

■ Rationale for Mid-Cycle Time

The analysis of the COS data leading to the design of this experiment was not completed until after the last proposal deadline. The observations proposed here and the experiment they enable, a test of the Ly α line reconstruction routines, will be of immediate use to multiple groups and projects, and will contribute to the analysis of many past and (most likely) future HST observing programs.

■ Science Justification

The H I Lyman α (Ly α) line at 1215.67 Å is a paradox of stellar observational astronomy: Vitally important for the study of stellar atmospheres and their effects on orbiting exoplanets, contributing as it does a large fraction of the ultraviolet flux (≈ 30 –70 per cent, France et al. 2013) of low mass stars; but extremely difficult to observe, occulted almost entirely by a combination of absorption by interstellar hydrogen and airglow emission from the Earth’s atmosphere. Nevertheless, observations of the Ly α line are the focus of a large number of HST observing programs, returning data from dozens of stars to date. These programs have been used to, for example, measure stellar winds (Wood, 2018), estimate the extreme ultraviolet flux of stars (Linsky et al., 2014), and model the atmospheres of the TRAPPIST-1 planets (Bourrier et al., 2017; Wunderlich et al., 2020).

Such observations rely on the fact that the Ly α lines of their targets are broad enough that the wings of the line are detectable to one or both sides of the regions occluded by ISM absorption and/or airglow. The full profile and strength of the Ly α line can then be reconstructed from the wings. Multiple methods have been developed for the reconstruction, such as using metal lines to characterise and thus remove the ISM (Wood et al., 2005) and/or fitting model line profiles to the wings (Bourrier et al., 2015; Youngblood et al., 2016), with broad agreement between techniques and recipes. However, testing the absolute accuracy of these reconstructions is challenging, as the ground truth of the Ly α profile of any given star cannot be obtained. In some cases the Ly α line can be fully observed at stars with sufficiently high radial velocities to shift the line out of the airglow and the deepest ISM absorption, the best example being Kapteyn’s star at 245 km s $^{-1}$ (Guinan et al., 2016; Schneider et al., 2019). Unfortunately they cannot be used as tests for the reconstruction techniques, as they cannot also be observed with the line occulted. What is required is a star where the radial velocity changes by many 10s of km s $^{-1}$ over time, allowing observations to be taken at low velocities when the Ly α line is occulted, and the reconstruction based on that data compared with unocculted, high-velocity Ly α observations. Such conditions exist in close binaries. We have identified perhaps the only system where this experiment is possible, and request STIS time to obtain the observations necessary to validate the vital Ly α reconstructions.

EG UMa is a close binary comprised of a M4 type Mdwarf in a 16 hour orbit of a white dwarf (Lanning, 1982; Bleach et al., 2000). The white dwarf is unusually cool for such systems with an effective temperature of only ≈ 13000 K (Sion et al., 1984), such that the ultraviolet emission is not completely dominated by the white dwarf but contains significant contribution from the Mdwarf. Figure 1 shows the A segment of a COS G130M spectrum

of the system. Strong emission lines from ions including C III, Si II and N V in the M dwarf atmosphere with peak fluxes several times greater than the white dwarf continuum are readily detected. We found no significant change in the line strengths over the four subspectra taken during the COS observation, indicating that the star was not flaring. Furthermore, the white dwarf spectrum is very well described by a Koester (2010) model atmosphere fit (orange line in Figure 1) and can be subtracted, leaving an M dwarf emission line spectrum analogous to what would be observed at any given single M dwarf. The short orbital period provides the large range of radial velocities that would allow the system to be observed at multiple levels of Ly α occultation, allowing a comprehensive test of Ly α reconstruction routines. The peak radial velocity (combining the orbital motion of the M dwarf and net velocity of the system relative to Earth) is $\approx -160 \text{ km s}^{-1}$, at which point the peak and $\gtrsim 90$ percent of the wings of the Ly α profile will be well clear of the airglow occultation and the deepest ISM absorption (Figure 3, right panel).

The wide, slitless aperture of COS means that the contribution from airglow at Ly α completely obscures the emission from the star, as Figure 1 clearly shows. We will therefore observe with STIS, using the G140M grating at a central wavelength of 1222 \AA , the setup used for the majority of Ly α stellar observations. As detailed in the description of the observations, we constructed a predicted spectrum based on the COS data and used that to confirm that STIS has the required sensitivity for these observations,

Radial velocity measurements of EGUMa by (Bleach et al., 2000) provided a precise determination of the orbital period and ephemeris, allowing for accurately phase-resolved observations. The observing strategy is outlined in Figure 2, showing the radial velocity curve of the M dwarf and the ideal observing times. Note however that around the peaks the radial velocity changes by only $\sim 10 \text{ km s}^{-1}$ over several hours, so the phase timing requirements for the program can be quite forgiving.

Two (observations 2 and 5 in Figure 2) will observe the system when the net radial velocity of the M dwarf is zero, providing the maximum occultation of the Ly α line. Observing for two orbits will increase the S/N of the Ly α wings to lower the statistical error on the line reconstruction process. We will then obtain a spectrum at the peak redshift at $\approx -90 \text{ km s}^{-1}$, representative of the spread of shifts seen at single M dwarfs. The first two panels of Figure 3 show our simulated G140M spectra at these phases, with the noise level from an exposure time of 2000s calculated using the STIS Exposure Time Calculator. Finally, we will observe at the peak blueshift with a radial velocity of $\approx -160 \text{ km s}^{-1}$, providing the almost entirely unocculted Ly α profile against which we can test the accuracy of our reconstructions to both the fully and partially obscured lines.

We are therefore testing the reconstructions in two different ways: How do the reconstructions compare to the true Ly α profile; and how do two reconstructions of the same star at different levels of occultation compare. Combined, these experiments will be a comprehensive diagnostic of any systematic uncertainties present in the reconstruction recipes, and will provide the ground truth data required to correct such uncertainties. Our observing strategy also accounts for potential interference from flares and/or heating from the companion, as

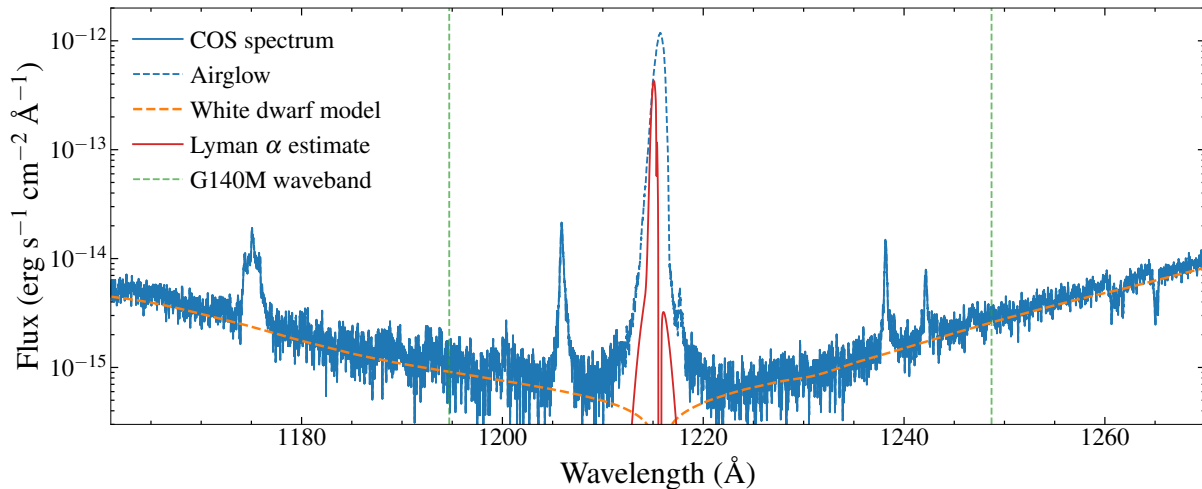


Figure 1: Segment A of the COS G130L spectrum of EG UMa. The spectrum is dominated by multiple emission lines from the M dwarf. The predicted strong Lyman α line is entirely lost to airglow in the COS observation, but would be easily detectable at multiple velocities with STIS.

detailed further in the description of the observations.

In conclusion, we have shown that the observations and experiment design proposed here will allow us to successfully validate the Ly α reconstruction methods. Given the huge amount of HST time invested in Ly α observations, this experiment and the data behind it represent a vital resource for interpreting Ly α observations and, by extension, understanding the atmospheres of stars and exoplanets.

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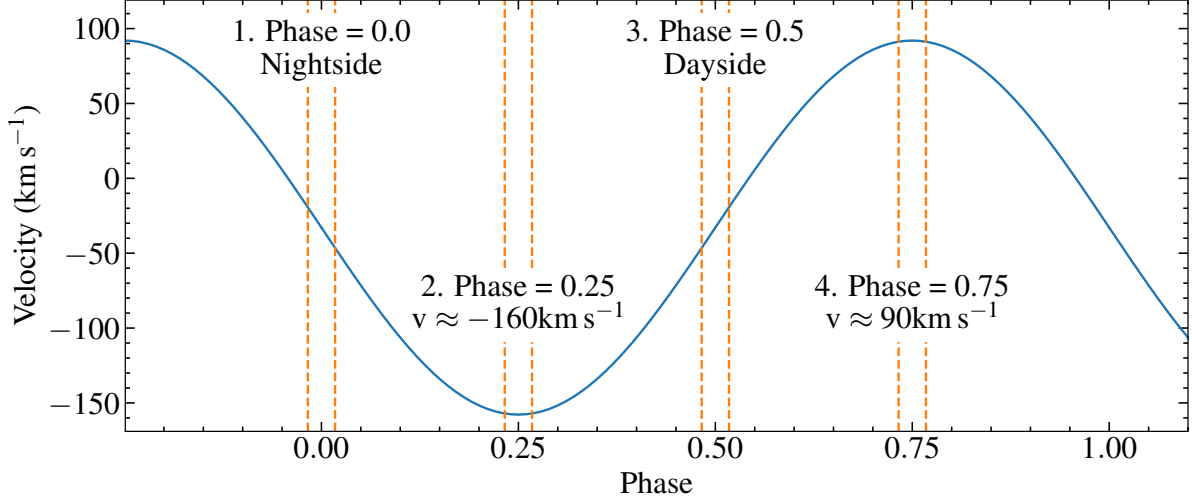


Figure 2: [FIX PHASE POSITIONS TO MATCH EPH] Radial velocity phase curve of the system showing the planned observation epochs. The dashed lines show the phase coverage of the approximate time-on-target achievable within a single HST orbit. The long period means that the velocity does not change by more than a few km s^{-1} per HST orbit at the peaks, giving considerable flexibility when scheduling the observations

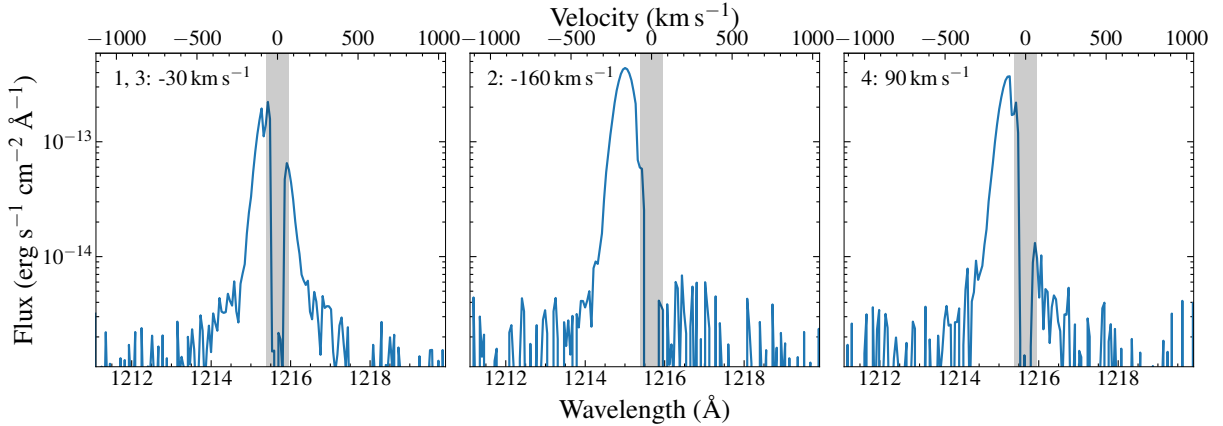


Figure 3: Simulated Lyman α lines at each of the observed epochs in Figure 2. The grey bar shows the approximate range lost to airglow. We will reconstruct the Lyman α line based on epoch 1, 3, and 4 (left and middle panels), and compare the accuracy of our reconstruction with the spectrum at epoch 2 (right panel), where the majority of the line profile is clear of the airglow and deep ISM absorption.

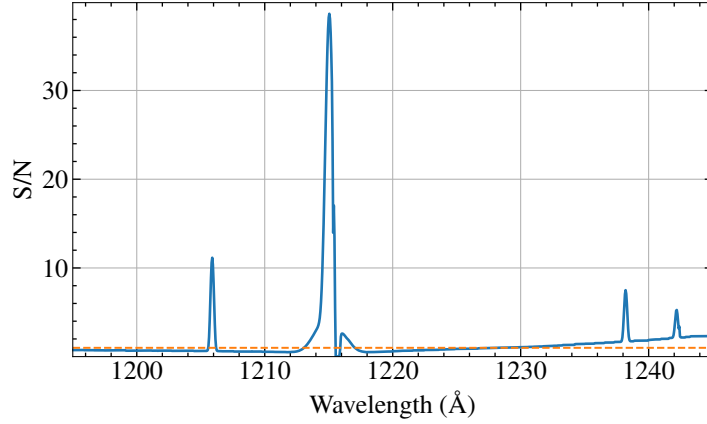


Figure 4: Signal to noise prediction for a single orbit produced using our predicted spectrum and the STIS ETC. The orange dashed line shows $S/N=1$. The $\text{Ly}\alpha$ line (if unocculted) and other emission lines are clearly observed in a single orbit. However the S/N of the $\text{Ly}\alpha$ wings is lower, hence the request for two orbits at phases with low velocity where some or all of the peak is obscured.

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■ Description of the Observations

We will observe the binary EG UMa for four orbits, phase resolved as described in the scheduling requirements. The observations will use STIS in spectroscopic mode with the G140M grating and a cenwave of 1222Å.

We constructed a simulated spectrum based on the white dwarf model, fits to the observed emission lines in the COS spectrum, an approximate $\text{Ly}\alpha$ profile estimated from the strength of those emission lines, and an ISM profile estimated from the Redfield & Linsky (2008) velocity calculator and a 2D interpolation of available H I density measurements to the sightline of EG UMa, all interpolated onto the wavelength grid of an archival STIS G140M spectrum. The ISM profile was calculated with velocity centroid of 1.45 km s^{-1} , Doppler $b = 11.5 \text{ km s}^{-1}$ and $\log N(\text{HI}) = 17.94$.

Using the model spectrum as an input for the STIS ETC we estimate achieving a peak S/N of ≈ 40 for the $\text{Ly}\alpha$ a single orbit, sufficient for the aims of this program (Figure 4. Emission lines of Si III and N V are also detected with $S/N \approx 10$, which we can use to track for flares and (unlikely) heating effects from the companion.

The target has already been cleared for bright object protection for the previous COS observation.

Our observing strategy accounts for two potential concerns. Firstly, the M dwarf is

active, with multiple flares in the TESS light curve of EG UMa. We calculate a flare duty cycle of ≈ 5 per cent, so the chances of the star flaring occurring during any of the observations proposed here are low. Should a flare occur, we will detect it by using the TIME-TAG data to produce light curves of the emission lines, and extract time-resolved spectra to remove the affected times. At the unocculted phases we calculate that we can remove roughly half an orbit of exposure time before the S/N becomes too low to measure the Ly α line with the precision required for this experiment. A flare lasting longer than this would be rare (Froning et al., 2019), and an interesting observation in its own right!

Secondly, the system demonstrates periodic variations caused by the illumination and heating of the side of the Mdwarf facing the white dwarf, which may be a factor when obtaining phase resolved spectra. However, we do not expect this to affect the strength of the emission lines in the ultraviolet. The effect is small at ≈ 1.5 percent in the optical bandpass, corresponding to a change in temperature of ≈ 50 K. As the emission lines are generated in the stellar atmosphere with formation temperatures of $10^3 - 10^6$ K, the heating should have no noticeable effect in our observations. Even if this prediction is wrong, by taking zero-velocity observations at both the day and night side (Figure 2), the combined zero-velocity spectra will be an average of the two, equivalent to the maximum velocity phases where half the illuminated side of the Mdwarf is visible. We will be able to monitor for any changes caused by illumination by comparing the fluxes of the other emission lines included in the G140M bandpass, and detecting any change at all would be a novel, unexpected discovery.

■ Scheduling Requirements

The target has an ephemeris of $\text{HJD} = 2449800.79131(58) + 0.66765930(57)$ (Bleach et al., 2000). We require a single orbit visit at each of phases 0, 0.25, 0.5 and 0.75, with an acceptable phase error of ± 0.05 . As is standard Ly α observations, we require that the observations be obtained such that the Earth’s radial velocity relative to the ISM in the direction of the target is small so that the airglow falls into regions where the ISM absorption is deep. Earth radial velocities of $\pm 20 \text{ km s}^{-1}$ are acceptable, resulting in observing windows of February 09–May 03 and August 09–November 11.