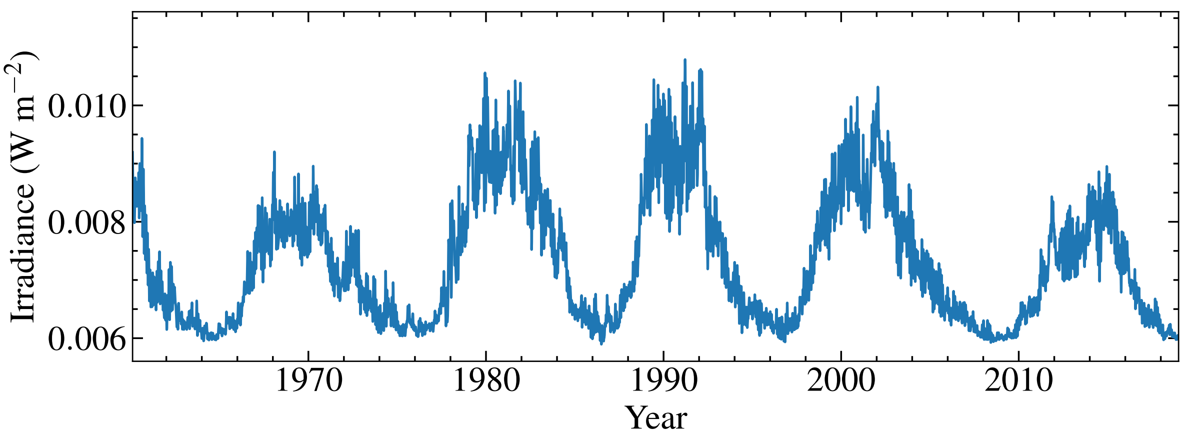


Figure 1: Lyman $\alpha$ irradiance from the Sun since the beginning of the Space Age, which varies with both rotation and on the $\approx$11 year Solar cycle (Machol et al., 2019). We have detected the first evidence for similar Lyman $\alpha$ variation linked with a stellar cycle and/or rotation at an M dwarf. Here we propose follow-up observations to confirm the period of the variation.

## ■ Scientific Justification

The Solar Cycle, a roughly 11-year fluctuation in stellar activity indicators such as Sun spot number, flare rate and emission line strength, is a well-established behaviour of the Sun. Similar long-term (multi-year) cycles have been detected at other stars via decades-long measurements of Ca II H&K emission line strength, which is a strong tracer of the Solar cycle on the Sun. However, these stars have been for the most part G- and K-type stars, along with a number of early-type M dwarfs (Suárez Mascareño et al., 2018). Pushing down to lower-mass M dwarfs is challenging as their Ca II H&K lines tend to be too faint to reliably measure variation, requiring the use of alternative observational signatures.

Searching for stellar cycles on low-mass stars is important, both for a complete understanding of stellar astrophysics, as M dwarfs represent the majority of all stars and probe changes in magnetic field behavior across the fully convective limit, and also because M dwarfs are the most promising targets for exoplanet research in the next decade. The small size of M dwarfs makes finding rocky plants around them relativity easy compared with larger stars. In particular they are prime targets for discovering planets with Earth-like equilibrium temperatures, as the orbital periods of such planets are relatively short so less observing time is required to confirm their presence, and the smaller star-to-planet radius ratio makes transmission spectroscopy of the planetary atmospheres feasible (de Wit et al., 2018). However, as these temperate planets are therefore much closer to their stars, the potential effects from stellar activity can be considerably stronger than at the Earth. Understanding stellar activity is a core requirement for assessing the surface conditions on those planets, having strong effects on, for example, the density and chemistry of planetary atmospheres and the

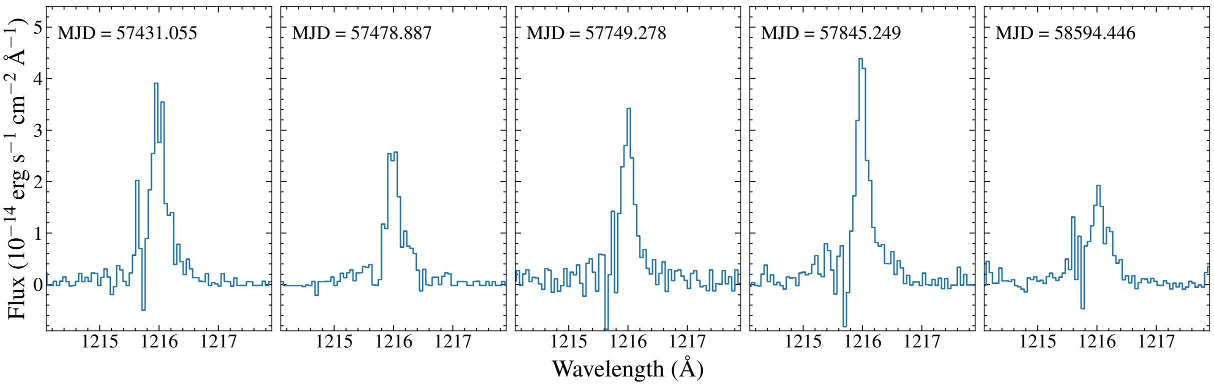


Figure 2: Example STIS G140M spectra of the Lyman $\alpha$ line at GJ 1132, which is clearly varying over time. Figure 3 shows the integrated flux for each observation over the range 1215.8–1216.3 Å.

surface radiation conditions (Airapetian et al., 2019).

Along with the aforementioned Ca II H&K lines, previous measurements of stellar cycles on M dwarfs have tracked changes in apparent rotation rates caused by star spots appearing at different latitudes on the differentially-rotating star over the course of the cycle. Around 30 stars have tentatively identified cycle periods, mostly measured from photometric data obtained with the *Kepler* spacecraft (Küker et al., 2019, and references therein). The periods fall into two populations: stars with short ($\sim 10$ day) average rotation periods have $\approx 500$ day cycles; more slowly-rotating stars having cycles of 1000 days or more (Vida et al., 2014). The most extensively studied stellar cycle of an M dwarf is that of the closest, Proxima Centauri, for which a seven year cycle was reported by Wargelin et al. (2017) based on changes in V-band magnitude combined with repeated *Swift* ultraviolet and x-ray observations.

Here we present evidence for the detection of a stellar cycle by a new technique and propose a small investment of *HST* time to confirm it. One of the best established tracers of the Solar cycle is emission from the H I 1215 Å Lyman $\alpha$ line (Machol et al., 2019). Figure 1 shows the record of the Solar Lyman $\alpha$ strength over the past few decades, clearly showing the 11-year cycle. As the strongest ultraviolet line, Lyman $\alpha$ is a key contributor to the changing Solar forcing of the Earth's atmosphere over the Solar cycle. For M dwarfs the effects of Lyman $\alpha$ emission may be more profound, as planets with the same temperature as the Earth are much closer to their stars, experiencing stronger ultraviolet fluxes; Lyman $\alpha$ also dominates the far-ultraviolet emission in M dwarfs and is the key driver of ultraviolet photochemistry in exoplanet atmospheres (France et al., 2016).

We have detected evidence for long-term variation in Lyman $\alpha$ strength in the planet-hosting M4 dwarf GJ 1132. Berta-Thompson et al. (2015) discovered a 1.2 Earth-radius planet in a 1.6 day orbit around this star, followed by radial velocity observations by (Bonfils et al., 2018) that firmly identified a second planet, with evidence for a third. GJ 1132 b is close enough to the host star that evidence for an escaping hydrogen exosphere could have been

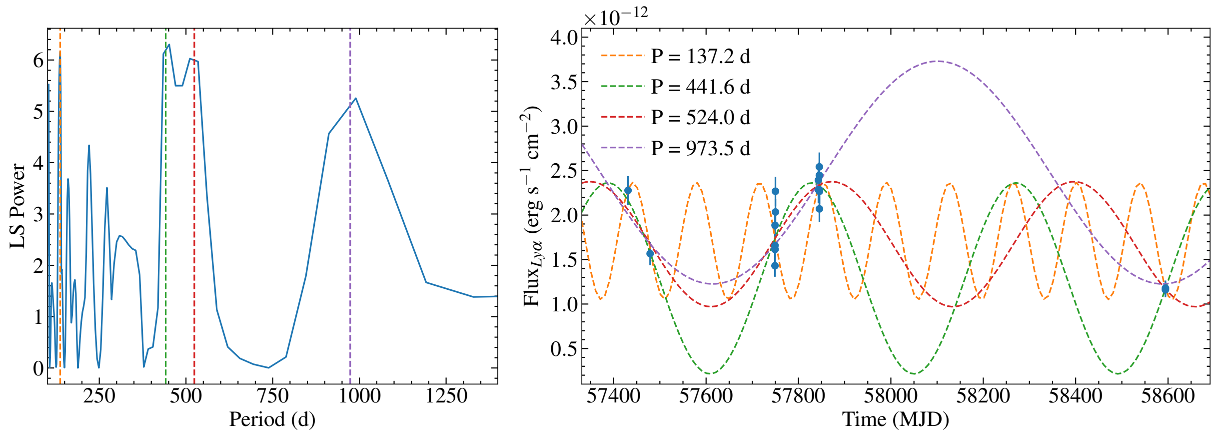


Figure 3: Left: Lomb-Scargle periodogram of the Lyman $\alpha$ flux of GJ 1132. Strong peaks are seen, but the precise period is poorly constrained. Right: Lyman $\alpha$ flux as a function of time, as well as the best-fit candidate periods. The predicted fluxes for the various period are easily distinguishable at $\gtrsim 5\,\sigma$ at most epochs: two new observations in cycle 28 will allow us to measure the true period, or rule out periodicity altogether.

detected by observing the Lyman $\alpha$ line during planetary transits. GJ 1132 has therefore been observed at five different epochs using the STIS G140M grating: Twice in 2016 to establish the detectability of the Lyman $\alpha$ line, then twice again in 2017 in an extensive search for a transiting exosphere, which resulted in a non-detection (Waalkes et al., 2019), and finally in 2019 as part of the Mega-MUSCLES Treasury survey. When we extracted each of these datasets in a consistent manner, we found that the strength of the Lyman $\alpha$ line has significantly varied over time. Figure 2 shows example spectra from each of the five epochs that clearly demonstrate the changes in line flux over a range of around a factor two. This is even more remarkable given that most of the line is obscured by a combination of geocoronal emission and interstellar absorption, leaving only the red line wing to exhibit this dramatic variability.

Intriguingly, the Lyman $\alpha$ variability shows signs of being periodic. Computing a Lomb-Scargle periodogram of the integrated Lyman $\alpha$ fluxes (Figure 3) reveals three broad peaks, which were used to fit sine functions to the data to find candidate periods of $\approx$441, 524 and 973 days. The last $\sim$ 1000 d period is almost certainly either a harmonic of one of the first $\sim$ 500 day periods, or vice versa. The existing data better explore the range of flux values predicted by the shorter periods, but the longer period is more consistent with the photometric measurements that predict that a star with the rotation period of GJ 1132 ($P_{\rm rot} \approx 125$ d) should have a stellar cycle with a period of roughly 1000 days. Therefore, the existing data are insufficient to distinguish between the candidate periods, or indeed if the Lyman $\alpha$ flux is periodic at all. Alternatively, the modulation could be driven by rotation. There is a peak at 137 days, similar to the existing rotation period

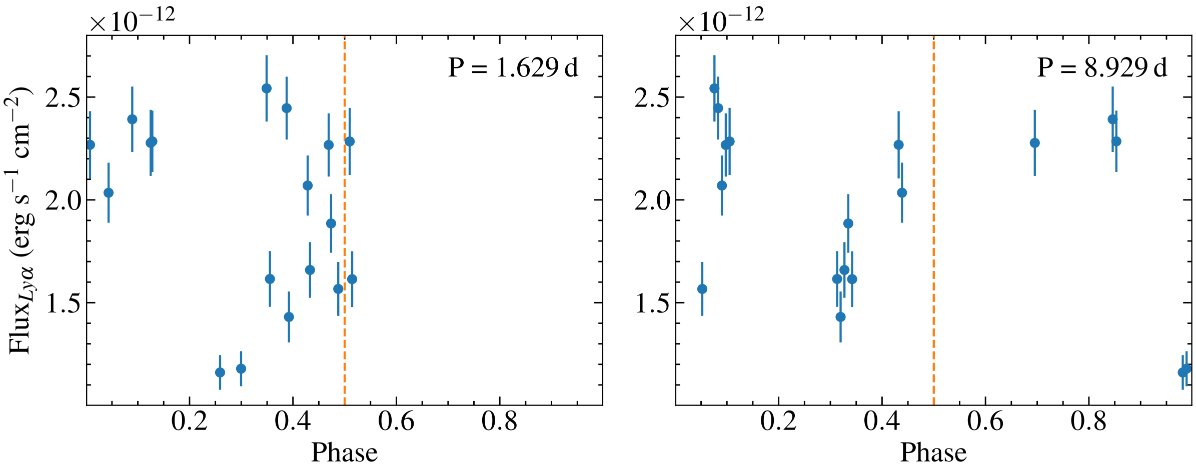


Figure 4: Lyman $\alpha$ flux folded onto the orbital period of planets GJ 1132 b (left) and c (right). The orange line shows the time of inferior conjunction (equivalent to the transit midpoint for planet b). The Lyman $\alpha$ flux shows no sign of structure on the orbital periods of the planets.

measurement. Confirmation that the Lyman $\alpha$ strength varies strongly with rotation would be an equally compelling result, with implications for the ongoing searches for escaping planetary exospheres via measurements of Lyman $\alpha$ transits (e.g. Bourrier et al., 2017). The Lyman $\alpha$ variation is not directly linked to the orbiting planets: Figure 4 shows the Lyman $\alpha$ flux folded onto the orbital period of planets b and c, with no sign of periodic behaviour or structure. Neither is it due to the "breathing" effect caused by thermally-driven changes in telescope focus during an orbit: We extracted sub-orbit light curves for each spectrum using the STISTOOLS inttag tool, and saw no evidence for the intra-orbit variation characteristic of observations strongly affected by breathing.

To confirm the periodicity of the Lyman $\alpha$ variation and measure the true period, we request two new STIS/G140M observations during Cycle 28. Spacing out the observations by at least a month will ensure that the predicted flux for the longer candidate periods has changed between epochs, but beyond that the timing can be random (Burt et al., 2018).

If confirmed, this would be the first detection of either a stellar cycle or rotation via changes in Lyman $\alpha$ flux for any M dwarf, or indeed at any star at all apart from the Sun. A successful demonstration of this technique would provide a new method to measure the stellar cycles of M dwarfs, adding to the small sample size of cycles measured via photometric methods. It may in fact be the only usable technique for many M dwarfs: Changes in rotation rates are too faint to be detected in long-term ground-based photometric surveys (and the *TESS* time on target is far too short), and the Ca II H&K lines are too weak to reliably measure variation (Figure 5). Many M dwarfs already have multiple epochs of Lyman $\alpha$ data, so future searches for stellar cycles and/or rotation at these stars could be designed using only a small amount of *HST* time per star.

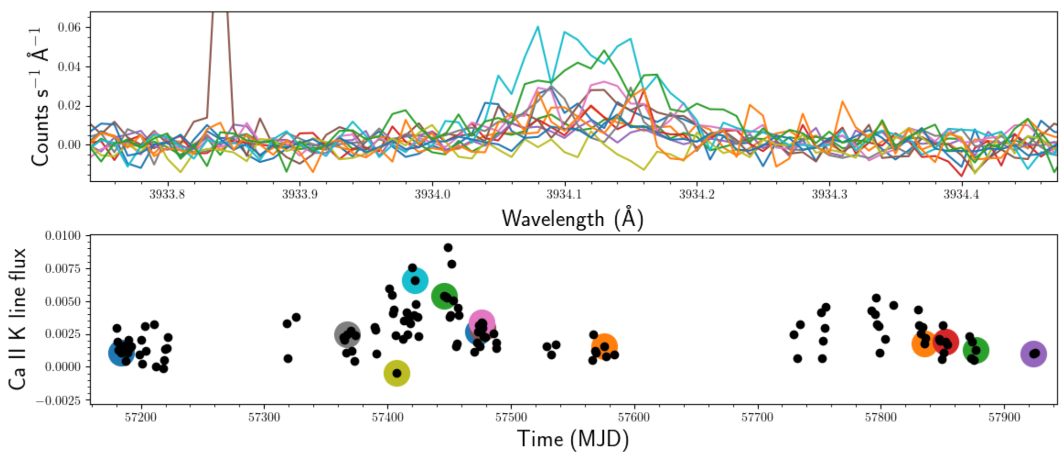


Figure 5: Top: HARPS spectra of GJ 1132 showing the Ca II H&K lines. Bottom: Light curve of the integrated fluxes from the spectra, with the example spectra shown in the top plot color-coded. The lines are only weakly detected and no continuum is detected (a requirement for accurately assessing the line strength as absolute flux calibration is challenging for these stars), leading to the scatter on the light curve being too high to reliably measure a stellar cycle.

### References


Airapetian, V. S., Barnes, R., Cohen, O., et al. 2019, arXiv e-prints, arXiv:1905.05093

Suárez Mascareño, A., Rebolo, R., González Hernández, J. I., et al. 2018, , 612, A89

Wargelin, B. J., Saar, S. H., Pojmański, G., et al. 2017, , 464, 3281

Berta-Thompson, Z. K., Irwin, J., Charbonneau, D., et al. 2015, , 527, 204

Vida, K., Oláh, K., & Szabó, R. 2014, , 441, 2744

Küker, M., Rüdiger, G., Oláh, K., et al. 2019, arXiv e-prints, arXiv:1911.13094

Waalkes, W. C., Berta-Thompson, Z., Bourrier, V., et al. 2019, , 158, 50

Machol, J., Snow, M., Woodraska, D., et al. 2019, Earth and Space Science, 6, 2263

France, K., Loyd, R. O. P., Youngblood, A., et al. 2016, , 820, 89

Bourrier, V., de Wit, J., Bolmont, E., et al. 2017, , 154, 121

Bonfils, X., Almenara, J.-M., Cloutier, R., et al. 2018, , 618, A142

de Wit, J., Wakeford, H. R., Lewis, N. K., et al. 2018, Nature Astronomy, 2, 214

Burt, J., Holden, B., Wolfgang, A., et al. 2018, , 156, 255


## Description of the Observations

We request two visits of two orbits each using STIS/G140M to obtain observations of the Ly$\alpha$ emission line. This observing setup has been used in the previous observations of this target (GO #14462, #14757, and #15071) and been verified to return sufficient SNR to reconstruct the intrinsic (ISM-corrected) profile of the line and measure its flux and velocity centroid. The target has also been cleared for bright object protection for M stars in this observing mode.

## Special Requirements

Figure 3 indicates that two well-spaced observations would distinguish between the candidate periods. We therefore do not request specific timings for the proposed observations, only that they should be separated by $\gtrsim 1$ month.

## Coordinated Observations

None

## Justify Duplications

As this proposal is following up the detection of variability in previous *HST* observations, the proposed observations are duplications by design.