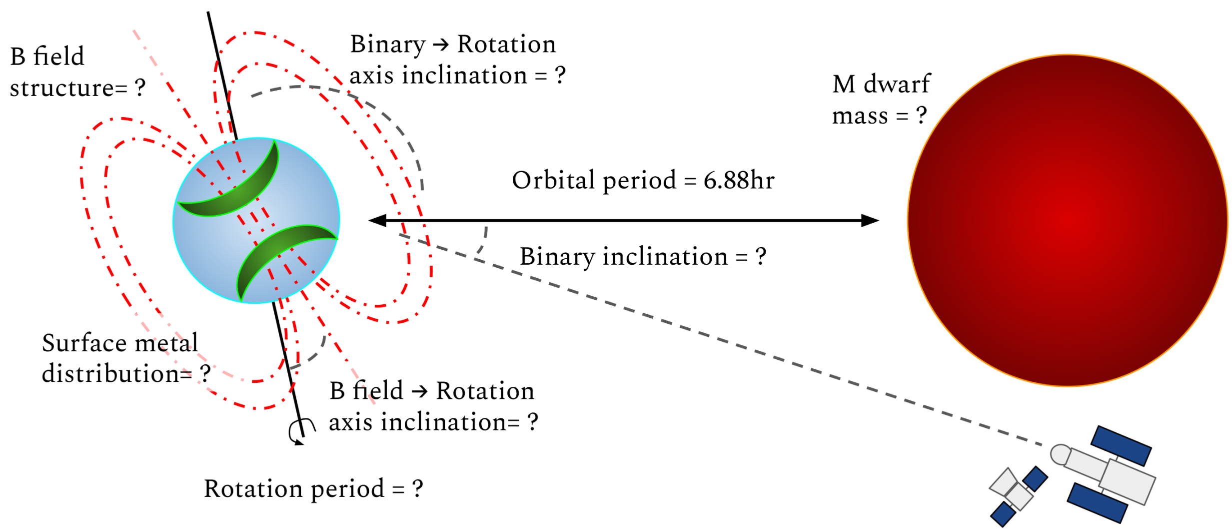

Figure 1: Schematic of the CC Cet binary system (not to scale), a white dwarf accreting magnetically channelled stellar wind from an M dwarf companion. We propose to obtain a combined *HST* and *TESS* dataset that will enable measurements of all of the unknown parameters labelled as "?", including the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

Cataclysmic Variables (CVs) are comprised of a white dwarf accreting material from a main-sequence companion via Roche lobe overflow. Roughly one third of the white dwarfs in CVs are magnetic, with field strengths ranging from hundreds of kG (Intermediate Polars) to tens of MG (Polars) (Pala et al., 2020). CVs evolve from Post Common Envelope Binaries (PCEBs), close but detached white dwarf-main sequence binaries that lose angular momentum to gravitational wave radiation and magnetic breaking until the secondary overflows its Roche lobe. As PCEBs are the direct progenitors of CVs, we would expect them to have the same $\approx$ one third incidence of magnetic white dwarfs. Nothing could be further from the truth: of the several thousand known PCEBs, fewer than twenty have detected magnetic fields, mostly pre-Polars (Schmidt et al., 2005). Only two pre-Intermediate polars are known (Sion et al., 1998; Parsons et al., 2013). Most proposed mechanisms for the formation of magnetic fields in white dwarfs require them to form either before or during evolution through the giant stages, so the lack of magnetic PCEBs is a complete mystery (Liebert et al., 2005).

Using data from *HST*, we have detected a white dwarf in a PCEB with a $\sim 700\,$kG magnetic field, the third known pre-Intermediate polar. Here we request further *HST* spectroscopy to produce a phase-resolved map of the white dwarf surface, obtained in concert with two minute cadence optical photometry from *TESS*.

CC Cet is a PCEB consisting of a low-mass white dwarf and an M-4.5 companion (Saffer et al., 1993). 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). Figure 1 shows a schematic of the system, as well as the unknown parameters that our program will quantify.

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 our two *HST* spectra, clearly Zeeman-split in comparison with a non-magnetic object. Similar splitting is seen in the C III, Si III as well as in the Balmer lines of optical UVES spectra obtained almost 20 years ago. The splitting at each line is consistent with a magnetic field of $\approx$700 kG, making this system only the third known pre-Intermediate Polar. Such pre-IPs are actually the only IPs where the exact magnetic field strengths can be measured, as the accretion discs at true IPs obscure the photospheres where Zeeman-split lines would be visible (Ferrario et al., 2015).

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 $\approx$ 30 minutes, depending on the inclination. This is much faster than either the $\sim$day long orbital periods of single white dwarfs or of the binary orbital period of CC Cet: The white has been spun up to a 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. Inhomogenous accretion of stellar wind governed by magnetic field is essentially the same

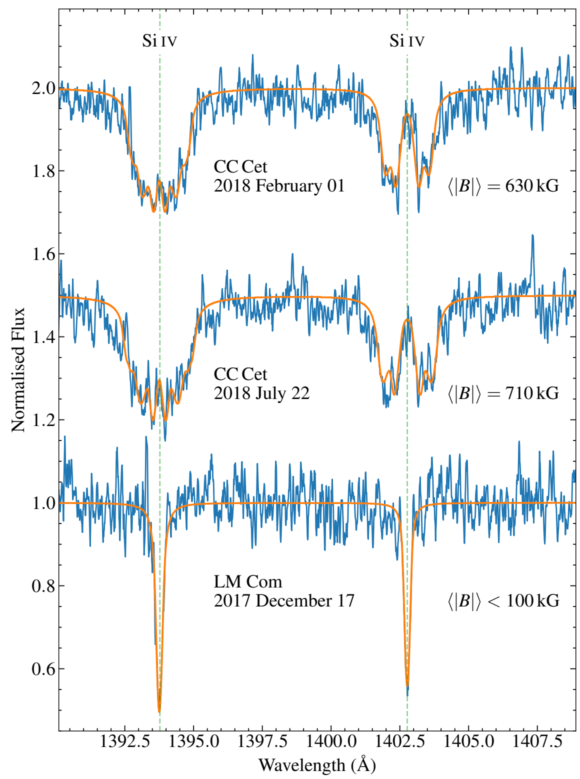

Figure 2: Silicon Si IV lines in the two *HST*/COS spectra of CC Cet, along with a spectrum of LM Com, another PCEB with a similar T_{eff} and $\log g$. The difference between the Zeeman-split lines in CC Cet and the non-magnetic LM Com is readily apparent. The orange line shows the best-fit magnetic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

process that produces the Aurora on Earth — at CC Cet, we are seeing aurora on a star!

The inhomogenous 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. 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. We will extract time-series spectra using the COSTOOLS routines, and measure the variation in the morphology of the spectral lines as a function of time. If the *TESS* observations are successful in observing the rotation period, we will phase-fold the spectra onto the *TESS* period and ephemeris; if not, we will search for the rotation period in the line changes directly.

The time-series 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 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 measure the following characteristics of the CC Cet system shown 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-spltting 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.

Having the full characteristics of the CC Cet system in hand will provide an insight into its formation history, and perhaps finally answer the question of why so few magnetic PCEBs exist in comparison to their CV cousins.

Secondary science: Flares: Although previous optical data (and the original COS observations) indicate that the M dwarf in CC Cet is relatively quiet, there is a reasonable chance that is will flare during the observation. Multi-wavelength observations of flares (in this case FUV with COS and optical 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 ≈900 s around the key Si IV 1400 Å lines, allowing us to resolve ≈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.

Scheduling Requirements

The observations must be obtained within TESS sector 31 (2020 October 22–2020 November 18) with the exception of 4–5 November when TESS will not be on target. The APT visit planer shows that the target will be visible for essentially this entire window.