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Photometric Monitoring of the ZZ Ceti Star PG 1541+651

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ABSTRACT

The *Kepler* and *K2* missions discovered multiple ZZ Ceti white dwarf pulsators that exhibit recurrent outbursts. These outbursting white dwarfs are near the red edge of the ZZ Ceti instability strip, suggesting that the phenomenon is physically related to the cessation of pulsations. We present multi-day ground-based monitoring of the poorly studied red-edge ZZ Ceti pulsator PG 1541+651. We do not detect any outbursts in our data. We do find that this pulsator has a very rich and time-variable spectrum of modes in its periodogram. The white dwarf lies in the northern continuous viewing zone of *TESS*; therefore, it has extensive archival light curves ripe for a detailed asteroseismic analysis of this star.

1. INTRODUCTION

Several pulsating white dwarfs (WDs) of the ZZ Ceti class have been observed to undergo an outburst phenomenon. During an outburst, the WD brightens for several hours, and dramatic changes in the pulsation spectrum are observed (e.g., Bell et al. 2015, 2017). The outbursting pulsators are located toward the red edge of the ZZ Ceti instability strip, are closely connected with the pulsations, and therefore are proposed to be related to the ultimate cessation of pulsations (Hermes et al. 2015).

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To date, outbursting WDs have been detected primarily in *Kepler* and *K2* observations. However, occasional serendipitous detections of outburst-like phenomena in ground-based time series photometry have been reported (e.g., the "sforzando" of the DBV GD 358; Kepler et al. 2003). We therefore undertook a ground-based photometric monitoring campaign to search for outbursts in a red-edge ZZ Ceti WD.

Our chosen target is PG 1541+651, first identified as a ZZ Ceti by Vauclair et al. (2000) but otherwise lacking in published time-series analyses. This choice of target was motivated by three factors: PG 1541+651 is well-placed for long-term observations during our summer observing campaign, its atmospheric parameters ($T = 11239 \pm 132\,\mathrm{K}$, $\log g = 8.01 + / - 0.01$; Kilic et al. 2020) place it near the red edge of the ZZ Ceti instability strip, and the significant differences in the power spectra observed over two consecutive nights in the discovery observations are reminiscent of those observed in ZZ Ceti outbursts.

2. OBSERVATIONS AND DATA REDUCTION

Observations took place over five nights: UT 2021 Jun 15 and 16, and UT 2021 Jul 9, 14, and 15. PG 1541+651 was observed remotely through Texas A&M-Commerce's Planewave CDK 700 27-inch Telescope with an Andor iKon-L CCD camera. Image series were continuous 60 s exposures taken through an IR-blocking luminance filter with short hourly breaks for refocusing. A total of 979 minutes of exposure time was obtained over the five nights.

We reduced each night's images using AstroImageJ (Collins et al. 2017). We bias-corrected all images, subtracted scaled dark frames, and applied flat-fields. AstroImageJ corrected all image timing to TDB. We obtained relative differential photometry using circular apertures with a variable radius of 1.4× the full-width half maximum measured on each image. We used the same comparison stars for all nights' photometry.

We then calculated periodograms using Period04 (Lenz & Breger 2014). We identified significant pulsation modes as those with an amplitude higher than four times the average amplitude of the noise in the periodogram of 2002 Jul 14 (the best quality night), resulting in a minimum significant amplitude of 1.6%.

We combined data from all nights iteratively. We added one night at a time and recalculated the frequencies and amplitudes of each significant mode of pulsation. For each iteration, only one alias of each mode was consistent with the previous iteration's frequency and uncertainty. The derived frequencies, periods, amplitudes, phases, and associated errors are listed in Table 1. The stated errors are from formal least-square calculations and likely significantly underestimate the actual uncertainties.

3. DISCUSSION

We did not observe any outbursts during our observations. This absence is not surprising, as our observations cover a minuscule fraction of the total time elapsed –

Table 1. Best-fit Pulsation Mode Parameters for PG 1541+651

Frequency (d^{-1})	Period (s)	Amplitude (%)	Phase[a]
107.94732 ± 0.00078	800.390 ± 0.006	2.16 ± 0.13	0.99 ± 0.26
118.2715 ± 0.0010	730.523 ± 0.006	1.73 ± 0.14	0.84 ± 0.30
125.99333 ± 0.00092	685.751 ± 0.005	1.91 ± 0.014	0.23 ± 0.28
159.62461 ± 0.00086	541.270 ± 0.003	1.97 ± 0.14	0.92 ± 0.28

[a]Phase at $T_0 = \mathrm{BJD}\,2459000$

in addition to the diurnal cycle, significant potential coverage was lost due to cloudy weather or high humidity during a wetter-than-average summer.

Further, after we analyzed these observations, we realized that PG 1541+651 is in the northern Continuous Viewing Zone of *TESS*. A quick-look reduction of the complete TESS data set as of the summer of 2022 by Keaton Bell revealed no outbursts had been observed by *TESS*, suggesting that PG 1541+651 is not an outbursting ZZ Ceti, or at least that any outbursts are highly sporadic.

We only clearly recover one pulsational mode reported by Vauclair et al. (2000): the 686 s mode. Notably, this mode dominated their periodogram on the second night of their observations with an amplitude more than twice our reported value. The power spectrum presented by Vauclair et al. (2000) for their first night shows significant power corresponding to our 108 s and 541 s modes that, interestingly, are eliminated by their auto-regressive parametric model in their final analysis. Our data failed to recover their reported 757 s and 564 s periods.

Our analyses strongly suggest that additional likely modes of pulsation are present in our data, but these modes' amplitudes are below our significance threshold. In particular, there seem to be closely spaced modes near the 800 s pulsation, and a complex of modes with time-variable amplitudes is present near $f \approx 215\ \mathrm{d}^{-1}$ ($P \approx 402$ s) in our data. The latter is likely a combination of modes and/or harmonics of the ~ 800 s modes.

Finally, the measured phases are poorly constrained in the combined data, potentially indicating phase wandering. These behaviors of wandering frequencies, significant amplitude variations, and unstable phases are not unusual in red-edge pulsators.

4. CONCLUSIONS

The red-edge ZZ Ceti star PG 1541+651 does not show signs of outburst behavior. Otherwise, its pulsational profile is qualitatively similar to other red-edge pulsators. The periodogram of *TESS* data for PG 1541+651 exhibits a very rich spectrum (K. Bell, personal communication). Finally, we note that PG 1541+651 shows an infrared excess which has been interpreted as a dusty debris disk (e.g., Kilic et al. 2012). We suggest that this relatively unstudied ZZ Ceti may be a highly interesting target for a detailed asteroseismic analysis. In fact, we became aware during the final editing of this manuscript that such an analysis has recently been published (Romero et al. 2023).

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