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MASTER OT J055845.55+391533.4: SU UMa star with a dip and long rebrightening

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Abstract

We analyzed Asteroid Terrestrial-impact Last Alert System (ATLAS), Zwicky Transient Facility (ZTF) and All-Sky Automated Survey for Supernovae (ASAS-SN) data of MASTER OT J055845.55+391533.4 and found that this object repeats superoutburst with a dip in the middle of the outburst followed by long and sometimes oscillating rebrightening, just like a WZ Sge-type dwarf nova or an AM CVn-type object. The mean supercycle was 298(8) d, too short for a WZ Sge star, but with only a few normal outbursts. We also observed the 2023 February–March superoutburst and established the superhump period of 0.05509(2) d. This period appears to exclude the possibility of an AM CVn star. Although the 2023 observations could not detect superhumps after the dip, the 2014, 2016 and 2021 data seem to suggest that low-amplitude superhumps were present during the rebrightening phase. We note that a dip during a superoutburst is a feature common to the unusual SU UMa-type dwarf nova MASTER OT J172758.09+380021.5 during some of its superoutbursts. These objects may comprise a new class of rebrightening phenomenon in SU UMa-type dwarf novae.

1 Introduction

MASTER OT J055845.55+391533.4 was detected as an optical transient on 2014 February 19 at a magnitude of 14.4 (Yecheistov et al. 2014). The object was found to be already at 13.9 mag on 2014 February 13. Two past outbursts had been detected (Yecheistov et al. 2014). This object was confirmed to be an SU UMa star by the detection of superhumps in 2014 (Kato et al. 2015). The superhump period and supercycle were suggested to be 0.0563(4) d and 360–450 d, respectively (Kato et al. 2015) [for general information of cataclysmic variables (CVs) and dwarf novae (DNe), see e.g., Warner (1995)]. Kato et al. (2017) observed this object on three nights in 2016 and obtained a period of 0.0581 d. Kato et al. (2017) already reported that the outburst behavior was rather strange. We have noticed that this object showed a dip and rebrightening in superoutbursts recorded in modern survey data (see below). Furthermore, such superoutburst with a dip and (sometimes complex) rebrightening occur successively without intervening normal outbursts. Such behavior was very unusual for a hydrogen-rich DN but is frequently seen in helium-rich AM CVn objects [although not very apparent in figure 2 of Levitan et al. (2015), CP Eri is such an object (see section 4)]. We therefore initiated a time-resolved photometic campaign during the 2023 February–March superoutburst to see the development of superhumps and the superoutburst. This object is also known as a variable star ZTF J055845.48+391533.1 (Ofek et al. 2020) and Gaia DR3 3458275544681382912 (=Gaia16bgq, type CV) (Gaia Collaboration et al. 2022).

2 Data analysis

We used Asteroid Terrestrial-impact Last Alert System (ATLAS: Tonry et al. 2018) forced photometry (Shingles et al. 2021), Zwicky Transient Facility (ZTF: Masci et al. 2019)[1] and All-Sky Automated Survey for Supernovae (ASAS-SN: Shappee et al. 2014) Sky Patrol (Kochanek et al. 2017) data to examine the long-term behavior. The ASAS-SN positive detections fainter than V=16.3 or g=16.5 were excluded as noises close to the detection limit. The ASAS-SN data around BJD 2459252 were included even below this limit since the reality of these data were confirmed by a comparison with the ZTF data. Some unfiltered snapshot observations reported to VSOLJ and VSNET (Kato et al. 2004) were also included (hereafter CCD).

Time-resolved photometry during the 2023 February–March superoutburst was obtained by VSOLJ members and the VSNET Collaboration using 30cm-class telescopes. We also obtained observations during the 2021 January–February superoutburst. The log of these observations is listed in table 1. Superhumps maxima were determined using the template fitting method introduced in Kato et al. (2009) after correcting zero-point differences between the observers and removing outburst trends by locally-weighted polynomial regression (LOWESS: Cleveland 1979). The superhump period was determined using the phase dispersion minimization (PDM: Stellingwerf 1978) method, whose errors were estimated by the methods of Fernie (1989); Kato et al. (2010).

3 Results

3.1 Long-term behavior

Long-term light curves are shown in figures 1 and 2. The ATLAS data in quiescence were systematically brighter than the ZTF data. This is probably due to the contamination from a red nearby (physically unrelated) companion Gaia DR3 3458275544681383552 (Gaia BP=18.53 and RP=16.65, Gaia Collaboration et al. 2022). Eight superoutbursts were recorded in this interval. Four representative well-observed superoutbursts are also shown in figure 3 to show more details.

- 2016 January–February (BJD 2457416–2457434, first panel in figure 1). ASAS-SN recorded a dip in the middle of this outburst.

- 2016 August–September (BJD 2457631–2457646, first panel in figure 1). This outburst was observed by ASAS-SN with on three nights. There was fading in the middle of the outburst, although observations before and after it were very sparse. There were also time-resolved observations in the late stage (Kato et al. 2017) and the long duration of the outburst was secure. We consider that this outburst was likely a superoutburst with a dip.

- 2018 April–May (BJD 2458215–2458236, third panel in figure 1 and first panel in figure 3). ZTF and ASAS-SN observations clearly showed the presence of a dip in the middle of this outburst (the ASAS-SN observation during the dip completely overlapped the ZTF point and is invisible in the figures). The duration of the dip appeared to be relatively short.

- 2019 March–April (BJD 2458571–2458596, fourth panel in figure 1 and second panel in figure 3). A relatively long dip was clearly present in ZTF, ATLAS and ASAS-SN observations.

[1]The ZTF data can be obtained from IRSA <https://irsa.ipac.caltech.edu/Missions/ztf.html> using the interface <https://irsa.ipac.caltech.edu/docs/program_interface/ztf_api.html> or using a wrapper of the above IRSA API <https://github.com/MickaelRigault/ztfquery>.

Table 1: Log of time-resolved photometry.

Start*	End*	Mean mag.	Error	$N^\dagger$	Observer‡	Filter
2459254.9039	2459255.1868	14.254	0.002	235	Kub	C
2459256.0870	2459256.1791	14.223	0.006	73	Kub	C
2459998.2890	2459998.5102	14.368	0.004	200	Van	CV
2459999.0367	2459999.1477	14.405	0.006	236	Kis	C
2460001.4188	2460001.5810	14.748	0.003	226	Van	CV
2460001.9571	2460002.1224	14.833	0.004	371	Kis	C
2460001.9729	2460002.0829	14.631	0.008	95	Kub	V
2460002.0046	2460002.1895	14.713	0.004	269	Ioh	C
2460002.9033	2460003.1528	14.788	0.002	448	Ioh	C
2460003.0090	2460003.1402	14.931	0.003	306	Kis	C
2460003.9171	2460004.1300	14.962	0.004	325	Ioh	C
2460004.0440	2460004.1377	15.151	0.006	121	Kis	C
2460004.2960	2460004.5102	15.280	0.005	225	Van	CV
2460006.9644	2460007.1752	15.400	0.004	237	Ioh	C
2460007.2965	2460007.4774	2.401	0.003	129	Vih	C
2460007.9093	2460008.1102	15.400	0.034	66	Ioh	C
2460010.0027	2460010.1063	15.976	0.033	30	Ioh	C
2460010.0181	2460010.1208	16.142	0.015	127	Kis	C
2460010.9498	2460011.1429	15.506	0.007	178	Ioh	C
2460011.9477	2460012.0664	15.325	0.022	31	Ioh	C
2460013.9407	2460014.1841	15.532	0.013	206	Ioh	C
2460014.4756	2460014.5524	15.670	0.007	77	Van	CV
2460014.9528	2460015.1516	16.167	0.017	113	Ioh	C
2460015.3553	2460015.5511	16.328	0.006	187	Van	CV
2460016.4865	2460016.5698	15.912	0.003	103	RFD	CV
2460017.3520	2460017.5518	16.972	0.006	175	Van	CV
2460018.3133	2460018.5511	17.267	0.006	194	Van	CV
2460019.3032	2460019.3055	17.440	0.078	3	Van	CV
2460020.3226	2460020.3339	4.305	0.006	8	Vih	C

*BJD−2400000.

†Number of observations.

‡Itoh (Ioh), Kiyota (Kis), Kubodera (Kub), Romanov (RFD), Vanmunster (Van), Vihorlat team (Vih).

Table 2: Superhump maxima of MASTER OT J055845.55+391533.4 (2023).

E	Max*	Error	$O-C$†	N‡	E	Max*	Error	$O-C$†	N‡
0	59998.3208	0.0007	0.0003	50	69	60002.1227	0.0031	0.0017	120
1	59998.3778	0.0008	0.0022	39	70	60002.1726	0.0020	−0.0035	39
2	59998.4322	0.0007	0.0015	33	84	60002.9464	0.0010	−0.0008	80
3	59998.4864	0.0010	0.0006	37	85	60003.0000	0.0017	−0.0023	102
13	59999.0432	0.0013	0.0067	58	86	60003.0619	0.0012	0.0046	181
14	59999.0911	0.0012	−0.0006	103	87	60003.1125	0.0022	0.0001	183
57	60001.4559	0.0004	−0.0042	63	103	60004.0014	0.0031	0.0077	72
58	60001.5058	0.0009	−0.0093	65	104	60004.0509	0.0028	0.0021	107
59	60001.5686	0.0006	−0.0016	45	105	60004.1005	0.0034	−0.0034	122
67	60002.0086	0.0019	−0.0023	167	110	60004.3823	0.0022	0.0031	54
68	60002.0608	0.0009	−0.0052	215	111	60004.4368	0.0045	0.0025	51

*BJD−2400000.
†Against max = 2459998.3205 + 0.055079E.
‡Number of points used to determine the maximum.

- 2020 May (BJD 2458975–2458981, first panel in figure 2). Only the initial part of the outburst was recorded due to the seasonal gap in observation. The duration of the outburst, however, was sufficient for a superoutburst.
- 2021 January–February (BJD 2459242–2459263, second panel in figure 2 and third panel in figure 3). A relatively long dip was clearly present in ZTF, ATLAS and ASAS-SN observations. This outburst showed some short-term variations (oscillations) after the dip.
- 2021 September–October (BJD 2459467–2459488, third panel in figure 2 and fourth panel in figure 3). A relatively long dip was clearly present in ZTF, ATLAS and CCD observations. An outburst in ZTF and ATLAS on 2021 September 2–5 (BJD 2459460–2459463) was apparently a precursor.
- 2023 February–March (BJD 2459997–2460020, fourth panel in figure 2). There was a dip in the middle of the outburst. This is the superoutburst during which we made a time-resolved photometric campaign in this paper (see figure 5).

The shortest intervals between the superoutburst was 215 d, 225 d being the second shortest. Assuming that two superoutbursts were missed during the seasonal gaps in 2017 and 2022, the mean interval of the superoutbursts was 298(8) d.

Only three normal outbursts were detected: 2017 February 13 (BJD 2457798, second panel in figure 1), 2018 September 16 (BJD 2458378, fourth panel in figure 1) and 2022 February 8 (BJD 2459619, third panel in figure 1). These results indicate that normal outbursts are essentially rare in this object.

3.2 2023 February–March superoutburst

A PDM analysis and the mean profile of superhumps before the dip are shown in figure 4. The mean period in this interval was 0.05509(2) d. Superhumps were below the detection limit during the rebrightening phase after the dip. The times of superhump maxima are listed in table 2. The period derivative ($P_{\rm dot} = \dot{P}/P$) was +7(2) $\times$ 10^{-5} (see Kato et al. 2009). The $O-C$ diagram, variation of the superhump amplitudes and the light curve are shown in figure 5.

3.3 2021 January–February superoutburst

We also observed this object on two nights during the 2021 January–February superoutburst (second panel in figure 2). The observations (BJD 2459254.907–2459256.183) were after the dip. A PDM analysis detected superhumps with a period of 0.05454(12) d (figure 6).

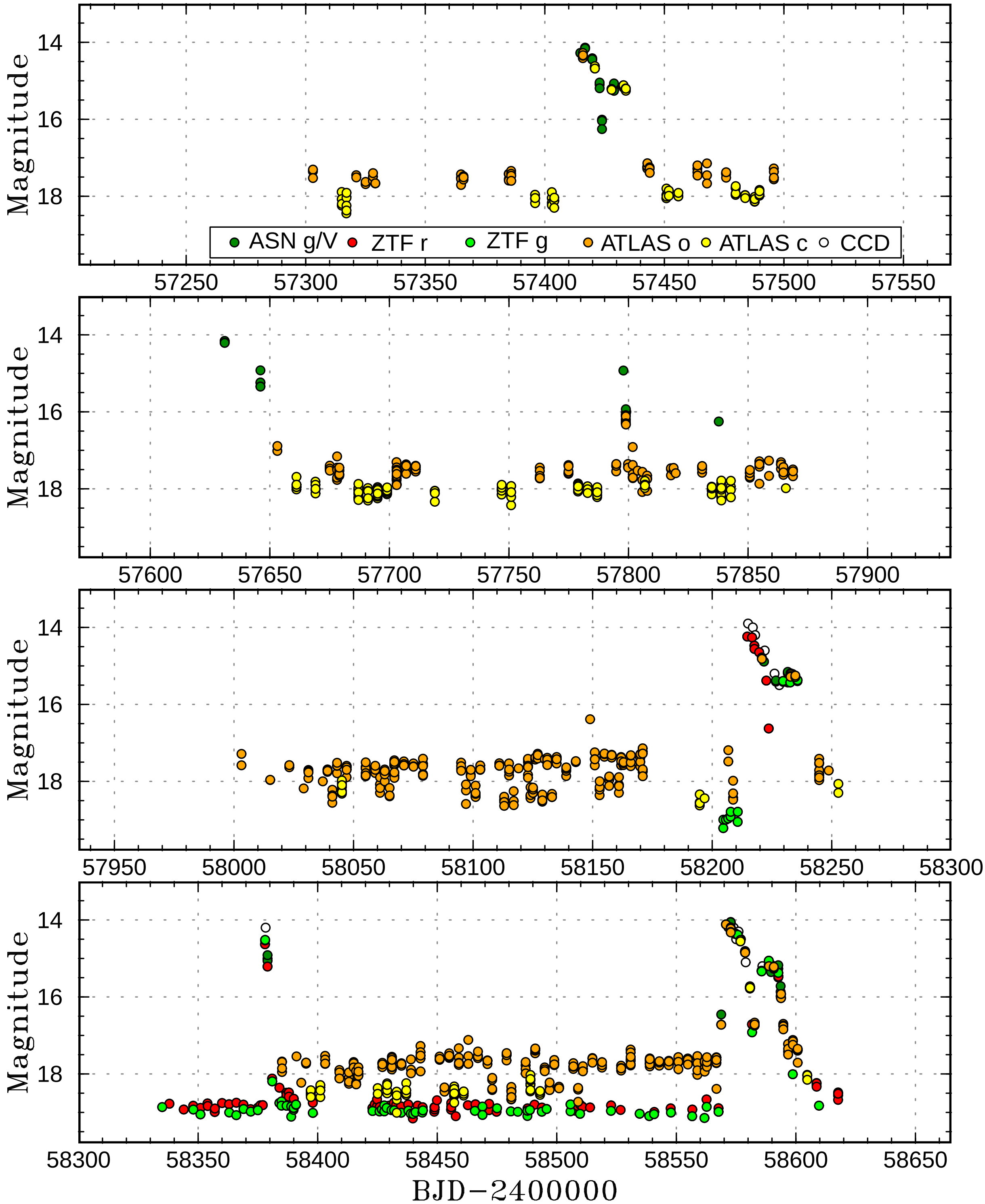

Figure 1: Light curve of MASTER OT J055845.55+391533.4 in 2015–2019. ASN refers to ASAS-SN and CCD refers to unfiltered snapshot observations.

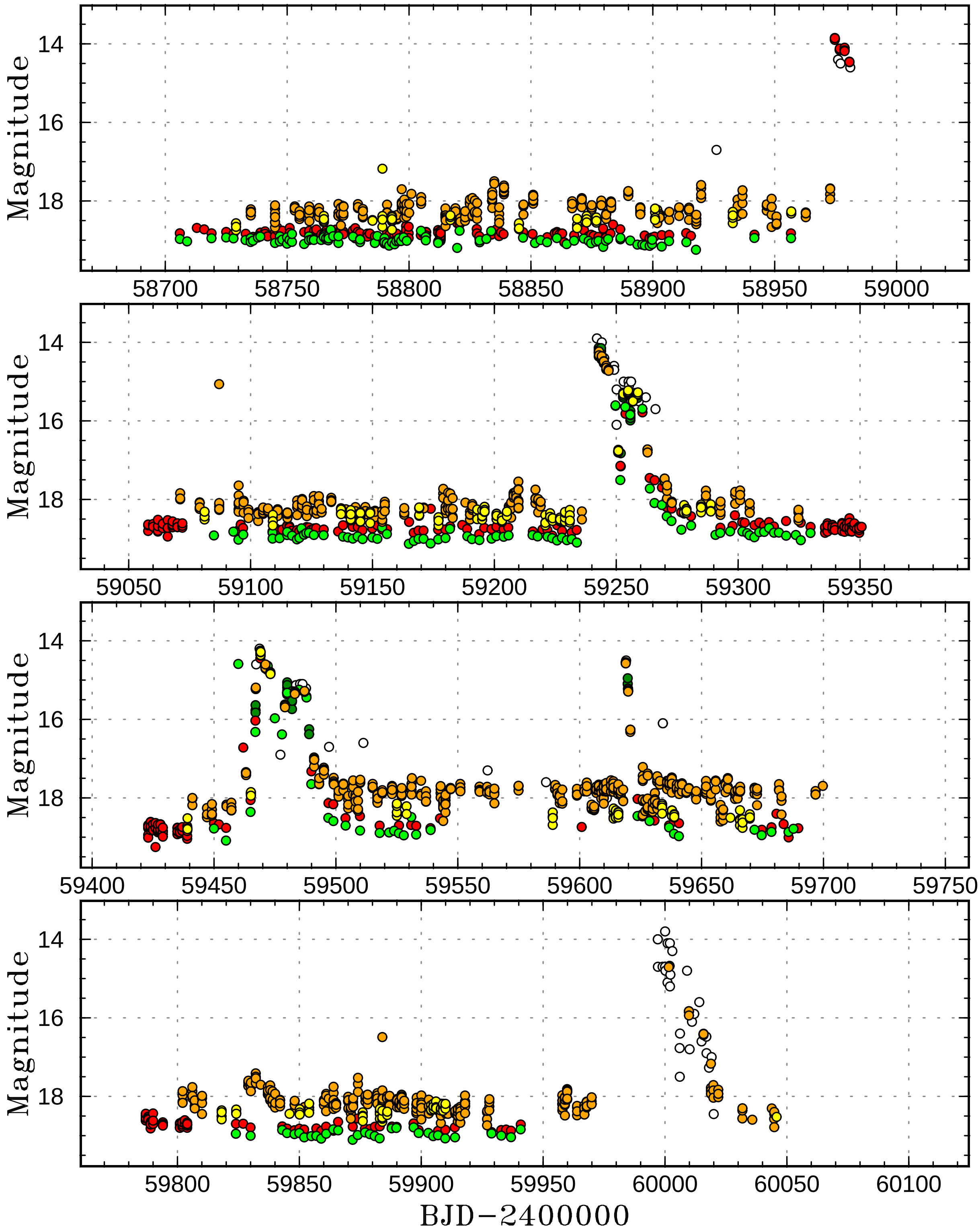

Figure 2: Light curve of MASTER OT J055845.55+391533.4 in 2019–2023. The symbols are the same as in figure 1.

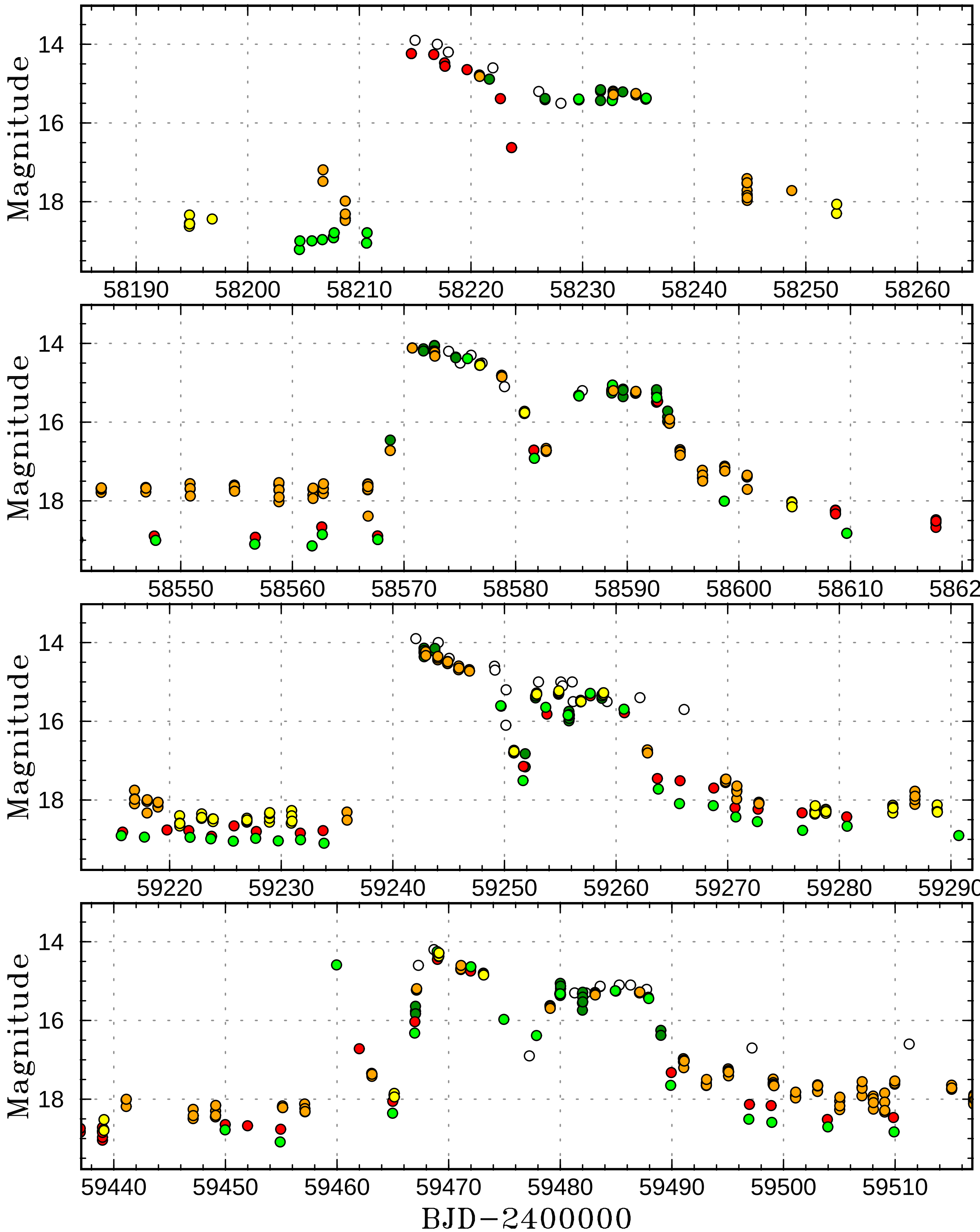

Figure 3: Well-observed superoutbursts of MASTER OT J055845.55+391533.4. The symbols are the same as in figure 1. All superoutbursts had a dip in the middle and subsequent long rebrightening.

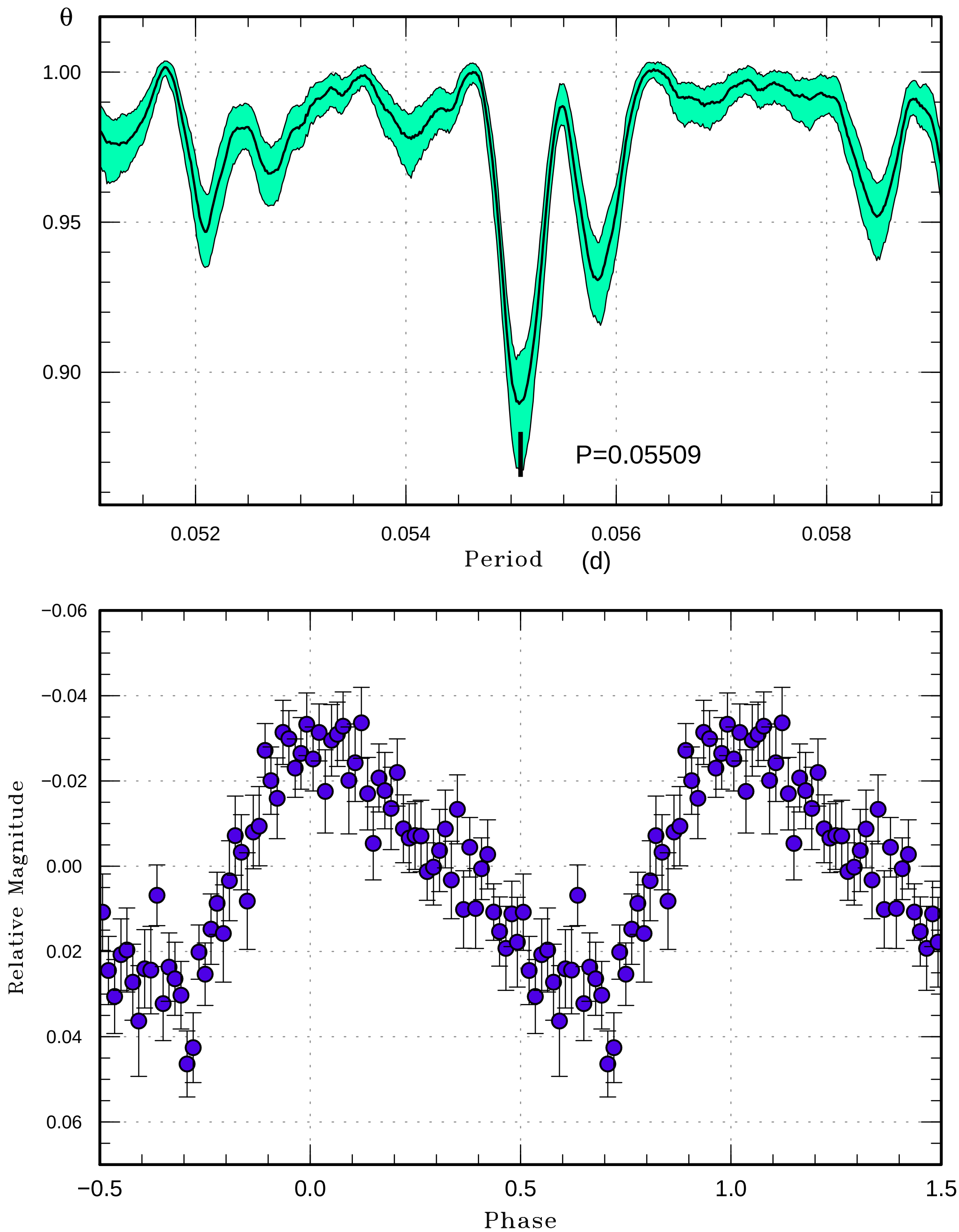

Figure 4: Mean superhump profile of MASTER OT J055845.55+391533.4 during the 2023 February–March superoutburst. The data before the dip (before BJD 2460005) were used. (Upper): PDM analysis. The bootstrap result using randomly contain 50% of observations is shown as a form of 90% confidence intervals in the resultant θ statistics. (Lower): Phase plot.

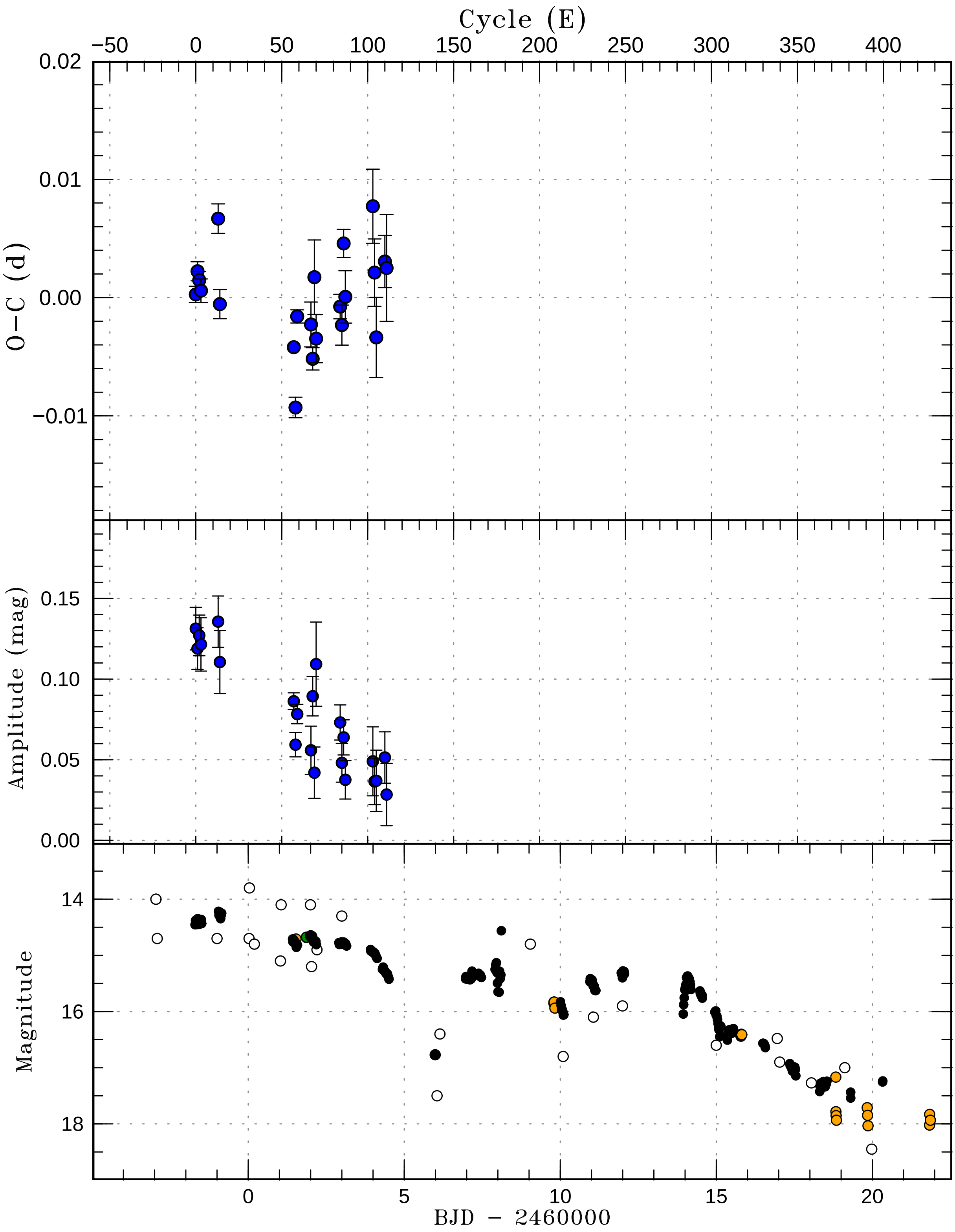

Figure 5: 2023 February–March superoutburst of MASTER OT J055845.55+391533.4. (Upper:) $O-C$ variation. The ephemeris of BJD(max) $= 2459998.3205 + 0.055079E$ was used. The data are in table 2. (Middle:) Superhump amplitude. (Lower:) Light curve. The data were binned to 0.018 d (black filled circles). Other symbols are the same as in figure 1.

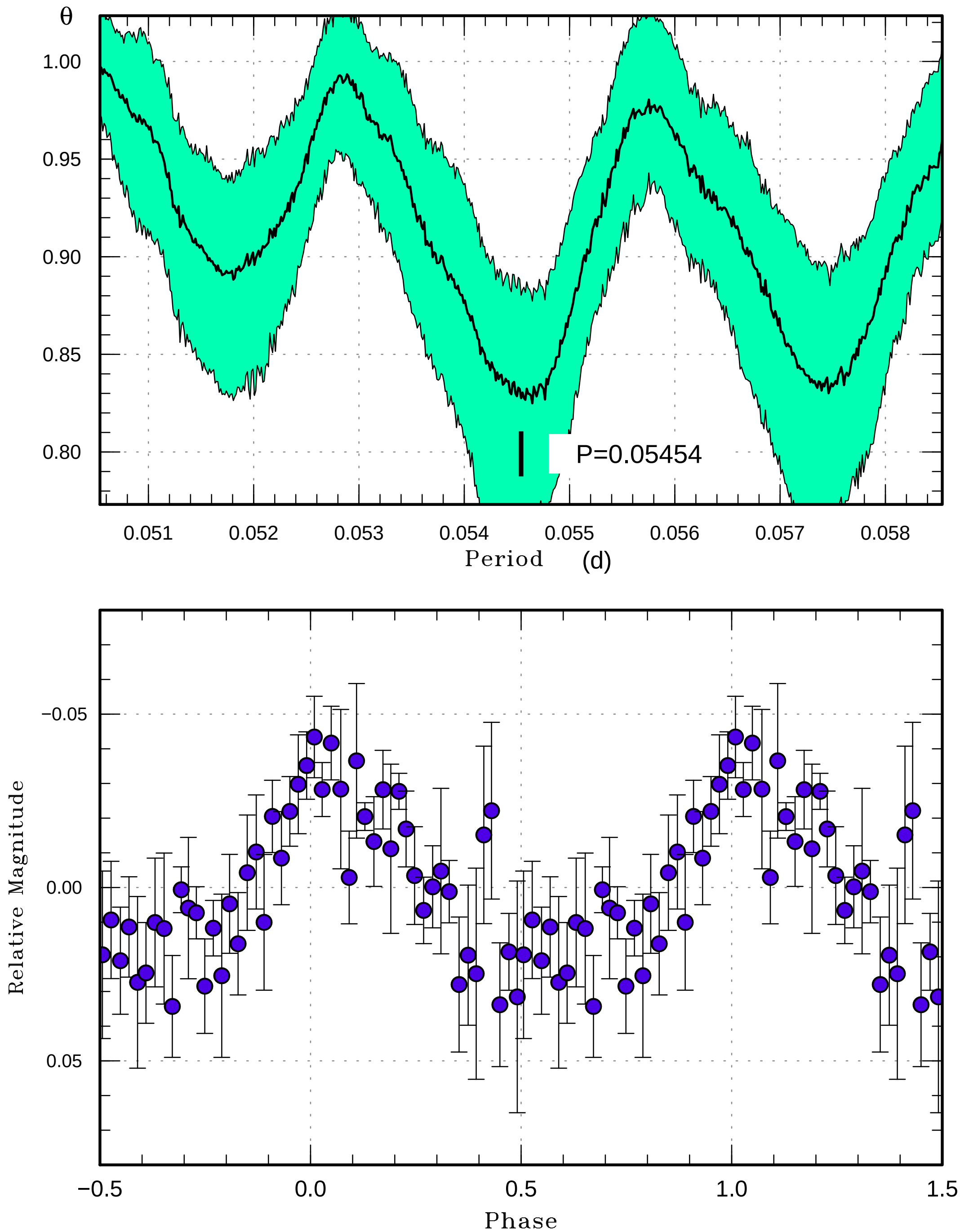

Figure 6: Mean superhump profile of MASTER OT J055845.55+391533.4 during the 2021 January–February superoutburst. The two-night data were obtained after the dip. (Upper): PDM analysis. (Lower): Phase plot.

4 Discussion

The recorded superhumps in 2023 were identified as stage B (for superhump stages, see Kato et al. 2009) based on the profile, decreasing amplitude and the epoch when superhumps were observed. The observed $P_{\rm dot} = +7(2) \times 10^{-5}$ was not unusual for this short superhump period (Kato et al. 2009).

In Kato et al. (2015), the 2014 superoutburst was observed already at least 15 d after the start of the outburst and the recorded superhumps were suggested to be stage C. The 2023 data, however, showed no sign of stage C nor evidence for superhumps in the late stage of the superoutburst. Although the period 0.0563(4) d was slightly different from the current measurement, it can be consistent with the present result considering that the amplitude of superhumps was very small in the 2014 data and that the period was based on single-night data by a single observer. The 2016 observations (Kato et al. 2017) were also obtained near the end of the superoutburst. The period (0.0581 d) appears to be a one-day alias of the present result. Although the 2021 observations (subsection 3.3) were limited, superhumps after the dip appeared to have been detected. These results suggest that low-amplitude superhumps were present during the rebrightening phase, which were below the detection limit of the 2023 observations. The superhump period during the rebrightening phase, however, has not yet been well-determined.

The presence of a dip in the middle of a superoutburst is a strange feature in this object. As stated in section 1, AM CVn stars generally show this feature. We present a light curve of CP Eri in figure 7 for a comparison. All well-observed superoutbursts have a dip in the middle and the number of normal outbursts is relatively low despite the short supercycle. The observed superhump period of MASTER OT J055845.55+391533.4, however, is strongly against the possibility of an AM CVn-type object.

There is another known example of very complex superoutbursts in the very unusual object MASTER OT J172758.09+380021.5, which has a short superhump period of 0.05829 d and a short supercycle of 50–100 d (Pavlenko et al. 2021). The complex superoutburst recorded in 2022 is shown in figure 8 (see also figure 5 in Pavlenko et al. 2021 for the past ones). After a relatively long dip and short rebrightening, this object entered long rebrightening. The behavior is similar to MASTER OT J055845.55+391533.4 in that the superoutburst showed a dip (but more structured) in the middle of a superoutburst. The short orbital period and supercycle are also similar to MASTER OT J055845.55+391533.4. In the case of MASTER OT J172758.09+380021.5, optical spectra confirmed its hydrogen-rich nature (Thorstensen et al. 2016; Pavlenko et al. 2021). The differences between MASTER OT J055845.55+391533.4 and MASTER OT J172758.09+380021.5 are that the dip in superoutburst is highly reproducible in the former while it is not in the latter and that the supercycle is a few times shorter in the latter.

Such a dip during a superoutburst and long rebrightening are usually seen in WZ Sge stars (Kato 2015), but not in ordinary SU UMa stars. In WZ Sge stars, a cooling wave in the accretion disk somehow occurs during a superoutburst and the remaining matter in the disk is considered to be responsible for long or repeated rebrightening (Meyer and Meyer-Hofmeister 2015). Low mass-ratios (q) such as in WZ Sge stars (and some ER UMa stars such as RZ LMi) have been proposed to be a cause of such premature quenching of a superoutburst (Hellier 2001; Osaki 1995). The q value of MASTER OT J172758.09+380021.5 was estimated to be 0.08 (Pavlenko et al. 2021), which seems to be consistent with this interpretation. There have been no indication of WZ Sge-type behavior neither in MASTER OT J055845.55+391533.4 nor MASTER OT J172758.09+380021.5, and these objects may comprise a new class of rebrightening phenomenon in SU UMa-type dwarf novae. Further observations of MASTER OT J055845.55+391533.4 are needed to establish the orbital period, and hopefully the period of stage A to estimate q (Kato and Osaki 2013; Kato 2022), and spectrocopy is needed to estimate the chemical composition. Since superoutbursts of MASTER OT J055845.55+391533.4 are not rare, planned observations for a future superoutburst are requested.

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This work has made use of data from the Asteroid Terrestrial-impact Last Alert System (ATLAS) project.

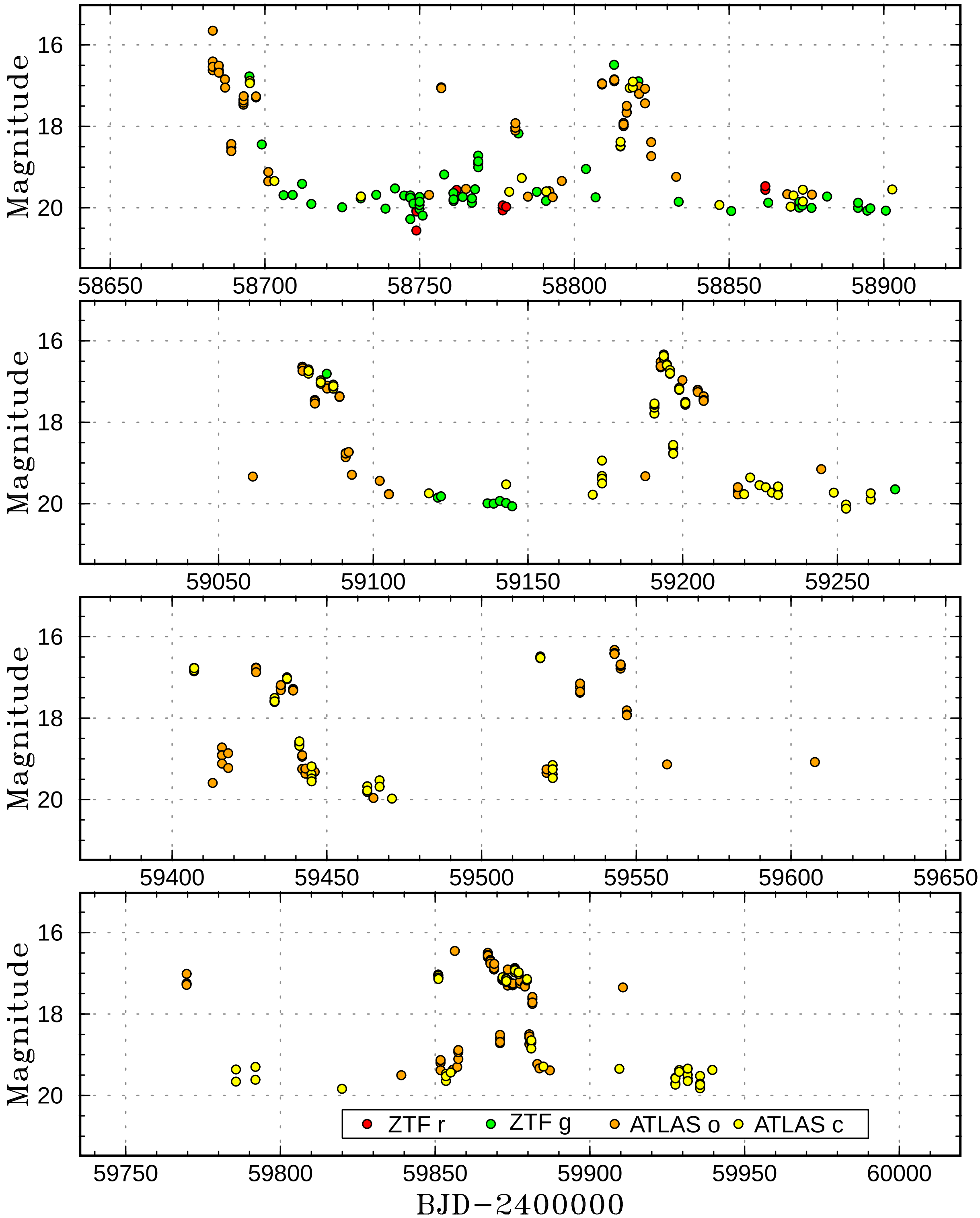

Figure 7: Light curve of CP Eri. The presence of a dip in the middle of a superoutburst is the feature common to MASTER OT J055845.55+391533.4.

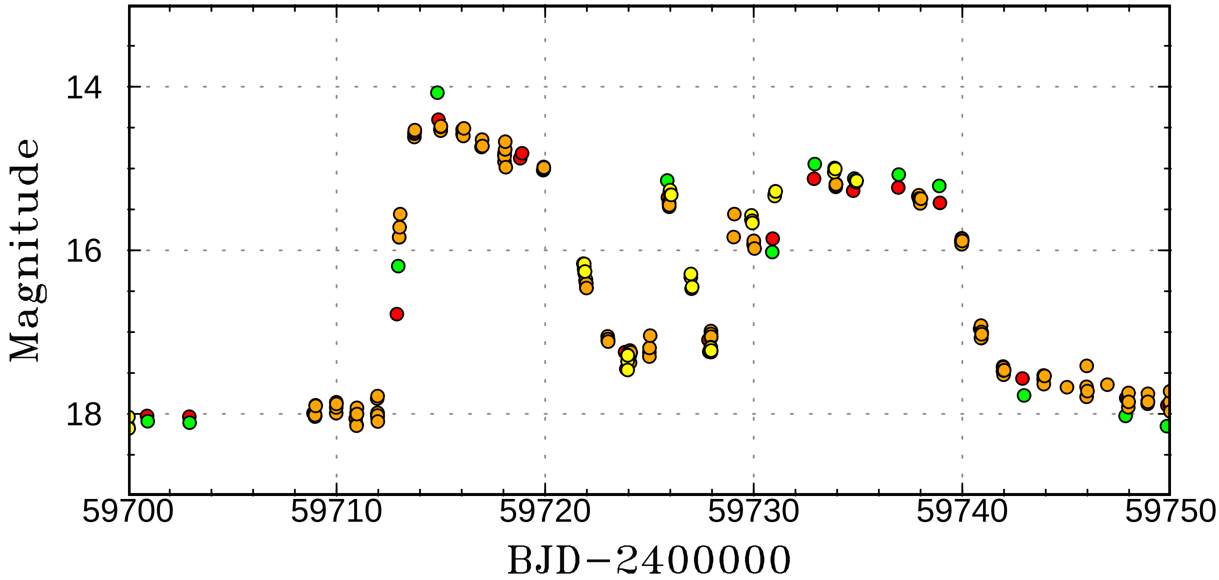

Figure 8: Complex superoutburst in MASTER OT J172758.09+380021.5 recorded in 2022. The symbols are the same as in figure 7.

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List of objects in this paper

AM CVn, CP Eri, RZ LMi, WZ Sge, SU UMa, ER UMa, Gaia DR3 3458275544681382912, Gaia DR3 3458275544681383552, Gaia16bgq, MASTER OT J055845.55+391533.4, MASTER OT J172758.09+380021.5, ZTF J055845.48+391533.1

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