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Letter to the Editor

Four new eclipsing accreting ultracompact white dwarf binaries found with the Zwicky Transient Facility

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ABSTRACT

Context. Accreting ultracompact white dwarf binaries contain a white dwarf that is accreting from a degenerate object. They have orbital periods shorter than 65 min.
Aims. We report the discovery and the orbital period of four new eclipsing accreting ultracompact white dwarf binaries found using the Zwicky Transient Facility (ZTF) and discuss their photometric properties.
Methods. We searched through a list of 4171 dwarf novae compiled using the ZTF and used the box least square method to search for periodic signals in the data.
Results. We found four eclipsing accreting ultracompact binaries with orbital periods between 25.9 and 56 min. One had previously been published as an AM Canum Venaticorum (AM CVn), and the other three systems are new discoveries. The two shorter-period systems are likely also AM CVn systems, while the longest-period system, with a period of 56 min, showed multiple super-outbursts over two years, which is more consistent with it being a helium CV.

Key words. binaries : close – binaries: eclipsing – stars: dwarf novae – white dwarfs

1. Introduction

Binary star systems with very short orbital periods ($\lesssim$65 min) are called ultracompact binaries. To fit in such a short orbit, they have to contain two stellar remnants. Such remnants can be white dwarfs (e.g. Burdge et al. 2020), stripped highly evolved stars (e.g Kupfer et al. 2020; Burdge et al. 2022), neutron stars, or black holes (e.g. Armas Padilla et al. 2023)

One of the most common types of ultracompact binaries are accreting white dwarfs that are stably accreting from a degenerate or semi-degenerate donor. These objects can be divided further into subclasses based on the nature of the donor star. The most common subtypes are AM Canum Venaticorum (AM CVn) systems that do not show any hydrogen and consist mostly of helium (recent overview articles include Solheim 2010 and Ramsay et al. 2018). Because of their short orbital periods, their orbital evolution is governed by gravitational wave radiation, and short-period AM CVn systems will be detectable by the Laser Interferometer Space Antenna (LISA) satellite (e.g. Amaro-Seoane et al. 2023; Kupfer et al. 2023).

Other types of accreting ultracompact white dwarf binary systems are helium cataclysmic variables. They are less common than AM CVn systems and can also have short orbital periods. What distinguishes them from AM CVn systems is that they still have detectable hydrogen in their atmospheres. Examples are CSS 120422:J111127+571239 with a period of 55.3 min (Garnavich et al. 2012), CRTS J112253.3–111037 with a period of 65.2 min (Breedt et al. 2012), V418 Ser with a 65.9 min period, and CRTS J1028-0819 with a 52.1 min period (Green et al. 2020). In most of these systems, the donor is cold, but there are a few exceptions where the donor is warm and can be detected in the optical (e.g. Burdge et al. 2022).

The formation channel of the different accreting ultracompact binaries is uncertain, which is one of the major open issues in the broader context of compact binary evolution. The formation channels involve a sequence of binary interactions: one or more common-envelope events and/or phases of stable mass transfer. Understanding the evolutionary history of accreting ultracompact binaries is part of the larger question of the final fate of (merging) white dwarf binary stars (see the Horizon-2020 paper Toloza et al. 2019).

The number of known accreting ultracompact binaries is small but is steadily increasing (Green 2023) thanks to large-scale surveys such as the time-domain survey conducted by the Zwicky Transient Facility (ZTF; Masci et al. 2019; Bellm et al. 2019; Graham et al. 2019; Dekany et al. 2020). The ZTF has imaged the visible sky every two or three nights since 2018. It has already been used to detect dwarf novae (Szkody et al. 2020,

2021), including dwarf novae associated with accreting ultracompact binaries (van Roestel et al. 2021). Additionally, ZTF light curves of stars are also analysed to find short-period variability (Burdge et al. 2020) and have been used to find new eclipsing AM CVn stars (van Roestel et al. 2022). In addition to optical photometric surveys, X-ray missions such as the ROentgen SATellite (ROSAT) and the Spectrum-Roentgen-Gamma (SRG)/eROSITA have been used to identify AM CVns, including eclipsing systems (Rodriguez et al. 2023). Eclipsing accreting ultracompact binaries are particularly useful because, with only a high-speed light curve, all binary parameters can be measured (Copperwheat et al. 2011; Green et al. 2018; van Roestel et al. 2022).

In this Letter we present four eclipsing accreting ultracompact binaries that were initially detected as dwarf nova outbursts by the ZTF. Section 2 briefly describes the selection of dwarf novae and the ZTF light curves. In Sect. 3 we discuss how the ZTF light curves were analysed and how the new systems were discovered. We summarise the results in Sect. 4 and discuss them in Sect. 5. We conclude in Sect. 6.

2. Data

As a list of targets, we used all dwarf novae identified using the ZTF. This list was compiled by human scanners who frequently check the ZTF alert stream for stars that brighten by 1.5 mag using the Fritz marshal (van der Walt et al. 2019; Coughlin et al. 2023). A detailed description of the selection of dwarf novae is provided in Szkody et al. (2020, 2021), van Roestel et al. (2021), and Szkody & Van Roestel (2023). The sample of dwarf novae we analysed contains a total of 4171 objects.

We used the ZTF forced-photometry service to obtain the light curve of each object (Masci et al. 2023). Low-quality data were removed on the basis of the conditions outlined in Masci et al. (2023). In addition, we also removed epochs with anomalous zero points. The criteria are as follows: (i) infobitssci $\geq 33\,554\,432$, (ii) scisigpix > 25, (iii) sciinpseeing $> 4''$, (iv) nearestrefsharp is not null, and (v) zpdiff > 26.5. The rejected epochs either have serious calibration issues or are unusable due to high noise.

3. Method and analysis

We searched through the ZTF light curve to find eclipses with periods of less than 65 min using the box-least-squares (BLS) method (Kovács et al. 2002). The BLS method is an algorithm that searches for periodic eclipse-like signals in time-series data and provides the best estimate for the period. Because accreting ultracompact binaries tend to have very deep eclipses and do not show much other periodic variability, the BLS algorithm is well suited to find the periodic eclipses of accreting ultracompact binaries (see also van Roestel et al. 2022). The BLS implementation that we used comes from the ASTROBASE package (Bhatti et al. 2017). We restricted our search to periods of 4.32–288 min and used a linear grid in frequency, with a fixed frequency step size of 10^{-5} per day. The frequency step size was determined using the minimum eclipse width in frequency (0.02) and the time baseline of the light curve (5 years). We used the built-in sigma-clipping function of the ASTROBASE package to remove outbursts in the data, since they confuse the BLS algorithm. To do this, we used sigma-clipping values of [99, 3].

The HELIOS computer cluster was used to run our code on the 4171 light curves. We visually inspected the output and identified strong peaks in the periodogram at short periods (65 min or less). We then looked at the folded light curves to identify clear eclipses and found four systems that showed clear eclipses.

4. Results

We found four eclipsing accreting ultracompact binaries in our sample of ZTF dwarf novae (see Table 1). ZTF20aabowdt was identified as a white dwarf candidate by Gentile Fusillo et al. (2021) using *Gaia* data, and we identified it as an accreting ultracompact white dwarf binary system with an orbital period of 25.9854 ± 0.0003 min. We estimated the uncertainty on the period by measuring the BLS power peak width. ZTF18acgmwpt was detected by van Roestel et al. (2021), who identify it as an AM CV system with He absorption lines in its spectrum. Using the super-outburst recurrence time, they estimated that the orbital period should be between 30.7 and 34.5 min. We confirm that the system's period is 32.4904 ± 0.0001 min. ZTF19abugzba and ZTF21abbxnbm are new discoveries that have not been reported in the literature; they have orbital periods of 39.6116 ± 0.0003 and 56.1440 ± 0.0007 min, respectively.

All systems are faint, with *Gaia G*-mag values varying between 20.07 and 20.64. The faintest system (ZTF21abbxnbm) does not have a parallax measurement in *Gaia* and therefore we have no information regarding its distance.

Accreting ultracompact binary systems are typically blue because the donor is cold and is not visible in the near-infrared (e.g. Fig. 11 in van Roestel et al. 2022). In order to compare the colours of the new systems with known systems, we collected the *Gaia* and Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) colours, and determined the colours from the ZTF light curves by measuring the robust average brightness in each band using a sigma-clipped average value. Table 1 shows that the ZTF colour data follow the predicted trend: longer-orbital-period systems are redder, and shorter-orbital-period systems are bluer. The *BP–RP* and *PS (g-r)* roughly follow the same trend but show more scatter and higher uncertainties. This is due to both outbursts and the faintness of the systems.

ZTF20aabowdt and ZTF18acgmwpt have a blue colour typical of accreting ultracompact white dwarf binaries, with *BP–RP* values of 0.07 and 0.14 and ZTF *(g-r)* values of −0.42 and −0.25, respectively. ZTF19abugzba and ZTF21abbxnbm have redder colours, *BP–RP* values of 0.64 and 2.36 and ZTF *(g-r)* values of −0.06 and −0.04, respectively, which are more unusual for ultracompact white dwarf systems. However, the precision of the *BP–RP* colour is low due to the faint nature of the systems, especially ZTF21abbxnbm, rendering some of the *BP–RP* values unreliable. The likely more robust ZTF colours for these two systems are consistent with those of accreting ultracompact white dwarf binaries.

Figures 1–4 show the ZTF light curves for each object. The system ZTF20aabowdt shows two super-outbursts, ZTF18acgmwpt shows three super-outbursts, ZTF19abugzba shows a single super-outburst, and ZTF21abbxnbm shows three super-outbursts. All four systems show other outbursts with smaller amplitudes and durations.

ZTF20aabowdt, ZTF18acgmwpt, and ZTF21abbxnbm have deep eclipses (flux decreases to almost 0). However, ZTF19abugzba has a shallow eclipse, with the flux decreasing to about half its peak value. ZTF20aabowdt also seems to exhibit a narrower eclipse than the other systems.

Table 1. Properties of the four new eclipsing ultracompact binary systems.

Name	RA	Dec	$P_{\rm orb}$ min	G Vega-mag	$BP-RP$ Vega-mag	ZTF g-r AB-mag	PS g-r AB-mag	Parallax mas	Distance pc
ZTF20aabowdt	$07^{\rm h}29^{\rm m}07.69^{\rm s}$	$-06°02'46.61''$	25.9854(3)	20.41	0.07±0.15	−0.41±0.02	0.33±0.24	1.17±0.64	2029^{+3612}_{-930}
ZTF18acgmwpt	$07^{\rm h}01^{\rm m}15.77^{\rm s}$	$+50°23'21.46''$	32.4904(1)	20.50	0.14±0.28	−0.25±0.01	−0.24±0.04	0.50±0.62	1636^{+1289}_{-668}
ZTF19abugzba	$18^{\rm h}38^{\rm m}47.16^{\rm s}$	$+07°44'46.23''$	39.6116(3)	20.07	0.64±0.21	−0.06±0.01	0.03±0.06	1.43±0.54	1740^{+1692}_{-851}
ZTF21abbxnbm	$21^{\rm h}16^{\rm m}04.73^{\rm s}$	$+24°46'20.53''$	56.1440(7)	20.64	2.36±0.88	−0.04±0.01	−0.09±0.08	–	–

Notes. The *Gaia* magnitudes and parallaxes are taken from Gaia Collaboration (2023, 2016). The ZTF colours were determined by measuring the robust average brightness in each band using a sigma-clipped average value. The Pan-STARRS data were taken from Chambers et al. (2016). Distances are taken from Bailer-Jones et al. (2018).

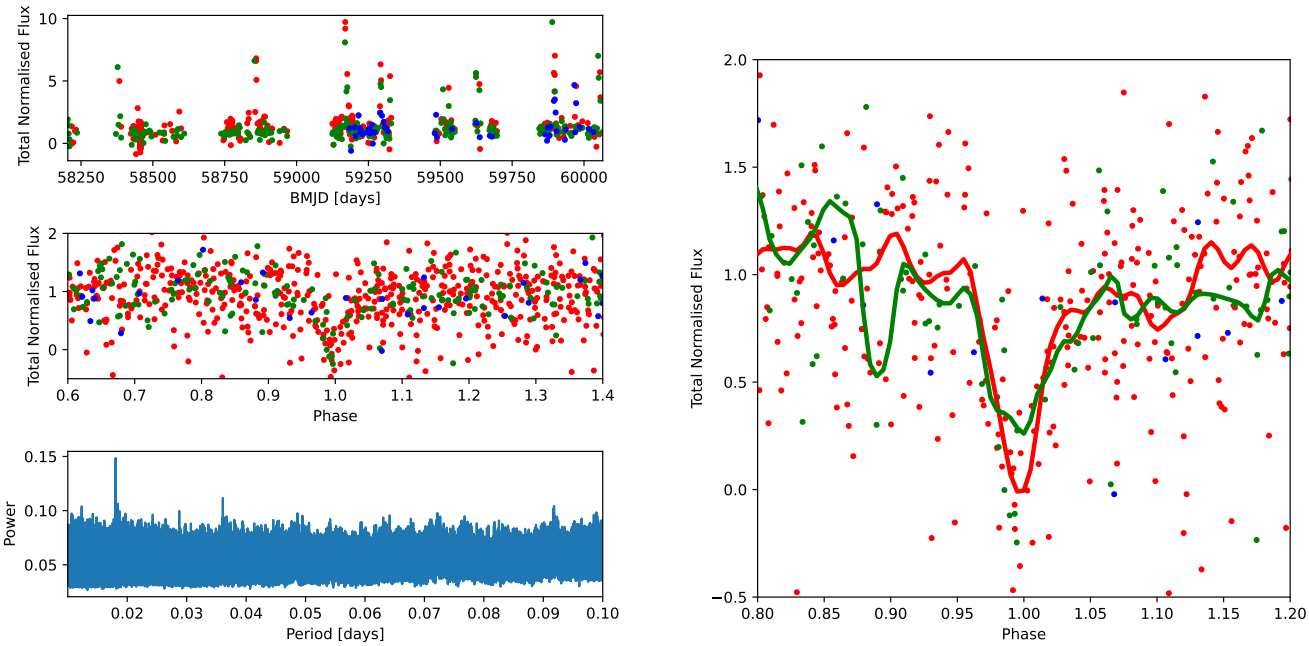

Fig. 1. ZTF data of ZTF20aabowdt. On the left, the upper panel shows the light curve, the middle panel shows the folded light curve (P = 25.98 min), and the final panel shows the periodogram. The median uncertainty on the ZTF measurements is 33% and is not shown, for clarity. On the right is a zoomed-in view of the eclipse of the folded light curve. The smoothed light curve (using a Gaussian kernel) is overplotted. Legend: The data from the g, r, and i bands are shown in green, red, and blue.

5. Discussion

In this section we compare the observed properties of the four systems with the currently known AM CVn systems and other accreting ultracompact binaries.

5.1. Outburst behaviour

If we assume that all four systems are AM CVn systems, we can estimate the expected outburst recurrence time. To calculate it, we used the empirical equation provided by Levitan et al. (2015):

$$P_{\rm rec} = (1.53 \times 10^{-9}) P_{\rm orb}^{7.35} + 24.7,$$

where $P_{\rm rec}$ is the super-outburst recurrence time in days and $P_{\rm orb}$ is the orbital period in minutes. The predicted recurrence times for ZTF20aabowdt, ZTF18acgmwpt, ZTF19abugzba, and ZTF21abbxnbm in days are: 62, 221, 873 (≈2.4 yr), and 11065 (≈30 yr), respectively.

ZTF20aabowdt shows two super-outbursts and nine outbursts with smaller amplitudes and durations. The predicted recurrence time for this system (62 days) suggests that it should show more super-outbursts, which are likely missed due to the poor sampling by the ZTF, which in turn is due to the system's low declination.

ZTF18acgmwpt shows three clear super-outbursts and three with smaller amplitudes and shorter durations. The times between the three large super-outbursts are 450 and 320 days. Notably, no super-outbursts were detected in the last 2 years of the data. The system's expected outburst recurrence time (221 days) suggests that we might be missing at least two more super-outbursts, or that the outburst recurrence time is longer compared to other AM CVn systems with this orbital period. Due to the gaps in the ZTF data, we cannot draw a definite conclusion.

ZTF19abugzba shows a single, faint, super-outburst and multiple echo outbursts with smaller amplitudes and short durations starting at 59050 MJD. Similar faint super-outbursts with many echo outbursts have been seen in other AM CVn systems (e.g. Kato & Kojiguchi 2021). The calculated recurrence time (873 days) suggests that one or two super-outbursts are missed because of a lack of observations. We see increased activity at the very end of the light curve, which suggests that a super-outburst occurred in a gap in the data. As in the previous cases, we cannot

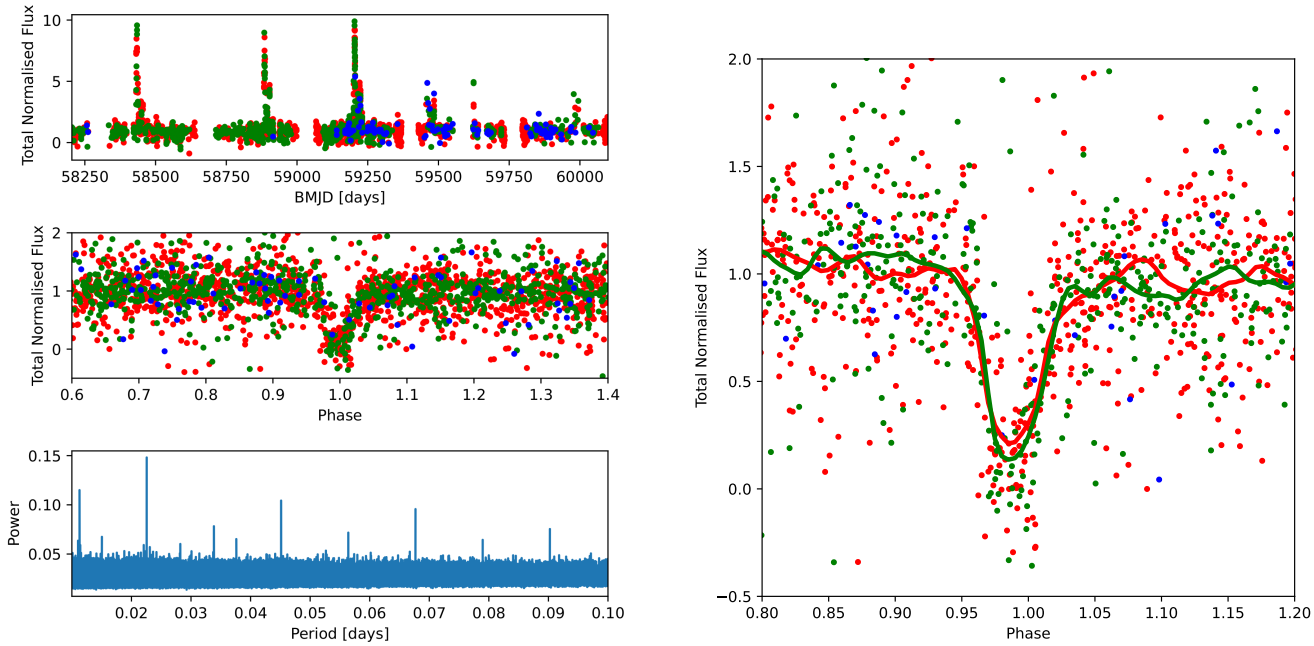

Fig. 2. ZTF data of ZTF18acgmwpt. On the left, the upper panel is the light curve, the middle panel is the folded light curve, and the final panel is the periodogram. The median uncertainty is 21% and is not shown, for clarity. On the right is a zoomed-in view of the eclipse of the folded light curve (P = 32.49 min). The smoothed light curve (using a Gaussian kernel) is overplotted. Legend: The g, r, and i band data are shown in green, red, and blue.

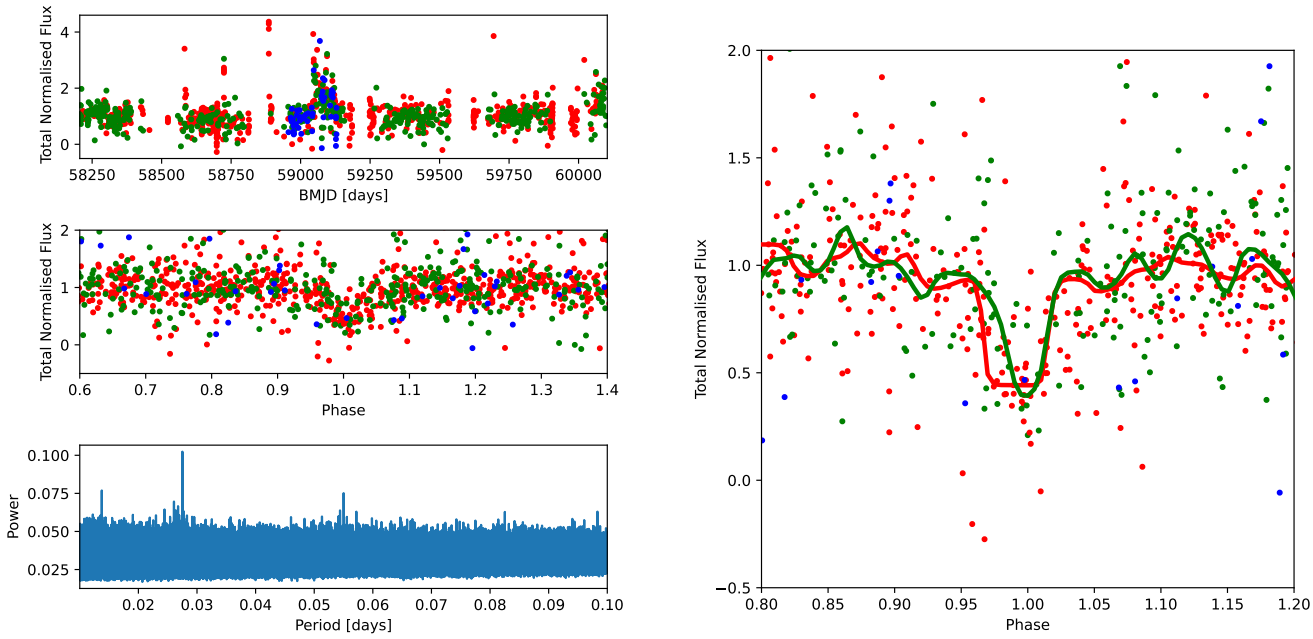

Fig. 3. ZTF data of ZTF19abugzba. On the left, the upper panel is the light curve, the middle panel is the folded light curve (P = 39.61 min), and the final panel is the periodogram. The median uncertainty is 11% and is not shown, for clarity. On the right is a zoomed-in view of the eclipse of the folded light curve. The smoothed light curve (using a Gaussian kernel) is overplotted. Legend: The g, r, and i band data are shown in green, red, and blue.

determine if we missed the outburst or if the outburst recurrence rate is lower than expected.

ZTF21abbxnbm shows a clear deviation from predictions. The system's calculated recurrence time suggests a single outburst every ≈30 years, while we see three super-outbursts in a period of roughly three years. This behaviour is highly inconsistent with the behaviour of other known long-period AM CVns. Similar AM CVn systems in Levitan et al. (2015) have been reported to have no visible outbursts or to have only one detected outburst. Helium CVs, on the other hand, tend to show frequent outbursts at orbital periods of 50 to 70 min. Therefore, we speculate that ZTF21abbxnbm is a helium CV instead of a classical long-period AM CVn system.

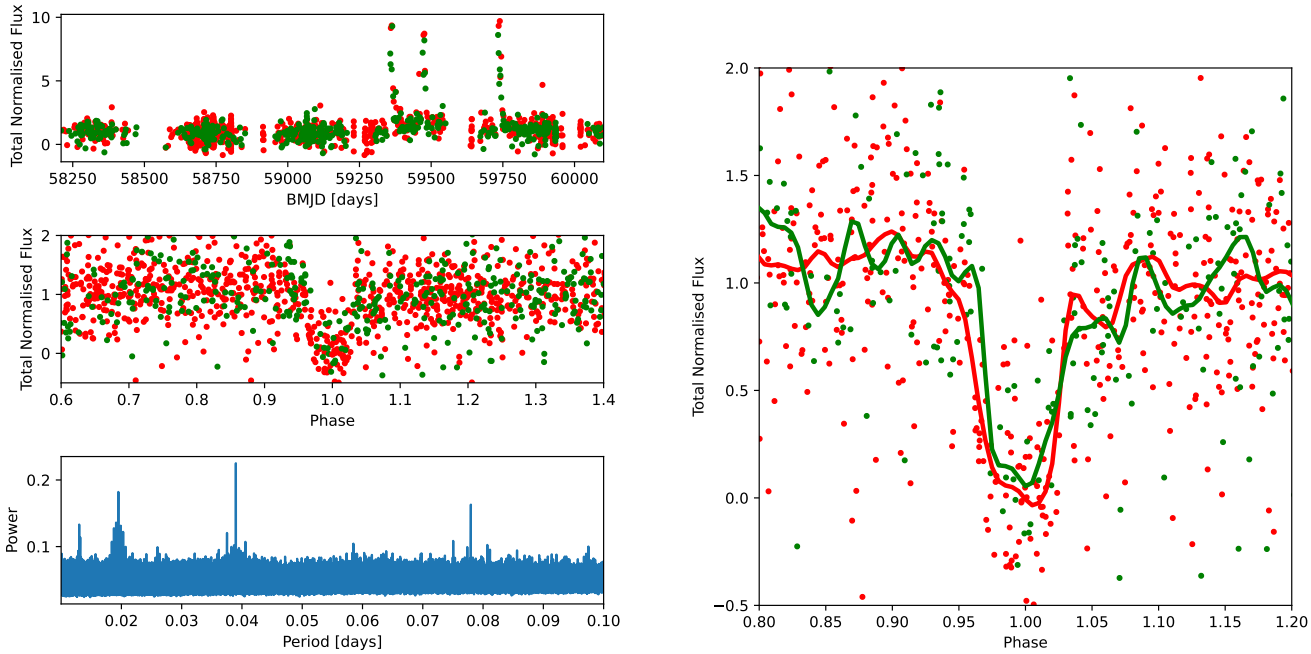

Fig. 4. ZTF data of ZTF21abbxnbm. On the left, the upper panel is the light curve, the middle panel is the folded light curve (P = 56.14 min), and the final panel is the periodogram. The median uncertainty is 35% and is not shown, for clarity. On the right is a zoomed-in view of the eclipse of the folded light curve. The smoothed light curve (using a Gaussian kernel) is overplotted. Legend: The g, r, and i band data are shown in green, red, and blue.

5.2. Eclipse shape

The eclipse depth for AM CVn systems (and most other accreting ultracompact binaries) is mostly determined by the brightness of the accretion disk because the donor is cold and does not contribute any significant amount of light in the optical. For long-period systems (which typically have a lower accretion rate), the accretion disk is typically fainter, resulting in a deeper eclipse (e.g. Bildsten et al. 2006). YZ LMi, the first discovered eclipsing AM CVn (Copperwheat et al. 2011), has a period of 28.31 min and a white dwarf that contributes about 70% of all light[1]. ZTF20aabowdt shows an eclipse so deep it suggests that the disk brightness is still only a small fraction of the overall luminosity of the system and is very similar to the slightly longer-period eclipsing system YZ LMi. The fact that we are seeing a much smaller contribution from the disk compared to the prediction from Bildsten et al. (2006) is mostly due to the high inclination angle, which means the visible projected area is very small.

ZTF18acgmwpt has an orbital period of 32.47 min. It is comparable to ZTFJ0407-0007 in period and also shows a deep eclipse (van Roestel et al. 2022). On the other hand, ZTF19abugzba has a shallow eclipse that only reaches the depth of about half of the maximum flux, which is unexpected for a system with a period of 39.61 min. The shallow eclipse could be due to an increase in the accretion disk activity, but we are much more likely seeing only partial eclipses of the white dwarf.

ZTF21abbxnbm behaves as expected, with a deep eclipse that is characteristic of long-period AM CVn systems. ZTF21abbxnbm has a period of 56.16 min. If this system is a helium CV instead of a long-period AM CVn system, we would also expect to see deep eclipses because in both cases the donor stars are cold.

6. Conclusion

We searched for periodic eclipses in a sample of dwarf novae found with the ZTF. The BLS method was used to search for orbital periods of 4.32 and 65 min. We found four eclipsing accreting ultracompact binaries with orbital periods between 25.92 and 56.16 min. The shorter-period systems behave roughly as expected for AM CV systems, with one of the systems only showing a grazing eclipse. The system with the longest period (P = 56.16 min) is unusual because the ZTF light curve showed three super-outbursts in three years, which suggests that it is a helium CV instead of a typical long-period AM CVn. Both high-speed photometry and spectroscopic follow-up observations are underway to better characterise these four systems.

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[1] YZ LMi shows a grazing eclipse, and therefore the eclipse is only 60% deep. If the inclination for YZ LMi were 90°, the eclipse depth would be ≈97%.

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