HST and XMM combine to characterise a unique magnetic white dwarf binary

Scientific Category: Stellar Physics and Stellar Types

Scientific Keywords: Binary Stars / Trinary Stars, Stellar Phenomena, Variable Stars, White Dwarf Stars

Instruments: COS

Exclusive Access Period: 6 months

Proposal Size: Small XMM-Newton: 30.0 ksec UV Initiative: Yes

Orbit Request	Prime	Parallel
Cycle 32	5	0

Abstract

We propose to obtain 5 orbits of COS ultraviolet spectroscopy of the close white dwarf/M dwarf binary system CC Cet, observing in concert with XMM-Newton. Existing COS spectroscopy has revealed that the white dwarf is magnetic, and is accreting the stellar wind of the M dwarf along the magnetic field lines to produce an inhomogeneous surface. Magnetic systems in close but detached binaries are extremely rare, a mystery given the one-third magnetic incidence in the Cataclysmic Variables that they will evolve into. The white dwarf is also spinning much faster than the orbital period.

Whilst the two existing COS spectra show that the observed magnetic field strength and metal distribution vary with time, the phase of the observations are unknown and the S/N too low to extract meaningful time series spectroscopy. With five orbits, obtained simultaneously with X-ray photometry, we will measure the spin period of the white dwarf, resolve the changes in magnetic field strength and metal abundances as a function of spin, and obtain the radial velocity curve of the white dwarf.

This rich dataset will allow us to solve the magnetic field structure, map out the distribution of the wind accretion across the white dwarf photosphere, and solve for the binary masses and inclinations. With all the relevant parameters of the system known, we will be able to tightly constrain formation models of the system, and perhaps gain insight into why magnetic white dwarfs in detached binaries are so rare. There is also a possibility that the M dwarf will flare during our observation, providing a multi-wavelength dataset that can probe the physics of stellar activity.

Target Summary:

Target	RA	Dec	Magnitude
V-CC-CET	03 10 55.0405	+09 49 24.42	

Observing Summary:

Target	Config Mode and Spectral Elements	Flags	Orbits
V-CC-CET	COS/FUV Spectroscopic G130M (1291)		5

Total prime orbits: 5

Investigators:

Investigators and Team Expertise are included in this preview for your team to review. These will not appear in the version of the proposal given to the TAC, to allow for a dual anonymous review.

Role		Investigator	Institution	Country
CoI		Dr. Jeremy J. Drake	Lockheed Martin Space	USA/CA
CoI	*	Prof. Boris T. Gaensicke	The University of Warwick	GBR
CoI		Dr. JJ Hermes	Boston University	USA/MA
CoI	*	Prof. Detlev G. Koester	Universitat Kiel	DEU
CoI	!	Dr. John D. Landstreet	The University of Western Ontario (Retired)	CAN
CoI		Dr. Odette Fabiola Toloza Castillo	Universidad Tecnica Federico Santa Maria	CHL
PI	&	Dr. David John Wilson	University of Colorado at Boulder	USA/CO

Number of investigators: 7
* ESA investigators: 2
! CSA investigators: 1
& Contacts: 1

Team Expertise:

David Wilson is a PI of four previous HST programs obtaining ultraviolet observations of stars using all four active science instruments, and has published multiple first-author papers based on HST data. He was the PI for the original COS observations of CC Cet and lead author on the discovery paper, and has completed bright-object protection checks for that and multiple other programs.

Boris Gaensicke is a leading expert in observations of white dwarfs, and has multiple HST programs amounting to hundreds of orbits observing white dwarfs. He has published dozens of papers on white dwarfs, including co-authoring a major review on magnetic white dwarfs.

John Landstreet has studied magnetic white dwarfs for decades, having been involved in the discovery of the first one known. He is the developer of the ZEEMAN.F code that we use here to fit the magnetic line profiles.

Odette Toloza is an expert in ultraviolet spectroscopy of white dwarfs, having led several HST programs observing variable white dwarfs. She has a particular focus on the model atmosphere fitting and time-resolved observations, both of which will be utilised in this program.

Jeremy Drake is a member of the Chandra science division and has published multiple studies on the high energy environment of stars, and will provide his expertise to the XMM data requested here.

Detlev Koester has developed white dwarf atmosphere models that are used extensively throughout the community, and which will be applied to this data to confirm the atmospheric parameters of the CC Cet white dwarf.

JJ Hermes is an expert on white dwarf stars, especially the analysis of photometric variability of strongly magnetic white dwarfs.

■ Scientific Justification

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 orbits of *HST* observations, Wilson et al. (2021) identified the first PCEB with a hot (25000 K) and young ($\approx$ 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.** Resolving the exact properties of this system will provide constraints on formation models that must now explain why the generation of magnetic fields in young PCEBs occurs rarely, but not never.

The first young magnetic PCEB: 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 as part of a program to asses stellar wind strengths. 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 strong 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 example of a magnetic Pre-CV to be discovered.**

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 $\approx$ 30 minutes, depending on the inclination. This is much faster than either the $\sim$day long rotation periods of isolated

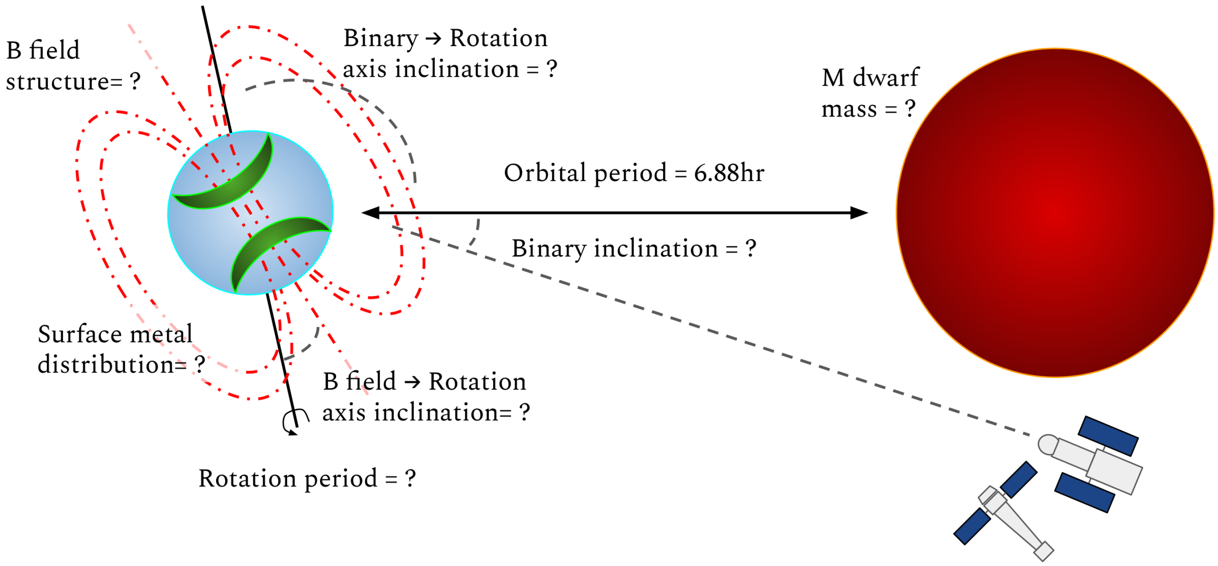

Figure 1: Schematic of the CC Cet binary system (not to scale), a white dwarf accreting magnetically channelled stellar wind from an M dwarf companion. Our proposed *HST* and *XMM* observations will enable measurements of all of the unknown parameters labelled as "?", including the spin period of the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

white dwarfs (Hermes et al., 2017) 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.**

Despite the fact that both spectra likely cover more than a full white dwarf rotation cycle, 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, covering 10 or more white dwarf rotation cycles with a total exposure time of over 2.5

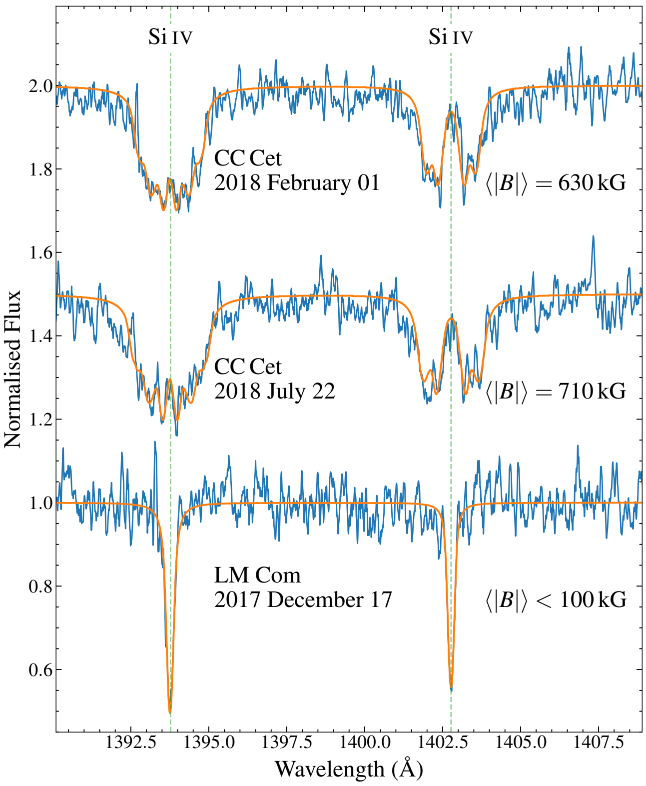

Figure 2: Silicon Si IV lines in the two *HST*/COS spectra of CC Cet, along with a spectrum of LM Com, another PCEB with a similar T_{eff} and $\log g$. The difference between the Zeeman-split lines in CC Cet and the non-magnetic LM Com is readily apparent. The orange line shows the best-fit magnetic 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 uncertainly in the magnetic filed strength fit is ≈ 10 kG. 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.

hours. Using the Costools routines we will extract time-series spectra and photometry, measuring 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 divided into $\approx$10 phase-bins. **The phase-resolved spectra will provide a measurement of the mean magnetic field strength and mean metal abundance of the facing hemisphere as a function of rotation phase.** 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 metal 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 (see for e.g. Landstreet et al., 2017).

The total time-on-target of the observations (including portions of the *HST* 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 full radial velocity curve of the white dwarf. 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 (Wilson et al., 2021), 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 (measured from the comparison of $v \sin i$ and the spin period) 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.

***XMM-Newton* observations:** X-ray emission induced by accretion and modulated on the white dwarf rotation period is a defining feature of Intermediate Polars (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 from 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 $L_X/L_{bol} = 10^{-3}$. **With deeper X-ray observations we will search for excess X-ray emission being generated by the wind accretion onto the white dwarf**, providing an independent measurement of the accretion rate over the facing side and further constraining the surface metal distribution and magnetic field structure. The wind accretion will be channelled onto the magnetic poles, so we also expect the X-ray flux to vary as a function of the white dwarf rotation phase, allowing a independent measurement of the white dwarf rotation period. We request 30 ks of *XMM* time, entirely overlapping the *HST* observations to precisely compare any variation in either waveband.

Secondary science: Flares and CMEs: 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, especially with simultaneous X-ray observations.** Furthermore, flares may be coupled with Coronal Mass Ejections (CMEs), which might be detected via an increase of the accretion rate onto the white dwarf a few tens of minutes after the flare. 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. Ultraviolet flares generally last less than one *HST* orbit, so will not compromise the primary science case. Multi-wavelength observations of flares are rare, and provide insight into the physics of flare generation and their link with particle emission, and a CME detection would be a remarkable breakthrough.

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 and X-ray light curves 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 white dwarf rotation 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, since the white dwarf mass is well constrained from model atmosphere fits.
- X-ray data will independently measure the accretion rate as a function of white dwarf rotation phase and enable the detection of multi-wavelength flares and CMEs.

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 ≈ 10 phases of line variation. The observations will span roughly 8 hours, covering the entire 6.8 hour binary orbital 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 30 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 measure the rotation period and magnetic-field structure of the WD, as well as the M dwarf mass and primary inclination, which could not be measured from previous, shorter observations.