CI Aquilae: a recurrent nova with an unusually long plateau phase

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ABSTRACT
We present the results of optical photometry of the recurrent nova CI Aql in a later phase of the outburst which occurred in 2000. Our observation revealed that the object reached the quiescent level between 2001 December and 2002 April, and therefore that CI Aql is a unique recurrent nova characterized by an extremely long (1.4–1.7 yr) plateau phase. The light curve obtained in the outburst suggests that the object is the first example of an intermediate between classical and recurrent novae. In comparison with the estimation given in published theoretical calculations, the long duration of the plateau phase supports a higher hydrogen content of the white dwarf envelope, whereas such an abundance of hydrogen requires a later cessation of the wind, which is in disagreement with the sudden fading observed in late November of 2000. The light curve obtained in the later phase of the outburst indicates that the object was fainter and the gradual decline was steeper than predicted. These discrepancies between the observation and the theoretical prediction demand a drastic modification of the present model of CI Aql.

Key words: accretion, accretion discs – stars: individual: CI Aql – novae, cataclysmic variables.

1 INTRODUCTION
Recurrent novae are a subclass of cataclysmic variables (CVs) that are binary systems which contain a white dwarf as an accretor and a mass-donor star that fills its Roche lobe. Non-magnetic CVs are generally classified into novae, novalike variables, and dwarf novae (e.g. Warner 1995, for a review). Novae are CVs showing outbursts due to thermonuclear runaway on the surface of the accreting white dwarf, and are classified into two types: classical novae and recurrent novae. The former are novae with single outburst detections, and the latter have a multiple record of outbursts. At present, about 300 novae, comprising about 30 per cent of CVs, are classified (Downes et al. 2001), and only 10 recurrent novae are known to be among them.

Differences between classical and recurrent novae principally result from a significant difference in mass of the accretor. White dwarfs in recurrent novae are believed to be massive compared with those in classical novae (e.g. Starrfield, Sparks & Shaviv 1988; Kahanuka et al. 1999; Hachisu et al. 2000; Thoroughgood et al. 2001; Hachisu & Kato 2001b). Such a condition produces frequent nova explosions for recurrent novae, which occur in shorter recurrence intervals (10–100 yr) compared with those for classical novae (≥10⁴ yr). A recurrent nova generally shows a faster decline from its outburst, which mainly depends on the mass of the accretor and its envelope mass at an eruption. In contrast, white dwarfs in classical novae are believed to have moderate masses and accumulate hydrogen-rich matter much slower than in recurrent novae. As a result, a part of the hydrogen diffuses into a white dwarf of a classical nova before an ignition so that a surface layer of the white dwarf is highly dredged-up into the hydrogen-rich envelope and blown off in the outburst wind (e.g. Prinilnik 1986; Kato & Hachisu 1994). This is consistent with the spectra of ejecta observed in outbursts of classical novae which show heavy elements such as carbon, oxygen, and neon, and thus outbursts of a classical nova provide a gradual erosion for the white dwarf. On the other hand, ejecta observed in outbursts of recurrent novae are not enriched by such metals, i.e. massive white dwarfs in those systems are not eroded. Hence, in recurrent novae, the white dwarfs probably increase mass toward the Chandrasekhar limit and are possibly fated to be Type Ia supernovae (Nomoto, Thielemann & Yokoi 1984; Nomoto & Kondo 1991).

The recurrent nova CI Aql was originally recorded as a possible nova in 1917 (Reinmuth 1925). Lack of detailed information on that event had unfortunately left the nature of the object unresolved for a long time. The object is a peculiar eclipsing binary system showing a 0.6-mag depth of primary eclipse with an orbital period of 0.618 355 d (Mennickent & Honeycutt 1995). The optical spectrum in quiescence shows more highly excited emission features of Hπ.

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See also http://icarus.stsci.edu/%7Edownes/cvcat/
and C iii–N iii complex on a reddened continuum, while all Balmer lines are detected as absorption lines (Greiner, Alcana & Wenzel 1996). Such absorption features generally imply non-CV nature, and the original ‘suspected CV’ classification (Duerbeck 1987) had almost been disregarded. However, CI Aql underwent the second-recorded outburst in 2000 April (Takamizawa, Kato & Yamamoto 2000), and spectroscopic observations revealed that the object is surely a recurrent nova (e.g. Uemura & Kato 2000; Kiss et al. 2001; Burlak & Esirov 2001). An optical light curve for the early part of the outburst was presented and discussed in Matsumoto et al. (2001). We have made a photometric observation of the object in 2001 and 2002 which revealed an unexpected late evolution of the outburst.

2 OBSERVATION AND DATA REDUCTION

The photometric observations were conducted on 27 nights between 2001 March 15 and 2002 October 9 at three sites; the Ouda station and the rooftop of the Department of Astronomy, Kyoto University, and the Bisei Astronomical Observatory (Table 1).

The Ouda observations were made by using an STe SI004AB CCD chip (PixelVision) attached to a Ritchey–Chretien Cassegrain telescope with a 60-cm aperture. An Rc filter was applied, and we made multicolour photometry in B, V, Rc, and Ic–bands on March 15 (Table 2). The exposure time was set to 30 s on March 15, and June 7 and 8. On March 19, the exposure time was varied from 15–60 s depending on sky conditions. The data reduction and analysis for which we used aperture photometry were performed using IRAF.2

The Kyoto observations were made by using SBIG ST-7 and ST-16IE CCD cameras attached to Schmidt–Cassegrain telescopes with 25- and 30-cm apertures (Meade LX-200). No filter was applied, and exposure time was set to 30 s. The data reduction and analysis for which we used point-spread function (PSF) photometry were performed by a Java-based aperture and PSF photometry package developed by one of the authors (TK).

The Bisei observation was made by using Mutoh CV-16II and CV-16IE CCD cameras attached to a classical Cassegrain telescope with a 101-cm aperture. An Rc filter was applied, and exposure time was set to 30 s. The data reduction and analysis for which we used aperture photometry were performed using IRAF.

The brightness of the object was determined relative to a local comparison star and a check star that confirmed the constancy of the comparison star. Those stars were GSC 5114.149 and GSC 5114.584 in the Ouda and Kyoto observations, and USNO 0825.13270569 and GSC 5114.247 in the Bisei observation. We used A. Henden’s photometric sequence for the observed field.3 Magnitudes obtained in the Kyoto observations correspond to those in Rc, according to sensitivities of the CCD chips.

3 REMARKABLY LONG PLATEAU STAGE

Table 2. A multicolour magnitude of CI Aql on 2001 March 15, which was obtained within a duration of orbital phase of 0.86–0.87.

<table>
<thead>
<tr>
<th>Mag</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>15.80</td>
</tr>
<tr>
<td>V</td>
<td>14.81</td>
</tr>
<tr>
<td>Rc</td>
<td>14.24</td>
</tr>
<tr>
<td>Ic</td>
<td>13.53</td>
</tr>
</tbody>
</table>

CI Aquilae: a recurrent nova

Fig. 1 shows an optical light curve of CI Aql for 2 yr after the second recorded eruption in 2000. The light curve consists of the early part of the outburst described in Matsumoto et al. (2001) and the present results given in Tables 1 and 2 (Rc only). It is noted that the data on 2001 February 16, March 9, and April 30 are excluded from Table 1, because they were already presented in Matsumoto et al. (2001).

The light curve indicates that the object kept a gradual decline of about 1 mag/200 d (plateau phase) since a sudden fading and recovery observed in late November of 2000 (around JD 2451870), after which the object became systematically about 0.5 mag fainter. On 2001 May 16, the object was observed to be somewhat fainter in the gradual decline, which was very probably due to a primary eclipse of the binary system (Table 1).

Szkody (1994) reported mv = 16.22 and 1 − R = 0.68 for the object in the previous quiescence. This estimation is in agreement with an independent record made by the RoboScope between 1995–1996, which shows a mv = 16.1–16.7 orbital variation with

Table 1. Log of the photometric observation. The orbital phase coverage, represented by ϕ, are based on the ephemeris given in Mennickent & Honeycutt (1995).

<table>
<thead>
<tr>
<th>Date</th>
<th>HJD (−450000.0)</th>
<th>Error</th>
<th>ϕ</th>
<th>Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2001)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mar. 15</td>
<td>1984.305–1984.317</td>
<td>0.03</td>
<td>0.86–0.87</td>
<td>O</td>
</tr>
<tr>
<td>19</td>
<td>1988.272–1988.343</td>
<td>0.03</td>
<td>0.26–0.38</td>
<td>O</td>
</tr>
<tr>
<td>May 4</td>
<td>2004.274–2004.288</td>
<td>0.33</td>
<td>0.66–0.68</td>
<td>K</td>
</tr>
<tr>
<td>16</td>
<td>2046.290–2046.306</td>
<td>0.26</td>
<td>0.09–0.11</td>
<td>K</td>
</tr>
<tr>
<td>25</td>
<td>2055.265–2055.291</td>
<td>0.17</td>
<td>0.60–0.64</td>
<td>K</td>
</tr>
<tr>
<td>28</td>
<td>2058.255–2058.278</td>
<td>0.10</td>
<td>0.44–0.47</td>
<td>K</td>
</tr>
<tr>
<td>31</td>
<td>2061.275–2061.302</td>
<td>0.30</td>
<td>0.32–0.36</td>
<td>K</td>
</tr>
<tr>
<td>Jun. 7</td>
<td>2068.189–2068.200</td>
<td>0.08</td>
<td>0.50–0.52</td>
<td>O</td>
</tr>
<tr>
<td>8</td>
<td>2069.252–2069.265</td>
<td>0.17</td>
<td>0.22–0.24</td>
<td>O</td>
</tr>
<tr>
<td>12</td>
<td>2073.287–2073.291</td>
<td>0.11</td>
<td>0.75–0.75</td>
<td>K</td>
</tr>
<tr>
<td>Jul. 1</td>
<td>2092.282–2092.292</td>
<td>0.28</td>
<td>0.47–0.48</td>
<td>K</td>
</tr>
<tr>
<td>19</td>
<td>2110.216–2110.226</td>
<td>0.13</td>
<td>0.47–0.48</td>
<td>K</td>
</tr>
<tr>
<td>20</td>
<td>2118.214–2118.228</td>
<td>0.42</td>
<td>0.40–0.42</td>
<td>K</td>
</tr>
<tr>
<td>23</td>
<td>2121.156–2121.173</td>
<td>0.25</td>
<td>0.16–0.19</td>
<td>K</td>
</tr>
<tr>
<td>Aug. 4</td>
<td>2126.223–2126.227</td>
<td>0.58</td>
<td>0.35–0.36</td>
<td>K</td>
</tr>
<tr>
<td>11</td>
<td>2133.083–2133.097</td>
<td>0.09</td>
<td>0.45–0.47</td>
<td>K</td>
</tr>
<tr>
<td>14</td>
<td>2136.181–2136.196</td>
<td>0.11</td>
<td>0.46–0.48</td>
<td>K</td>
</tr>
<tr>
<td>23</td>
<td>2144.987–2144.996</td>
<td>0.11</td>
<td>0.70–0.71</td>
<td>K</td>
</tr>
<tr>
<td>Sep. 1</td>
<td>2154.010–2154.030</td>
<td>0.19</td>
<td>0.29–0.32</td>
<td>K</td>
</tr>
<tr>
<td>17</td>
<td>2170.094–2170.105</td>
<td>0.45</td>
<td>0.30–0.32</td>
<td>K</td>
</tr>
<tr>
<td>Oct. 11</td>
<td>2194.021–2194.029</td>
<td>0.39</td>
<td>0.00–0.01</td>
<td>K</td>
</tr>
<tr>
<td>Dec. 4</td>
<td>2247.885–2247.893</td>
<td>0.29</td>
<td>0.11–0.12</td>
<td>K</td>
</tr>
<tr>
<td>(2002)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr. 5</td>
<td>2370.320–2370.331</td>
<td>0.30</td>
<td>0.11–0.12</td>
<td>K</td>
</tr>
<tr>
<td>Jun. 14</td>
<td>2440.150–2440.159</td>
<td>0.18</td>
<td>0.03–0.05</td>
<td>B</td>
</tr>
<tr>
<td>Aug. 26</td>
<td>2513.089–2513.117</td>
<td>0.10</td>
<td>0.98–0.02</td>
<td>B</td>
</tr>
<tr>
<td>Oct. 9</td>
<td>2556.933–2556.961</td>
<td>0.04</td>
<td>0.88–0.93</td>
<td>B</td>
</tr>
</tbody>
</table>
The optical light curve of the 2000 outburst of CI Aql is shown. The horizontal dashed line represents the expected quiescent level at outside of the eclipse.

typical accuracy of about 0.1 mag (Honeycutt, private communication⁴). Thus, in the quiescence it is expected that CI Aql is $m_r \sim 15.4$ and $\sim 16.0$ mag on the outside and at the minimum of a primary eclipse, respectively, with an assumptively constant $V - R = 0.68$ obtained outside an eclipse. The validity of that quiescent level is also supported by identifications for the object in records of POSS II (GSC2 S30213319926: $m_F = 15.79$, $m_V = 16.05$) and USNO (USNO 0825.13277160: $m_{red} = 15.7$, $m_{blue} = 16.8$). As seen in Fig. 1, the object was significantly brighter than the quiescent level in 2001.

The observation from 2001 October 11 indicates that the object was about 15.44 mag, which is comparable to the quiescent level. The orbital phase of the binary system was 0.0–0.01 at the observation, i.e. the timing corresponded to a minimum of the primary eclipse. Hence, assuming a 0.5–0.6 mag depth of the primary eclipse, the brightness observed on October 11 was consistent with the declining trendline, and we can conclude that CI Aql had still not reached quiescence at around JD 2452200. The next data point, from 2001 December 4, again demonstrates the same state of the object: the object was brighter than the quiescent level, whereas the orbital phase of the object was 0.11–0.12, i.e. in the middle of the egress.

In the observation made on 2002 April 5, however, we found that the object was 15.92 mag, which was not only considerably fainter than in 2001, but also $\sim 0.4$ mag fainter than the expected quiescent level. The orbital phase was 0.11–0.12 in the observation, and the magnitude expected for outside the primary eclipse on that occasion is very consistent with the quiescent level. Thus, we conclude that CI Aql was not in quiescence at least prior to 2001 December 4 and reached the quiescence prior to 2002 April 5, after the plateau phase which continued for an acceptable range of 510–630 d. This result is very consistent with the result given in Lederle & Kimeswenger (2001), and our observations made on 2002 June 14, August 26 and October 9 confirm the conclusion.

⁴It has been pointed out that the photometric $V$-magnitudes in 1991–1995 presented in fig. 1 of Mennickent & Honeycutt (1995) is insecure due to an unknown zero-point in their photometric calibration.

4 POSSIBLE NEW CLASS OF RECURRENT NOVAE

4.1 Distinctive properties

Most recurrent novae except T Pyx had been known as very fast novae which decline with $t_3 \sim 10$ d and completely fade to quiescence within several months in nova-outbursts. T Pyx is an exceptional recurrent nova; it has the shortest orbital period, 1.8 h (Schaefer et al. 1992), and it probably consists of a dwarf companion as the mass donor. The rest of the recurrent novae are divided into two subclasses; the RS Oph-type and the U Sco-type, which probably contain a red giant and a slightly evolved main-sequence star as mass donors, respectively (Hachisu & Kato 2001b). CI Aql apparently belongs to the latter, based on the orbital period, and the extremely long decline of $t_3 \sim 35$ d makes the object a peculiar member of the subclass (Matsumoto et al. 2001). Such a slower decline suggests a smaller mass of the white dwarf of CI Aql compared with those of other recurrent novae. This nature is also supported by the long duration of the plateau phase and the longest recurrence interval, 83 yr, in recurrent novae. Similar characteristics have been found in a recurrent nova IM Nor in the 2002 outburst: a slow decline of $t_3 \sim 50$ d and a recurrence interval of 82 yr are comparable to those of CI Aql⁵ (Kato et al. 2002). All recurrence intervals in recurrent novae except CI Aql and IM Nor are a few decades, which makes those novae easier to be detected as recurrent objects, and therefore most of them are suspected to contain extremely massive white dwarfs near the Chandrasekhar limit (e.g. Hachisu et al. 2000; Hachisu & Kato 2000, 2001b). Outbursts of classical novae are observed only once for each, as intervals of $\geq 10^4$ yr for outbursts are longer than the human history. Hence CI Aql is probably the recurrent nova closest to classical novae we have known.

The recorded amplitude of the 2000 outburst of CI Aql is approximately 7.5 mag, as depicted in the light curve, assuming that the maximum occurred on 2000 May 1. This amplitude is reasonable for an outburst of a recurrent nova ($\sim 8–11$ mag), and is significantly smaller than that of a classical nova (typically $9–14$ mag). However, as pointed out in Matsumoto et al. (2001), the exact occasion of the maximum is possibly uncertain, i.e. a brighter maximum which had occurred between 2000 April 11 and 30 is still possible. In recurrent novae, a dispersion of about 3 mag is seen in the distribution of amplitudes of outbursts, which can be interpreted as an effect of a correlation between absolute magnitudes and inclination angles for novae (Warner 1986). Larger outbursts with amplitudes of $\geq 10$ mag are observed in V394 CrA, IM Nor, U Sco and V745 Sco, and these objects are known or suspected to be binary systems with higher inclination angles in recurrent novae (e.g. Schaefer 1990; Hachisu & Kato 2000; Hachisu et al. 2000; Hachisu & Kato 2001b; Kato et al. 2002). The orbital light curve of CI Aql shows deep eclipses, strongly suggesting a higher inclination angle. This permits the possibility of a roughly 3-mag brighter maximum for the 2000 outburst of CI Aql; otherwise the object is a recurrent nova with an exceptionally smaller-amplitude outburst. If the maximum indeed occurred at about the middle of 2000 April, and if the 1917 outburst had been missed, the 2000 outburst of CI Aql might have been indistinguishable from a typical outburst of a classical nova.

In conclusion, these characteristics of CI Aql observed in the 2000 outburst indicate that this object is a recurrent nova that has

⁵As significant variations were superimposed on the decline of the 2000 outburst of CI Aql, the $t_3$ of the object is possibly larger than the value described above (see fig. 3 of Kato et al. 2002).
resemblances to classical novae in many aspects. We have found a recurrent nova showing a significantly slower evolution of an outburst which is probably attributable to a smaller-mass white dwarf. CI Aql is a very suggestive system of the first case of an intermediate between classical and recurrent novae.

4.2 Incompatibility with the current model

The 2000 outburst of CI Aql was theoretically modelled in Hachisu & Kato (2001a, 2002) by means of light curve analyses. Although the calculations well reproduced the observed light curve in the early part of the outburst prior to the plateau phase, the reproduction of the later phase suffered from an uncertainty in the duration of the plateau phase.

A principal discrepancy is that the observed duration of the plateau phase is evidently longer than the expectations. The light curves for the early parts of the outbursts in 1917 and 2000, providing decline rates of the fades from the eruptions (Williams 2000; Matsumoto et al. 2001), seem to tightly constrain a mass of the white dwarf to approximately 1.2\(M_\odot\). This is especially clear in the 1917 outburst which was reproduced with a hydrogen content of \(X = 0.7\) (Hachisu & Kato 2001a). As for the latter part of the 2000 outburst, the solution with \(X = 0.70\) is apparently suitable for the observed duration of the plateau phase. Hence a preferable situation is likely such a higher hydrogen content in the white-dwarf envelope of CI Aql. In this case, a major problem should be solved is a discrepancy on the occasion of the wind-stop which was observed in late November of 2001 as a drop and prompt recovery of the brightness. That sudden event is the most significant decline seen in the plateau phase and is therefore plausibly attributed to the wind-stop, which is the reason why helium-enriched cases for the white-dwarf envelope were considered in Hachisu & Kato (2001a, 2002), and no other explanation for the event has been proposed at present.

In the plateau phase, the object was predicted to exhibit a supersoft X-ray emissivity as a consequence of hydrogen burning on the surface of the white dwarf (Hachisu & Kato 2001a, 2002). In the 1999 outburst of a recurrent nova U Sco, supersoft X-ray was detected from that object in the plateau phase (Kahabka et al. 1999). The supersoft X-ray phase had been predicted by a theoretical model of hydrogen-burning surfaces of white dwarfs for recurrent novae (Kato 1996). Matsumoto, Kato & Hachisu (2003) obtained a photometric evolution of the 1999 outburst, and an orbital-period change from which the mass-transfer rate during the previous quiescence between 1987 and 1999 was observationally estimated was detected in the light curve. These observations of U Sco were successfully explained by a consistent model based on the scheme for recurrent novae (Hachisu et al. 2000), and the physical parameters led U Sco to the most probable candidate of a progenitor system of a type Ia supernova.

The expected mass of the white dwarf of CI Aql is a reasonable value for a supersoft X-ray source (e.g. van den Heuvel et al. 1992), though a definite detection of supersoft X-ray has not been reported in the 2000 outburst. Such softer X-ray may be difficult to be detected if it exists, because of the higher interstellar reddening on the line of sight toward the object which is demonstrated by several optical observations (Mennickent & Honeycutt 1995; Greiner et al. 1996; Kiss et al. 2001; Burlak & Esipov 2001). The prediction for the supersoft X-ray phase is also supported by a similarity in the shape of the orbital modulation during the plateau phase compared with shapes observed in orbital light curves of known supersoft X-ray sources with higher inclination angles (Matsumoto et al. 2001).

At the end of the plateau phase, a termination of the hydrogen burning should involve a final fading after which the outburst completely ended. In Fig. 1 we can see that no significant change of the plateau state was observed, implying that the hydrogen burning probably continued at least until the beginning of 2002. As described above, if the occasion of the wind-stop is fixed, a longer duration of the supersoft X-ray phase is required to interpret the observed epoch for the end of the outburst.

Other discrepancies between the observation and calculation are the brightness and decline-rate of the object in the plateau phase. The former was inevitably caused by lack of secure observation published to be compared with calculations, as described in the footnote of Section 3, i.e. the reproduced brightness of the object is brighter than the observation in the plateau phase (e.g. the multicolour magnitudes from 2001 March 15 provide the differences). The decline rate observed in the plateau phase was about 1 mag/200 d. In contrast, the gradient of the reproduced light curve is too flat to fit the observed light curve for the case of \(X = 0.7\) which is suitable to explain the duration of the plateau phase. A revised model in Hachisu & Kato (2002) showed a better agreement for the decline rate, but it requires a termination of the hydrogen burning to reduce the brightness, which necessarily shortens the duration of the plateau phase in contradiction with the observation.

In conclusion, the duration of the plateau phase of the 2000 outburst suggests a higher hydrogen content of the white dwarf envelope for CI Aql based on the current model of recurrent nova. However, the detailed behaviour observed in the later phase of the present outburst is inconsistent with the published models, which demands their drastic modification.

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