Optical and Near-Infrared Photometric Observation during the Superoutburst of the WZ Sge-Type Dwarf Nova, V455 Andromedae

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Abstract

We report on optical and infrared photometric observations of a WZ Sge-type dwarf nova, V455 And during a superoutburst in 2007. These observations were performed with the KANATA (V, J, and Ks bands) and MITSuME (g', Rc, and Ic bands) telescopes. Our 6-band simultaneous observations allowed us to investigate the temporal variation of the temperature and the size of the emitting region associated with the superoutburst and short-term modulations, such as early and ordinary superhumps. A hot (>11000 K) accretion disk suddenly disappeared when the superoutburst finished, while blackbody emission, probably from the disk, still remained dominant in the optical region with a moderately high temperature (∼8000 K). This indicates that a substantial amount of gas was stored in the disk even after the outburst. This remnant matter may be a sign of an expected mass-reservoir which can trigger echo outbursts observed in several WZ Sge stars. The color variation associated with superhumps indicates that viscous heating in a superhump source stopped on the way to the superhump maximum, and a subsequent expansion of a low-temperature region made the maximum. The color variation of early superhumps was totally different from that of superhumps: the object was bluest at the early superhump minimum. The temperature of the early superhump light source was lower than that of an underlying component, indicating that the early superhump light source was a vertically expanded low-temperature region at the outermost part of the disk.

Key words: accretion, accretion disk—stars: novae, cataclysmic variables—stars: individual(V455 Andromedae)

1. Introduction

Cataclysmic variables are semi-detached binary systems consisting of a primary white dwarf and a secondary red star. A Roche-lobe-filling red star loses mass through the inner Lagrangian point and the white dwarf accretes. Dwarf novae are a group of cataclysmic variables, showing repetitive outbursts having amplitudes of 2–8 mag (Warner 1995). In the quiescent state of dwarf novae, the optical emission is a superposition of the flux from several components, that is, the thermal emission from the white dwarf and the secondary star, and free-free emission from an optically thin accretion disk and a hot spot where the gas stream from the secondary hits the disk (Szkody 1976). In an outburst, the thermal emission from an optically thick disk is dominant (Clarke et al. 1984; Horne et al. 1990). SU UMa-type dwarf novae are a subgroup of dwarf novae, exhibiting two types of outburst: a short normal outburst and a long superoutburst. During superoutbursts, their light curves show short-term periodic modulations, called “superhumps”, which have a period that is a few percent longer than the orbital period (Warner 1985).

It is widely accepted that dwarf nova outbursts can be explained by two types of instabilities in the accretion disk (Osaki 1996). The first instability is a thermal insta-
bility (Hoshi 1979). According to the thermal instability model, the accretion disk can take only two thermally stable states. One is a low-viscosity, cool disk consisting of neutral hydrogen gas. The other one is a high-viscosity, hot disk consisting of ionized gas. The disk with partially ionized gas is predicted to be thermally unstable. Dwarf nova outbursts can be interpreted as a state transition from the cool to hot state, which occurs when the disk density reaches a critical value in the cool state.

The second instability is a tidal instability (Whitehurst 1988; Osaki 1989). According to this model, the disk becomes tidally unstable, and deforms to an eccentric disk when the disk radius reaches the 3:1 resonance radius. A strong tidal torque works in an eccentric disk, leading to bright superoutbursts observed in SU UMa stars. An eccentric disk is expected to show prograde precession in the inertial frame of binary systems. The superhump period, slightly longer than the orbital period, can naturally be explained by this precession.

WZ Sge-type dwarf novae form a subclass of SU UMa stars, which only experiences superoutbursts (O'Donoghue et al. 1991; Osaki 1995). They are characterized by quite long (∼10 yr) intervals of superoutbursts. WZ Sge stars have received attention because they show peculiar variations which are not seen in ordinary SU UMa stars, and whose mechanisms are poorly understood.

WZ Sge stars tend to show echo outbursts after the main superoutburst (Kato et al. 2004). According to the thermal–tidal instability model, the amount of gas in the disk should be minimum just after an superoutburst (Osaki 1989). The long duration of the echo outburst phase and its sudden cessation are, hence, problematic for the disk instability model. Hameury et al. (2000) proposed that an echo outburst is caused by an enhanced mass-transfer rate from the secondary. Patterson et al. (2002) reported that the observation of WZ Sge supported that scenario. On the other hand, Osaki et al. (2001) proposed that an echo outburst can be triggered if the disk viscosity remains high just after the outburst, and the gas is supplied from the outer disk (Kato et al. 1998; Kato et al. 2004). Hellier (2001) suggested that a subsonic disk becomes tidally unstable, and deforms to an eccentric disk. Observational evidence for such a mass reservoir for echo outbursts has, however, not been established (Uemura et al. 2008; Kato et al. 2008).

WZ Sge-type dwarf novae exhibit unique short-term periodic modulations only appearing in a very early phase of superoutbursts. They are called “early superhumps”, whose period is in agreement with the orbital period (Patterson et al. 1981; Kato et al. 1996). Since the amplitude of the early superhump depends on the inclination angle of binary systems, it is probably attributed not to the variation due to viscous heating, but to a geometric effect of the accretion disk (Kato 2002). It is proposed that a part of the disk is vertically expanded, and has a non-axisymmetric structure (Kato 2002; Osaki, Meyer 2002; Kunze, Speith 2005).

V455 And was discovered as a dwarf nova candidate from the Hamburg Quasar Survey. Follow-up observations showed an orbital period of 81.09 min and a spectrum similar to that of WZ Sge (Araujo-Betancor et al. 2004; Araujo-Betancor et al. 2005). The first-ever recorded outburst of V455 And was discovered on 2007 September 4. As reported in the following section of this paper, V455 And was actually confirmed to be one of the WZ Sge stars from observations during the outburst. The object became a very bright source, reaching the 8th magnitude in the V band at maximum. It, hence, provided a great chance to study WZ Sge phenomena in detail. We performed optical–near-infrared multi-band photometric observations in order to provide the color variation associated with a superoutburst as well as early and ordinary superhumps. In this paper, we report on the results of our observation. We, furthermore, investigate the temporal variation of the temperature and the size of the emitting region of the disk using the multi-band data. In section 2, the observation and image reduction are described. Our observational results are shown in section 3. The implication of the results is discussed in section 4. Finally, we summarize our findings in section 5.

2. Observations

We performed photometric observations at two sites. First, observations at Higashi-Hiroshima Observatory were carried out with the 1.5-m KANATA telescope. We used the instrument “TRISPEC (Triple Range Imager and SPECtrometer with Polarimetry)” attached to the Cassegrain focus of the telescope (Watanabe et al. 2005). Photometric observations were performed simultaneously.
in the $V$, $J$, and $K_s$ bands. The exposure times of $V$, $J$, and $K_s$-band observations were 10 or 30, 2 or 5, and 1 s, respectively, depending on the sky condition. An example of the $V$-band images is shown in figure 1. Second, the observations at Okayama Astrophysical Observatory were carried out with the 50-cm MITSuME telescope. The observations were performed simultaneously in the $g'$, $Rc$, and $Ic$ bands. The exposure times of the three bands were between 5 and 60s. The journal of the observations is given in tables 1 and 2 for the Higashi-Hiroshima and Okayama observatories, respectively.

After dark subtraction and flat fielding, we performed aperture photometry, and obtained differential magnitudes of the object relative to the comparison stars. The comparison stars that we used are indicated in figure 1. Comparison stars 1 and 2 are located at $RA = 23^h34^m04.19^s$, $DEC = +39^\circ 21^\prime 24^\prime\prime.1$, and $RA = 23^h34^m15.09^s$, $DEC = +39^\circ 22^\prime 47^\prime\prime.4$, respectively. The optical and near-infrared magnitudes of the comparison stars were quoted from Henden (2006) and the 2MASS catalog (Skrutskie et al. 2006), respectively. The magnitude of the comparison star in the $g'$ band was converted from the $B$ and $V$ magnitudes with the following formula (Smith et al. 2002):

$$g' = V + 0.54(B - V) - 0.07.
$$

The magnitudes of the comparison stars are listed in table 3.

| filter | mag (comp.1) | mag (comp.2) |
|--------|--------------|--------------|
| $g'$   | 13.17 ± 0.01 | 12.45 ± 0.01 |
| $V$    | 12.70 ± 0.01 | 12.20 ± 0.01 |
| $Rc$   | 12.12 ± 0.01 | 11.85 ± 0.01 |
| $Ic$   | 11.63 ± 0.01 | 11.50 ± 0.02 |
| $J$    | 10.89 ± 0.02 | 11.05 ± 0.02 |
| $K_s$  | 10.26 ± 0.02 | 10.71 ± 0.02 |

The constancy of the magnitude of comparison star 1 was checked with comparison star 2. No significant variation was seen over $\sim 0.04$ mag in the relative magnitude between comparison stars 1 and 2 throughout our observation. In the following sections, we show the results using comparison star 1. We confirmed that the magnitudes calculated with comparison star 2 are in agreement with those with comparison star 1 within the errors in all bands. The magnitude errors of the comparison star were included in those of the object in the following analysis for the spectral energy distribution (SED).

The interstellar extinction in the direction of V455 And is estimated to be small, $A_V = 0.34$, according to the database of Schlegel et al. (1998). This can be considered as being an upper-limit of the extinction in V455 And. The actual extinction is probably significantly smaller than the upper-limit, since V455 And is a nearby source; the distance is estimated to be 90±15pc (Araujo-Betancor et al. 2005). It is difficult to perform an accurate correction of the extinction with our available data. In this paper, we neglect the interstellar extinction.

### 3. Result

#### 3.1. The 2007 Outburst of V455 And

Figure 2 illustrates the overall light curve and color variation of V455 And during the 2007 outburst. The outburst of V455 And was discovered on 4 September 2007. We started to observe the object just after its discovery. The object was rapidly rising with $-5.8$ mag day$^{-1}$ in the $V$ band during our first night observation on 4 September. On the next day, 5 September, the outburst reached the maximum when the magnitude was 8.69 ± 0.01 in the $V$ band. Hereafter, we denote the time as $T$, the elapsed days from the outburst maximum, defining $T = 0$ as 5.5 September 2007 (JD 2454349.0).

After the object reached the maximum, it had declined from $V = 8.7$ to 11.9 for 17 d. The fading rate was calculated to be $0.31 \pm 0.02$ mag day$^{-1}$ in the $V$ band at $T = 0$–5. It, then, significantly decreased to $0.13 \pm 0.01$ mag day$^{-1}$ at $T = 9$–15. A change of the fading rate occurred at $T \sim 6$. Such a feature is commonly observed in WZ Sge-type dwarf novae (Kato et al. 2001). The outburst continued at least until $T \sim 17$, and then a rapid fading from the outburst was observed at $T = 20$. The rapid fading...
Table 1. Observation log for the KANATA telescope

| T' (days) | Time [+JD2454000] | V mag* | J mag* | K_s mag* | Frames |
|-----------|--------------------|--------|--------|----------|--------|
| -0.7027   | 48.2973 – 48.3461  | 14.00±0.03 | 13.09±0.04 | 12.64±0.05 | 34     |
| 0.1167    | 49.1167 – 49.3215  | 8.69±0.01  | 8.82±0.02 | 8.59±0.02 | 307    |
| 1.2300    | 50.2300 – 50.3142  | 9.14±0.02  | 9.27±0.02 | 8.97±0.02 | 77     |
| 2.1005    | 51.1005 – 51.2405  | 9.43±0.02  | 9.50±0.03 | 9.33±0.04 | 89     |
| 3.0409    | 52.0409 – 52.1868  | 9.71±0.01  | 9.75±0.02 | 9.51±0.02 | 352    |
| 5.1006    | 54.1006 – 54.2510  | 10.27±0.01 | 10.27±0.02 | 10.06±0.02 | 400    |
| 6.2552    | 55.2552 – 55.3128  | 10.54±0.01 | 10.48±0.02 | 10.27±0.02 | 170    |
| 7.1196    | 56.1196 – 56.2517  | 10.68±0.01 | 10.59±0.02 | 10.35±0.02 | 374    |
| 8.2005    | 57.2005 – 57.2681  | 10.86±0.01 | 10.75±0.02 | 10.51±0.02 | 199    |
| 9.0606    | 58.0606 – 58.3089  | 10.97±0.01 | 10.84±0.02 | 10.59±0.02 | 360    |
| 10.0668   | 59.0668 – 59.2980  | 11.15±0.01 | 11.02±0.02 | 10.77±0.03 | 194    |
| 13.2629   | 62.2629 – 62.3016  | 11.52±0.01 | 11.37±0.02 | 11.18±0.04 | 81     |
| 14.1349   | 63.1349 – 63.3122  | 11.74±0.01 | 11.53±0.02 | 11.29±0.02 | 1048   |
| 15.1447   | 64.1447 – 64.9998  | 11.80±0.01 | 11.60±0.02 | 11.34±0.02 | 790    |
| 16.0002   | 65.0002 – 65.1419  | 11.88±0.01 | 11.63±0.02 | 11.35±0.03 | 466    |
| 16.1350   | 65.1350 – 65.1456  | 12.74±0.02 | —       | —       | 18     |
| 21.0208   | 69.0208 – 60.0517  | 13.90±0.01 | 13.11±0.02 | 12.32±0.03 | 588    |
| 22.1129   | 71.1129 – 71.2611  | 13.99±0.02 | 13.09±0.04 | 12.43±0.08 | 62     |
| 22.9737   | 71.9737 – 71.9970  | 13.90±0.02 | 13.02±0.08 | 12.39±0.11 | 27     |
| 24.9586   | 73.9586 – 74.3170  | 14.16±0.02 | 13.30±0.03 | 12.54±0.04 | 127    |
| 28.1306   | 77.1306 – 77.3176  | 14.50±0.01 | 13.68±0.02 | 12.87±0.03 | 210    |
| 29.0899   | 78.0899 – 78.2791  | 14.47±0.02 | 13.62±0.02 | 12.83±0.03 | 173    |
| 30.0781   | 79.0781 – 79.2068  | 14.61±0.01 | 13.80±0.02 | 13.05±0.03 | 200    |
| 31.1622   | 80.1622 – 80.1672  | 14.59±0.02 | 13.77±0.04 | 13.07±0.22 | 8      |
| 36.1646   | 85.1646 – 85.2881  | 14.81±0.02 | 13.95±0.03 | 13.18±0.03 | 111    |
| 37.0321   | 86.0321 – 86.3320  | 14.82±0.02 | 14.00±0.02 | 13.10±0.05 | 84     |
| 38.1215   | 87.1215 – 87.1827  | 14.66±0.01 | 13.96±0.03 | 12.96±0.06 | 94     |
| 40.1162   | 89.1162 – 89.2183  | 14.88±0.01 | 14.09±0.02 | 13.23±0.03 | 170    |
| 41.1390   | 90.1390 – 90.2589  | 14.95±0.01 | 14.13±0.02 | 13.27±0.03 | 195    |
| 42.0532   | 91.0535 – 91.1757  | 15.04±0.01 | 14.23±0.02 | 13.35±0.03 | 145    |
| 42.9389   | 91.9389 – 92.2362  | 15.00±0.02 | 14.25±0.03 | 13.26±0.05 | 94     |
| 43.9468   | 92.9468 – 92.9531  | 15.05±0.02 | 14.19±0.03 | 13.35±0.04 | 10     |
| 45.1280   | 94.1280 – 94.1338  | 15.10±0.02 | 14.22±0.03 | 13.41±0.06 | 10     |
| 46.9391   | 95.9391 – 95.9449  | 15.13±0.03 | 14.33±0.08 | 12.88±0.12 | 9      |
| 48.0630   | 97.0630 – 97.2188  | 15.14±0.01 | 14.35±0.02 | 13.46±0.03 | 210    |
| 49.1694   | 98.1694 – 98.1754  | 14.99±0.02 | 14.19±0.03 | 13.64±0.05 | 10     |
| 52.0617   | 101.0617 – 101.1322| 15.18±0.01 | 14.41±0.02 | 13.44±0.04 | 103    |
| 55.0422   | 104.0422 – 104.1755| 15.16±0.01 | 14.35±0.02 | 13.45±0.03 | 200    |

*Magnitudes are averaged ones in each run.
stopped at 2.7 mag brighter than the quiescence in the $V$ band. Then, the object again started gradual fading. Those temporal behaviors are common to the light curves of the other wave-bands, that is, the $g'$, $Rc$, $Ic$, and $K_{s}$ bands. V455 And exhibited no echo outburst, which has been observed in several WZ Sge stars (Kato et al. 2004).

The color index took a minimum value of $V − J = −0.13 ± 0.01$ when the brightness was at the maximum. The color index gradually increased with time during the outburst. As can be seen in the lower panel of figure 2, the color curve also shows a break at $T ∼ 6$. The color suddenly changed to be red, $V − J ∼ 0.8$, at the same time as when the outburst finished. After the outburst, the color remained almost constant at $∼ 0.8$, while the brightness continued a gradual decline. Thus, the brightness—color relation in outburst was different from that after the outburst. This result suggests that a dominant radiation mechanism or component changed when the outburst finished.

### 3.2. SED Variation during the Outburst

Using 6-band photometric observations, we investigated the radiation mechanism, the size, and the temperature of the emitting region during and after the outburst. Figure 3 shows the SEDs of the optical–infrared region. The top, middle, and bottom panels show the SED at $T = 5, 13, \text{and} 22$, respectively.

We need to develop an SED model to obtain physical parameters of the emitting region for both the outburst and post-outburst states. It is considered that the thermal emission from the optically thick disk is dominant in the optical range during dwarf nova outbursts (Clarke et al. 1984; Horne et al. 1990). It has been proposed, however, that WZ Sge stars have more complex emission-components and structure of the accretion disk (Smak 1993; Nogami et al. 2009). In the post-outburst and quiescent states, furthermore, it has been believed that several components can contribute to the optical–near-infrared emission, for example, the white dwarf, the optically thick/thin disk, the hot spot, and the secondary star.
We, hence, tried to fit the SEDs with a blackbody radiation. In dwarf novae at quiescence, the free-free emission accounts for \(\sim 50\%\) of the optical flux (Szkody 1976). Its temperature has been estimated to be \((0.5-1) \times 10^5\) K. It probably originates from a hot spot or optically thin disk. Even in outburst, we can expect a contribution of the free-free emission from the optically thin area in the accretion disk. The contribution can be large in edge-on systems, such as V455 And (Araujo-Betancor et al. 2005), because the optically thin area above the optically thick disk is apparently large.

We tried to fit the SED with a combination model with blackbody and free-free emission. The temperature of the free-free emission could not, however, be significantly determined because the dependency of the spectral slope is quite low in the optical region in the case of a temperature of \(\gtrsim 10^4\) K. The excess over the blackbody emission is, furthermore, too small even in the near-infrared region to significantly constrain the temperature of the free-free emission. Consequently, we fixed the temperature of the free-free emission as \(10^5\) K in all cases. The best-fitted models are indicated by the dashed lines in panels (c), (f), and (i) in figure 3. Although the models in the middle and the right panels are different, both models well reproduce the observed SEDs. It is difficult to determine the SED model with only our available data. In this paper, we draw no conclusion about the emission mechanism of the \(K_s\)-band excess.

Table 4 gives the temperature of the blackbody emissions obtained with the three SED models. The first column gives the time in \(T\). The second column gives the temperature from the single blackbody model. The third and fourth columns give the temperatures from the two blackbody model. The fifth column gives the blackbody temperature from the combination model of blackbody and free-free emission. It is preferable that the additional component for the \(K_s\)-band excess has little influence on the high-temperature blackbody component, because the observed SEDs are almost reproduced by it. As can be seen from table 4, the temperature makes a sudden jump at \(T = 13\) in the two-blackbody model, which is less likely to indicate a real variation. It should also be noted that the low-temperature blackbody component has an atypical high temperature only at \(T = 2\). On the other hand, the blackbody temperature from the blackbody+free-free model shows a similar variation to that from the single blackbody model. These results indicate that the blackbody+free-free model is more suitable for our anal-

![Fig. 3. Observed SEDs and best models. The filled circles indicate the observed fluxes in the \(g', V, R_c, I_c, J,\) and \(K_s\) bands. Panels (a), (b), and (c) show the SEDs at \(T = 5\) when early superhumps appeared. Panels (d), (e), and (f) show those at \(T = 13\) when superhump appeared. Panels (g), (h), and (i) show those at \(T = 22\), after the outburst. The model SEDs in the left, middle, and right panels are a blackbody radiation, two blackbody components, and the combination model of blackbody and a \(10^5\) K free-free emissions, respectively. In the middle and right panels, we show each emission as well as the total model SEDs. Lower frame of each panel shows the ratio of the observed SED to the model. Errors of each point are shown in the figure, but most of them are smaller than the size of the symbols.](image-url)
rapidly declines to ∼8000 K blackbody emission was similar to that of the free-free one. As shown in the bottom panel of figure 4, the contribution of the free-free emission at 2.16 µm (or the degree of the $K_s$-band excess) was small at the maximum of the outburst. It, then, gradually increased between $T = 0$–40. It became dominant after the outburst. After $T \sim 40$, it was almost constant at a fraction of the total flux of about 0.85.

3.3. Short-Term Variation Observed in V455 And

V455 And showed short-term variations during the outburst. We report observational features of them in this section.

Figure 5 shows the light curves at $T = 3$ and 5. Clear short-term variations were detected with amplitudes of ∼0.4 mag on both days. Their profile consists of rapid variations with a timescale of ∼50 s superimposed on double-peaked periodic modulations (more clearly seen in the phase-averaged light curves in figure 7). The double-peaked feature is reminiscent of early superhumps observed in WZ Sge-type dwarf nova.

Maehara et al. (2007)$^3$ confirmed that those modulations were actually early superhumps based on their period analysis, which showed that the period was in agreement with the orbital period of V455 And. Kato et al. (2007)$^4$ reported the period of the early superhump to be 0.056267±0.000002 d.

Figure 6 shows the short-term variations at $T = 12$ and 14. In these cases, short-term variations had a single peak profile with amplitudes of ∼0.2 mag (also see figure 8). As in figure 5, rapid variations were still seen particularly at $T = 12$. Their features are consistent with those of superhumps observed in SU UMa-type dwarf novae. Kato et al. (2007)$^5$ confirmed that those modulations were actually superhumps based on their period analysis, which showed that the period was longer than the orbital period of V455 And. Maehara et al. (2007)$^6$ reported the superhump period to be 0.057093±0.000015 d. It is 1.39% longer than the orbital period of V455 And.

Those detections of the early and ordinary superhumps established the WZ Sge-type nature of V455 And. The outburst in 2007 was, hence, actually a superoutburst of...
Table 4. Temperature of the blackbody emission in the three models.

| T (days) | Single blackbody model | Two-blackbody model | Blackbody+free-free model |
|----------|------------------------|---------------------|---------------------------|
|          | Temp. (K)              | Temp.1 (K)          | Temp.2 (K)                | Temp. (K)       |
| 2.16024  | 13090 ± 540            | 14600 ± 180         | 5840 ± 140                | 13440 ± 370     |
| 5.18139  | 12560 ± 380            | 14510 ± 140         | 3850 ± 70                 | 12360 ± 340     |
| 7.17812  | 11730 ± 320            | 13410 ± 120         | 3700 ± 70                 | 12200 ± 180     |
| 8.13689  | 11550 ± 310            | 13140 ± 120         | 3650 ± 70                 | 12080 ± 160     |
| 9.00140  | 11510 ± 370            | 13040 ± 220         | 3650 ± 70                 | 11320 ± 200     |
| 13.0172  | 11110 ± 370            | 14000 ± 1060        | 5260 ± 500                | 11500 ± 400     |
| 16.1102  | 10760 ± 290            | 12710 ± 800         | 3670 ± 300                | 12200 ± 160     |
| 20.0287  | 7700 ± 170             | 8280 ± 60           | 2890 ± 50                 | 7800 ± 90       |
| 21.1294  | 7670 ± 140             | 8280 ± 90           | 2630 ± 60                 | 7780 ± 190      |
| 22.0726  | 7620 ± 170             | 8210 ± 70           | 2770 ± 50                 | 7740 ± 90       |
| 28.1200  | 7890 ± 170             | 8900 ± 320          | 2570 ± 120                | 8620 ± 360      |
| 30.1101  | 7960 ± 180             | 8820 ± 220          | 2560 ± 110                | 8320 ± 130      |
| 40.0859  | 8180 ± 200             | 8620 ± 60           | 2700 ± 20                 | 9640 ± 390      |
| 41.0600  | 8250 ± 200             | 9200 ± 140          | 2470 ± 50                 | 9740 ± 370      |
| 44.0659  | 8280 ± 210             | 9140 ± 80           | 2440 ± 50                 | 9520 ± 260      |
| 45.0812  | 8150 ± 200             | 9080 ± 210          | 2510 ± 70                 | 9320 ± 400      |
| 48.0548  | 8100 ± 190             | 9120 ± 60           | 2500 ± 10                 | 8960 ± 170      |
| 52.0996  | 8110 ± 190             | 8970 ± 60           | 2440 ± 50                 | 9240 ± 390      |
| 55.1236  | 8200 ± 210             | 8970 ± 60           | 2360 ± 20                 | 9400 ± 310      |

Fig. 5. Light curves of early superhumps at $T = 3$ and 5. The abscissa and ordinate denote the time in $T$ and mag, respectively. The left panel shows the light curves at $T = 3$ in $V$ and $J (+0.2)$ mag. The right panel shows those at $T = 5$ in $g'$ and $Ic (-0.2)$ mag.

Fig. 6. Light curves of superhumps at $T = 12$ and 14. The abscissa and ordinate denote the time in $T$ and magnitude, respectively. The left panel shows the light curves at $T = 12$ in $Ic$ and $g'$ mag. The right panel shows those at $T = 14$ in $V$ and $J$ mag.
WZ Sge-type dwarf novae. We detected typical early superhumps from \( T = 0 \) to \( 6 \). Photometric studies show that the superhump appeared from \( T = 7 \) and the early superhump completely disappeared on \( T = 8 \) (Maehara, H. in private communication).

### 3.4. Color and SED Variation Associated with Early and Ordinary Superhumps

Our multicolor photometry allowed us to investigate the color and SED variations associated with early and ordinary superhumps. In order to see small color variations, we analyzed phase-averaged light curves of them for each night.

Figure 7 shows the phase-averaged light curve and the color variations of early superhumps. In the left panel, the filled squares and open circles represent the \( V \)-band mag and \( V - J \) color at \( T = 3 \), respectively. In the right panel, they represent the \( g'\)-band mag and \( g - Ic \) color at \( T = 5 \). The abscissa represents the phase of an early superhump, and its origin shows the phase of the early superhump minimum.

Figure 8 is the same as figure 7, but for ordinary superhumps. The left and right panels represent the observations at \( T = 10 \) and 14, respectively. The filled squares and open circles represent \( V\)-band mag and \( V - J \) color, respectively. The abscissa represents the phase of superhump, and its origin shows the phase of the superhump minimum.

bluest before the superhump maximum. Thus, the color behaviors were different from that of early superhumps; the hump component was red in the early superhump, while it was blue in the ordinary superhump.

In order to study the temperature variation of the superhump light source from our data, we should know the structure of emitting sources. Early and ordinary superhump light sources have been considered to be located at an outer part of the accretion disk (Warner, O’Donoghue 1988; Osaki, Meyer 2002; Kato 2002). The inner part of the disk, on the other hand, probably remains non-variable even during the humps. The observed flux can, hence, be a superposition of the light from the hump component in the outer disk and the non-variable component in the inner disk. It might be better that we use an SED model including both the hump and non-variable components. As mentioned in subsection 3.2, on the other hand, it is difficult for our data to resolve both components without any assumptions. In this section, we present an analysis using a simple model, the same as in subsection 3.2: the blackbody and the \( 10^5 \) K free-free emission model. In other words, we regard the hump source as an entire disk in this section. We also performed an analysis using the model with both components, while the results depended on several assumptions for the non-variable component. It is presented in subsection 4.1.

The analysis of SED required simultaneous 6-band photometric data with high quality through a few hours of one night. We had four-night data at \( T = 5, 7, 8 \), and 14 which could be used for our SED analysis.

Figure 9 shows the temporal variation of the parameters of our SED model associated with early and ordinary superhumps. The top panels show the observed \( V\)-band light curves. The middle and bottom panels show the estimated temperature and the size of the blackbody emission region, respectively. Panels (a), (b), (c), and (d) represent the results at \( T = 5, 7, 8 \), and 14, respectively.

Figure 9a shows the result for the early superhump. At the early superhump minimum (phase \( \sim 0.00 \)), the temperature was highest and the emitting size was smallest. The light curve correlates well with the emitting size. This
Fig. 9. Temporal variation of the best-fitted parameters of the blackbody emission associated with early and ordinary superhumps. The top panels show the observed V-band light curves. The middle and bottom panels show the estimated temperature and the size of blackbody emission region, respectively. The emitting size was normalized at the phase of the minimum. The abscissa represents the phase of the humps. Panels (a), (b), (c), and (d) represent the results at $T = 5$, 7, 8, and 14, respectively.

suggests that the nature of early superhumps is the apparent expansion of a low temperature region.

Figure 9d shows the result for the ordinary superhump. From the superhump minimum (phase $\sim 0.00$), the temperature and the brightness increase, while the emitting size decreases. The temperature maximum precedes the superhump, and the superhump reaches maximum after the temperature starts to decline. After the superhump maximum, the object fades, first by a decrease in the temperature, and then by a decrease of the size.

The accretion disk is believed to be deformed to a precessing eccentric disk when superhumps are observed. Due to the orbital motion of the secondary star, the eccentric disk is periodically heated by a strong tidal torque, making superhumps. The early phase of the superhump (phase $\sim 0.00$ -- 0.15) in figure 9d probably corresponds to the phase that the disk temperature increased due to a viscous heating effect. After the heating stopped, the object entered an expansion--cooling phase. It was probably an outward expansion of the disk as a result of angular-momentum transported from the heated area.

Figure 9b and 9c show short-term modulations during the transition phase from the early to ordinary superhump phase. They have small amplitudes and double-peaked profiles. We can see a hint of two cycles of the heating and expansion-cooling process associated with the primary and secondary maximum in those panels. Their behavior is not similar to that of the early superhump, but rather is similar to that of the ordinary superhump. The early superhump signal may have already been quite weak at $T = 7$ and 8.

Figure 10 shows the temporal variation of the emitting size against the temperature of the blackbody emission. Panels (a), (b), (c), and (d) represent the results on $T = 5$, 7, 8, and 14, respectively. Panel (a) shows the result for the early superhump. First (phase $0.00$), the temperature is high, and then gradually declines as the emission size increase. Both the emitting size and the temperature increase in phase $\sim 0.40$. We note that heating--expanding feature is only seen in panel (a). After phase $0.70$ in panel (a), the object returns to the point of phase $0.00$ on a similar track to phase $0.00$--$0.30$. In the case of the superhump shown in panel (d), the disk is first heated and shrunk. After the temperature reaches the maximum, the object starts rapid cooling and expansion until phase $0.35$. This “V”-shaped track suggests a process with viscous heating and cooling by expansion. Such a “V”-shaped pattern is not seen in the track of early superhumps. In panels (b) and (c), two cycles of the heating and cooling process are indicated by the two “V”-shaped patterns around phase $0.20$ and $0.65$ in panel (b) and phase $0.05$ and $0.65$ in panel (c).

4. Discussion

4.1. Contribution of the Non-Variable Component from an Inner Part of the Accretion Disk

In subsection 3.4, we analyzed the SEDs, while assuming that the hump component is the entire disk. We also
We, hence, make further assumptions for the SED model of the non-variable component. We assumed the SED to be determined. The most simple way is to define the SED of the non-variable component as the observed SED at the hump minimum. In the case of the 80% contribution model, the observed SED at the hump minimum is the possible upper-limit of the hump minimum. The long dashed line in the left panel shows the observed SED. The long dashed, short dashed, and dotted lines denote the best-fitted model with 80% and 40% of the flux of the best-fitted model, respectively. The latter two models were used as the non-variable component in § 4.1 (for detail, see the text). The right panel shows the SED of the hump component in the case that the non-variable component is the 40% model. The long dashed, short dashed, and dotted lines denote the best-fitted model, its blackbody and free-free components, respectively. In the upper frames of each panel, the abscissa and ordinate denote the wavelength and flux, respectively. The errors of each point are smaller than the symbols. The lower frames show the ratio of the observed flux to the model.

Fig. 10. Temporal variation of the emitting size against the temperature of the blackbody emission. The abscissa and ordinate denote the blackbody temperature and the emitting size shown in figure 9, respectively. Typical errors of each point are shown at the upper-right corner of each panel. Panels (a), (b), (c), and (d) represent the results at $T = 5$, 7, 8, and 14, respectively. The numbers represent the hump phase.

Fig. 11. Example of the SEDs of the total flux and the hump component at $T = 5$ at the $g'$-band hump minimum. In the left panel, the filled circles show the observed SED. The long dashed, short dashed, and dotted lines denote the best-fitted model for the observed SED, 80% and 40% of the flux of the best-fitted model, respectively. The latter two models were used as the non-variable component in § 4.1 (for detail, see the text). The right panel shows the SED of the hump component in the case that the non-variable component is the 40% model. The long dashed, short dashed, and dotted lines denote the best-fitted model, its blackbody and free-free components, respectively. In the upper frames of each panel, the abscissa and ordinate denote the wavelength and flux, respectively. The errors of each point are smaller than the symbols. The lower frames show the ratio of the observed flux to the model.

analyzed the SEDs with a model including a non-variable component and discuss in this section how it changes the results.

We consider that the observed flux is a sum of the flux from the hump and the non-variable components. The SEDs of both components were assumed to be reproduced by the combination model of blackbody and $10^5$ K free-free emission, as used in the last sections. We could not, however, significantly determine all parameters of both components using the 6-band photometric data. We, hence, make further assumptions for the SED model of the non-variable component. The flux ratio of the hump to the non-variable components is, in particular, difficult to be determined. The most simple way is to define the flux of the non-variable component as the observed flux at the hump minimum. The flux ratio of the hump to the non-variable components is, in particular, difficult to be determined. The most simple way is to define the flux of the non-variable component as the observed flux at the hump minimum. The left panel of figure 11 shows the observed SEDs at the $g'$-band hump minimum at $T = 5$. The long dashed line indicates the best-fitted model. If we assume the SED defined by this long dashed line to be a non-variable component, it means that the flux contribution from the hump source is 0% at the hump minimum. It is, however, possible that the hump source had a significant contribution to the observed flux even at the hump minimum. The long dashed line in the left panel of figure 11 is, thereby, the possible upper-limit of the flux from the non-variable component. In the figure, we also show the model with 80% and 40% of the flux of the best-fitted model at the hump minimum, as indicated by the short dashed and the dotted lines. We used the 80 and 40% models as the non-variable component in our analysis. The right panel of figure 11 shows the SED of the hump component calculated by the subtraction of the SED of the non-variable component (the 40% model; the dotted line in the left panel) from the observed SED. As can be seen from the figure, the model well reproduces the SED of the hump component. Under those assumptions, we finally obtained the temperature and the emitting size of the blackbody emission region of the hump component.

Figure 12 shows the temporal variation of the model parameters of the blackbody emission for the hump component. The top, middle, and bottom panels show the same as figure 9. The filled squares, circles and triangles in the middle and bottom panels represent the results in the case that the non-variable component contributes 0%, 40%, and 80% of the flux at the $g'$-band hump minimum, respectively. The result from the 0% model corresponds to that reported in subsection 3.4. The left and right panels show the results of the early superhump at $T = 5$ and the ordinary superhump at $T = 14$, respectively.

In the case that the contribution of the non-variable component is large, the variation amplitudes of the parameters are large. This can naturally be understood because the observed SED variation must be reproduced by the flux from a small contribution of the hump component. Except for the variation amplitude, the temporal behaviors of the parameters are qualitatively almost the same in all cases, independent of the contribution of the non-variable component.

The size of the blackbody emission expands > 3 times from the hump minimum in the case of the 80% contri-
distribution model both in the early and ordinary superhumps. Early superhumps are proposed to be variations caused by the vertical deformation in the disk (Kato 2002). In this case, we can estimate the height, $h$, at the outermost region of the disk which is required to explain the >3 times expansion of the apparent emitting area. We consider that we see a flat part $(h=0)$ of the disk at an inclination angle of $75^\circ$ at the hump minimum and a vertically-expanded part at the hump maximum (Araujo-Betancor et al. 2005). We calculated the height to be $h > 1.1r$ at the hump maximum where $r$ is a disk radius. This height is, however, too large to be explained within the framework of the standard accretion disk model $(h \sim 0.1r$; Shakura, Syunyaev 1973). The 0% contribution model yields $h \sim 0.18r$, which is still slightly larger than that expected from the standard model. These results indicate that the contribution of the non-variable component in the inner disk should be small in the optical–infrared regime. In other words, the hump source significantly contributes even at the hump minimum.

4.2. Implication of the Remnant Hot Disk in Echo Outbursts

Some WZ Sge-type dwarf novae experienced echo outbursts after the main superoutburst (Kato et al. 2004). The echo outburst can be triggered if a substantial amount of gas is left at the outermost part of the disk even after the main outburst and works as a mass reservoir (Kato et al. 1998; Kato et al. 2004; Hellier 2001; Osaki et al. 2001). V455 And showed no echo outburst, while our analysis revealed an intriguing feature just after the superoutburst. As reported in subsection 3.2, the blackbody emission remained at a moderately high temperature for 10–20 days after the superoutburst. That period corresponds to the period in which echo outbursts are observed in the other WZ Sge stars. The strong contribution of the blackbody emission indicates the presence of a luminous accretion disk, in other words, a substantial amount of the gas remains even after the outburst. The remnant disk with the moderately high temperature can, therefore, be a sign of the expected mass reservoir. V455 And showed no echo outburst, possibly because the amount of the remnant gas was not enough to trigger an echo outburst.

Hameury et al. (2000) suggests that an echo outburst is caused by an enhanced mass-transfer rate from the secondary. In this case, we can expect a high luminosity of the hot spot just after the outburst, and hence a high contribution of the free-free emission from the hot spot to the observed SED. The contribution from the hot spot should then decrease after the echo outburst phase. Figure 4 indicates that the contribution of the free-free emission keeps a gradual increase for $T = 0–40$, and then becomes saturated after $T \sim 40$, without showing the decrease as expected from the enhanced mass-transfer scenario. Thus, no sign of the enhanced mass-transfer rate was confirmed in our data.

After $T \sim 40$, the temperature and the size of the blackbody emission region remains constant. Araujo-Betancor et al. (2005) estimates that the surface temperature of the white dwarf in V455 And is $\sim 10500$ K at quiescence, which is close to the estimated temperature after $T \sim 40$. We propose that the blackbody emission after $T \sim 40$ originated from the white dwarf, which becomes a dominant source in the blue part of the SED due to a weakening of the disk emission.

4.3. The Origin of the Early Superhump

Our SED analysis showed that the early superhump light source is an expanded low-temperature component. The site and the direction of the expansion are, however, unclear only in our analysis. Early superhumps are considered to be caused by a rotational effect of the accretion disk in which a part of the disk vertically expands (Kato 2002). According to the standard disk model, the temperature of the disk is lower in an outer region. Our result in subsection 3.4, hence, indicates that a part of the outer region in the disk is vertically expanded. The vertical expansion may be caused by scenarios proposed by Kato (2002) and Osaki, Meyer (2002). These models need to be re-examined to explain the color behavior associated with the early superhumps of V455 And which were observed for the first time in WZ Sge stars.

4.4. Temperature of Superhump: Observations and Theories

In subsections 3.4 and 4.1, we reported the temperature variation associated with the superhumps. There have...
been only few observations that provide the superhump temperature based on multi-band photometry. Hassall (1985) observed the superoutburst of EK TrA, and reported that the superhump light-source has a temperature of \( \sim 5700 \, \text{K} \). The color at the superhump maximum was redder than that at the hump minimum. Naylor et al. (1987) reported a similar result for OY Car, proposing a redder than that at the hump minimum. Naylor et al. of (1985) observed the superoutburst of EK TrA, and re-
ported that the superhump temperature should be quite high in order to reproduce the observed superhump amplitude. The superhump temperature is then predicted to be \( \gtrsim 15000 \, \text{K} \). In this case, the color at the hump maximum should be bluer than that at the minimum.

Our observation showed that the object reached the hump maximum after the heating phase ended, and the subsequent expansion started. Smak (2005) only discuss the heating phase of superhumps. The temperature at the hump maximum can, however, be lower than that at the temperature maximum. The apparently low-temperature superhumps reported in Hassall (1985) and Naylor et al. (1987) can be explained by a strong contribution of the expanded low-temperature region. In Smak (2005), an estimation of the temperature at the superhump light source was performed with a superhump amplitude of 0.2–0.3 mag. In the case of V455 And, the amplitude of the hump was so small (\( \sim 0.03 \, \text{mag} \)) during the heating phase that the superhump light source could avoid to take a quite high temperature. The discrepancy between the observed and theoretically expected temperatures can thus be reconciled in our results.

We note, however, that the color behavior associated with superhumps has not been established. As also commented in Smak (2005), there are several reports that systems become bluest at the superhump maximum (Schoembs, Vogt 1980; Stolz, Schoembs 1984). Such results are inconsistent with the observed color behavior in V455 And. It is possible that WZ Sge stars have a different structure of the superhump light source compared with ordinary SU UMa stars. Thus, it is premature to conclude that the color behavior observed in V455 And is common to all SU UMa stars.

5. Summary

We performed photometric observations of the 2007 superoutburst of V455 And. Our 6-band simultaneous observations allowed us to investigate the temporal variation of the temperature and the size of the emitting region associated with the superoutburst, early, and ordinary superhumps. We summarize our findings below.

- The optical emission was dominated by blackbody radiation from the accretion disk during the superoutburst, while small excesses were found in the observed flux in the near-infrared region.
- V455 And showed no echo outburst after the superoutburst. The temperature of the accretion disk rapidly declined at the same time when the object entered a rapid fading phase. The temperature decline then stopped at \( \sim 8000 \, \text{K} \). The size of the emitting region, on the other hand, kept a gradual decline. It indicates that the optically thick disk remained at a moderately high temperature even after the superoutburst. We propose that it is a sign of a mass reservoir that can trigger echo outbursts.
- A heating and a subsequent expansion-cooling processes were associated with the rising phase of superhumps. The temperature maximum preceded the superhump maximum. It indicates that the object reached the superhump maximum by the expansion of a low temperature region after the heating phase ended.
- In a cycle of early superhumps, the object was bluest at the hump minimum. This indicates that the temperature of the early superhump light source is lower than that of an underlying component. The early superhump light source is probably a low-temperature, vertically expanded region at the outermost part of the disk.

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