IR Com: Deeply Eclipsing Dwarf Nova Below the Period Gap
— A Twin of HT Cas?

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Abstract

We observed an X-ray selected, deeply eclipsing cataclysmic variable IR Com (=S 10932). We detected an outburst occurring on 1996 January 1. The light curve of the outburst closely resembled that of a normal outburst of an SU UMa-type dwarf nova, rather than that of an intermediate polar. Time-resolved photometry during outburst showed that eclipses became systematically deeper and narrower as the outburst faded. Full-orbit light curves in quiescence showed little evidence of orbital humps or asymmetry of eclipses. In addition to the presence of high–low transitions in quiescence, the overall behavior of outbursts and characteristics of the eclipse profiles suggest that IR Com can be best understood as a twin of HT Cas, a famous eclipsing SU UMa-type dwarf nova with a number of peculiarities.

Key words: accretion, accretion disks — stars: novae, cataclysmic variables — stars: dwarf novae — stars: binaries: eclipsing — stars: individual (IR Comae Berenices)

1. Introduction

Cataclysmic variables (CVs) are close binary systems consisting of a white dwarf and a red dwarf secondary transferring matter via the Roche-lobe overflow. Dwarf novae are a class of CVs showing outbursts, which is believed to be a result of disk instabilities [cite.osa96reviewOsaki(1996)] for a review]. Eclipsing CVs, especially eclipsing dwarf novae, provide a wonderful tool for studying geometrically resolving structures of the accretion disk (e.g. 000 [cite.EclipseMappingHorne(1985)]).

IR Com (=S 10932) was first discovered as a ROSAT source, RX J1239.5+2108 = 1RXS J123930.6+210815, which was identified with a cataclysmic variable (000 [cite.cite.ric95ircomRichter, Greiner(1995)]. [cite.cite.ric95ircomRichter, Greiner(1995)]) reported that IR Com showed both high and low states, and occasional brightenings, which resembled the behavior of a possible intermediate polar (IP), V426 Oph (000 [cite.cite.wen95ircomWenzel, Splittergerber(1990)]. [cite.cite.wen95ircomWenzel et al.(1995)] further revealed that IR Com is an eclipsing CV with an orbital period of 0.08703 d. The period is just below the famous period gap in the distribution of orbital periods of CVs, in which the number density of CVs is markedly reduced (cf. 000 [cite.cite.RitterCVRitter, Kolb(1998)]. Although [cite.cite.wen95ircomWenzel et al.(1995)] noted that most of CVs with such a period are either SU UMa-type dwarf novae [for a recent review of SU UMa-type stars and their observational properties, see [cite.cite.war95suumaWarner(1995)]. [cite.cite.war95suumaWarner(1995)]], they rather regarded IR Com as an object of a possibly new class, which shows high–low state transitions as well as infrequent dwarf nova-like outbursts.

We noticed the similarity of properties of IR Com with those of HT Cas, a famous eclipsing SU UMa-type dwarf nova with a number of peculiarities, and started observing IR Com since 1996. On the very first night of our observation (1996 January 1), we detected IR Com in outburst (000 [cite.cite.kat96ircomalert306Kato(1996)]. The only known previous outbursts were in 1959 February and 1988 February (000 [cite.cite.ric97ircomRichter et al.(1997)].

2. Observations

The observations were carried out on 15 nights between 1996 January 1 and 1997 April 25, using a CCD camera (Thomson TH 7882, 576×384 pixels) attached to the Cassegrain focus of the 60 cm reflector (focal length=4.8 m) at Ouda Station, Kyoto University (000 [cite.cite.OudaOhtani et al.(1992)]. An on-chip summation of 2×2 pixels to one pixel was adopted. An inter-
ference filter was used which had been designed to reproduce the Johnson V band. The frames were first corrected for standard de-biasing and flat fielding, and were then processed by a microcomputer-based PSF photometry package developed by one of the authors (TK). The relative fluxes of the variable were determined using the common comparison stars. The constancy of the comparison stars during the observation was confirmed by using the common check stars GSC 1448.1951 (V = 15.24), and the first run on 1996 January 2 (BJD 2450085.180 – .265; BJD = Barycentric Julian Date) used BD +21° 2440 = GSC 1448.1508 (V = 9.11) for comparison stars. The constancy of the comparison stars during the observation was confirmed by using the common check star GSC 1448.2307 (V = 16.07).

Barycentric corrections to the observed times were applied before the following analysis. The log of observations is summarized in table 1.

3. Results and discussion

3.1. Outburst observation

Although our observation did not cover the pre-maximum phase of the 1996 January outburst, the object reached at least V = 14.0, and faded rapidly, reaching a rate of ~0.9 mag d⁻¹ (figure 1). This decay from the outburst is quite characteristic to that of normal outbursts of SU UMa-type dwarf novae, and unlike brief (usually < 1 d), rapidly fading “outbursts” of intermediate polars observed in TV Col (cite.fer89errorFernie(1989)) and EX Hya (cite.hel89exhyaHellier et al.(1989)). The present observation seems to preclude the IP-type interpretation of “outbursts” of IR Com, that was originally proposed by te(cite.ric97ircomRichter et al.(1997)) ([cite.ric97ircomRichter et al.(1997)]). No evidence of superhumps was detected.

IR Com is now established as one of rare eclipsing dwarf novae which show deep eclipses even during outbursts. Only a very limited number of such systems are known especially below the period gap (Z Cha, OY Car, HT Cas, V2051 Oph, DV UMa and IY UMa). Since most of dwarf novae below the period gap are known to be SU UMa-type dwarf novae, the new specimen of a deeply eclipsing dwarf nova below the period gap is expected to provide an important role in studying the effect of the tidal instability which is responsible for superoutbursts and superhumps. Since the mass-ratio (q = M₂/M₁) of this relatively long-period (0.08703 d) system is expected to lie close to the stability border of the tidal instability (000 [cite.wii88tidalWhitehurst(1988)]), the role of IR Com would be especially important in studying the tidal instability near the stability border.

3.2. Eclipse ephemeris

Our observation has established that IR Com shows deep eclipses even during outbursts (figure 1). We have determined mid-eclipse times by minimizing the dispersions of the eclipse light curves folded at the mid-eclipse times. The error of eclipse times were estimated using the Lafler-Kinman class of methods, as applied by te(cite.fer89errorFernie(1989)) ([cite.fer89errorFernie(1989)]). The validity of the estimated errors has been confirmed by two independent methods: 1) application to different ranges (in eclipse depth) of the data in order to test the effect of the potential asymmetry, and 2) application to the binned data of the first January 2 high-speed photometry run in order to test the effect of reduced time resolution. The tests have proven that the both effects did not significantly affect the estimated errors.

Table 2 summarizes the observed times of eclipses (labeled as “this work”), together with the published eclipse times reported by te(cite.ric97ircomRichter et al.(1997)) ([cite.ric97ircomRichter et al.(1997)]). The times from te(cite.ric97ircomRichter et al.(1997)) ([cite.ric97ircomRichter et al.(1997)]) have been converted into the BJD system, common to the present observation. The cycle count (E) follows the definition by te(cite.ric97ircomRichter et al.(1997)) ([cite.ric97ircomRichter et al.(1997)]).

Eclipses before E = −24 having been chance detections on photographic plates with long exposure times, we used

1 Readers, however, should bear in mind that te(cite.ric97ircomRichter et al.(1997)) ([cite.ric97ircomRichter et al.(1997)]) reported 25 s difference between their B and R observations. Although B-band observations are expected to more susceptible to the spatial distribution of high-temperature structure in the disk (e.g. bright spot), our observation may have suffered from a lesser degree of similar systematic errors. The error estimates should therefore be treated as a statistical measure of the observational errors.
Table 1. Log of observations.

| Date    | BJD*(start–end) | N† | Mag‡ | Error∥ | Exp§ |
|---------|-----------------|----|------|--------|------|
| 1996 Jan. 1 | 50084.331 – 50084.387 | 68 | 14.00 | 0.02   | 60   |
| 1996 Jan. 2 | 50085.180 – 50085.265 | 463 | 14.71 | 0.01   | 7–9  |
| 1996 Jan. 2 | 50085.270 – 50085.382 | 256 | 14.87 | 0.01   | 30   |
| 1996 Jan. 3 | 50086.159 – 50086.383 | 402 | 15.89 | 0.01   | 40   |
| 1996 Jan. 4 | 50087.265 – 50087.386 | 130 | 16.62 | 0.01   | 60   |
| 1996 Jan. 12 | 50095.225 – 50095.333 | 91  | 16.91 | 0.03   | 90   |
| 1996 Jan. 2 | 50096.184 – 50096.344 | 89  | 16.93 | 0.03   | 90   |
| 1996 Jan. 21 | 50104.272 – 50104.338 | 48  | 17.23 | 0.02   | 90   |
| 1996 Jan. 26 | 50109.229 – 50109.279 | 42  | 16.88 | 0.02   | 90   |
| 1996 Feb. 5 | 50113.216 – 50113.271 | 23  | 17.17 | 0.04   | 90   |
| 1996 Feb. 23 | 50119.302 – 50119.381 | 21  | 17.10 | 0.08   | 90   |
| 1996 Feb. 27 | 50141.086 – 50141.195 | 60  | 17.09 | 0.02   | 90   |
| 1996 Mar. 26 | 50169.114 – 50169.136 | 49  | 15.36 | 0.02   | 30   |
| 1997 Apr. 24 | 50563.148 – 50563.246 | 115 | 17.18 | 0.02   | 90   |
| 1997 Apr. 25 | 50564.158 – 50564.254 | 27  | 17.52 | 0.12   | 90   |

*BJD – 2400000.
†Number of frames.
‡Averaged V magnitude outside eclipses.
∥Standard error of the averaged magnitude.
§Exposure time (s).

eclipse times only after BJD 2449484 in determining the eclipse ephemeris. We first obtained a linear regression to all the data. After rejecting eclipse times having $|O – C| > 0.0005$ d ($E=0$, $3457$, $3469$, $6994$), we obtained the following linear ephemeris. The orbital phases used in the following figures and discussions are based on this equation.

$$BJD_{\text{min}} = 2449486.48184(6) + 0.087038642(10)E.$$  

Figure 2 shows the $O – C$ diagram of the eclipse centers used to calculate equation 1. Although the $O – C$’s were rather constant between $E=−24$ and $E=7843$, there seems to be a systematic tendency of negative $O – C$’s after $E=12370$ (the deviation from the linear ephemeris before $E=12370$ was $−0.0003$ d or $−30$ s$^2$). Fitting a quadratic equation to the observed times has only yielded a marginally significant quadratic term of $−3.2 ± 2.3 \times 10^{−12} \times E^2$.

3.3. Eclipses in outburst

Figures 3 and 4 show phase-averaged light curves during the 1996 January outburst, obtained on four successive nights. The phases are calculated against equation 1. The trend of linear decline from the outburst maximum was first subtracted from the data, using a linear fit to the non-eclipsed portion of the light curve. No subtraction of the linear trend was made for the data on January 1, which showed a slight tendency of brightening, but the observation was too short to meaningfully fit the data.

The potential systematic $O – C$ variation, caused by different passbands and different outburst phases, is expected to be minimal, since the deviation was significant between the same V-band, outburst observations before and after $E=12370$.  

Fig. 2. $O – C$ diagram of eclipse minima. The $O – C$’s are calculated against equation 1. Filled circles with error bars and open circle represent this observation and te|cite.ric97ircomRichter et al.(1997) (cite.ric97ircomRichter et al.(1997)), respectively. Although the $O – C$’s were rather constant between $E=−24$ and $E=7843$, there seems to be a systematic tendency of negative $O – C$’s after $E=12370$. 


Table 2. Eclipses and $O-C$'s of IR Com.

| Eclipse | Error | $E$ | $O-C$ |
|---------|-------|-----|-------|
| 37778.386 | -134516 | -588 |
| 45044.468 | -51035 | 325 |
| 45814.407 | -42189 | -158 |
| 46910.398 | -29597 | -116 |
| 47612.455 | -21531 | -216 |
| 49483.432 | -24 | 5 |
| 49484.402 | -23 | 26 |
| 49486.482 | 0 | 56 |
| 49488.395 | 22 | -15 |
| 49488.483 | 23 | 12 |
| 49511.461 | 287 | -33 |
| 49748.468 | 3100 | 21 |
| 49758.477 | 3125 | 8 |
| 49771.446 | 3274 | 3 |
| 49771.533 | 3275 | -5 |
| 49787.373 | 3457 | -84 |
| 49787.461 | 3458 | -22 |
| 49787.548 | 3459 | -8 |
| 49787.635 | 3460 | -23 |
| 49788.419 | 3469 | 84 |
| 49788.505 | 3470 | -16 |
| 49788.593 | 3471 | -23 |
| 50084.350 | 6869 | 12 |
| 50085.220 | 6879 | 18 |
| 50085.307 | 6880 | 6 |
| 50086.178 | 6890 | 18 |
| 50086.265 | 6891 | 15 |
| 50086.352 | 6892 | 14 |
| 50087.309 | 6903 | 6 |
| 50087.570 | 6906 | -44 |
| 50087.657 | 6907 | 23 |
| 50095.230 | 6994 | 81 |
| 50104.282 | 7008 | 12 |
| 50109.245 | 7155 | 23 |
| 50169.126 | 7843 | 12 |
| 50563.149 | 81370 | -11 |
| 50563.236 | 12371 | -9 |
| 50564.194 | 12382 | -26 |

*Eclipse center. BJD−2400000.
†Estimated error in 10$^{-5}$ d.
‡Cycle count.
∥Against equation 1. Unit in 10$^{-5}$ d.
§Reference. 1: te[cite.ric97ircomRichter et al.(1997)] (cite)], 2: this work.
Fig. 4. Phase-averaged light curves during the 1996 January outburst (continued). Each point represents an average and standard error of each 0.01 phase bin. The fluxes are normalized to 1 outside eclipses. The trend of linear decline from the outburst maximum was subtracted.

Fig. 5. Enlarged light curves of eclipses during the 1996 January outburst. Each point represents an average and standard error of each 0.01 phase bin. The fluxes are normalized to 1 outside eclipses. The trend of linear decline from the outburst maximum was subtracted except for the January 1 data.

Table 3. Variation of the eclipse width and depth.

| Date       | Width (phase) | Depth (mag) |
|------------|---------------|-------------|
| 1996 Jan. 1| 0.14          | 1.5         |
| 1996 Jan. 2| 0.09          | 2.3         |
| 1996 Jan. 3| 0.08          | 2.4         |
| 1996 Jan. 4| 0.09          | 2.8         |

*Uncertainty 0.01.
†Uncertainty 0.2.
‡Slightly uncertain values because of the low signal-to-noise ratio.

Figure 6 is essentially same as observed in the 1996 January outburst. Since the observed eclipses were deeper than those observed during the early stage of the 1996 January outburst, the outburst should have been caught during the later stage of an outburst.

3.4. Quiescent eclipses

Figure 7 shows phase-averaged light curves on two quiescent epochs. The phases are calculated against equation 1. The fluxes are normalized to 1 outside eclipses. A slow fading trend on 1997 April 24 was removed by a linear fit to the observations outside eclipses before normalization. The panel (a) represents the period between 1996 January 12 and 26 (BJD 2450095.2 – 2450109.3). The panel (b) represents the period between 1997 April 24 and 25 (BJD 2450563.1 – 2450564.3). On both panels, deep (2.2±0.2 and 2.1±0.2 mag, respectively) and narrow (full widths 0.13 and 0.12 in phase, respectively) eclipses are evident. The profile of the eclipse and full-orbit light curve very much resembles that presented by te[cite.ric97ircomRichter et al.(1997)](cite.ric97ircomRichter et al.(1997)).
The most remarkable feature is the very weak (panel a), or almost absent (panel b) orbital humps preceding eclipses. Such a feature is rarely observed in high-inclination dwarf novae (see subsection 4.3 for a further discussion).

3.5. \(O-C\) change

As seen in figure 2, the eclipse timings were well represented by a constant period for the period 1994–1996. Looking more closely at the 1996 data, which covered outburst and quiescent stages, there was no significant difference of \(O-C\)'s between different brightness phases, in outburst and in quiescence. In most deeply eclipsing dwarf novae, the asymmetry of the eclipse light curve in quiescence (usually produced by the presence of a bright spot) results in a significant offset of eclipse centers in quiescence against the eclipse center of the white dwarf, or against eclipse centers observed in outburst. The apparent lack of this effect in IR Com suggests that the asymmetry of the accretion disk in quiescence is weak, which is in good agreement with the absence of orbital humps in quiescence (subsection 3.4).

\(O-C\)'s showed a small, but a statistically significant change between 1996 and 1997 (subsection 3.2). Fitting a quadratic equation to all observed times between 1994 and 1997 has yielded a marginal quadratic term of \(-3.2 \pm 2.3 \times 10^{-12} \times E^2\). This value may show the same order of a secular period change suggested in an eclipsing dwarf nova Z Cha (\(P=+1.6 \pm 0.2 \times 10^{-12} \) cycle\(^{-1}\)) (cite.coo81zchapdotCook, Warner(1981)). However, no superoutburst has been observed up to 2001, since the last one in 1985. The observed frequency of outbursts is lower than that expected from the observed quiescence mass-transfer rate (\(\dot{M}\)) (cite.zha86htcasZhang et al.(1986); cite.woo95htcasXrayWood et al.(1995)).

4. Comparison with HT Cas

Among the above eclipsing dwarf novae below the period gap, HT Cas is known to have peculiar characteristics. They can be summarized as below.

1. Among deeply eclipsing SU UMa-type dwarf novae, HT Cas does not show a clear supercycle (a cycle between successive superoutbursts). (cite.wen87htcasWenzel(1987)) studied Sonneberg plates and obtained a mean cycle length of 400\(\pm\)50 d. However, no superoutburst has been observed up to 2001, since the last one in 1985. The observed frequency of outbursts is lower than that expected from the observed quiescence mass-transfer rate (\(\dot{M}\)) (cite.zha86htcasZhang et al.(1986); cite.woo95htcasXrayWood et al.(1995)).

2. Both high (bright) and low (faint) states exist in quiescence. High states are typically \(\sim\)1 mag brighter than low states (cite.zha86htcasZhang et al.(1986); cite.woo95htcasXrayWood et al.(1995); cite.rob96htcasRobertson,
Honeycutt(1996)).

3. Orbital humps, which are considered to reflect the bright spot of the accretion impact point on the disk, are not prominent, and only occasionally seen in high-state quiescence (000 [cite]cite.zha86htcasZhang et al.(1986); 000 [cite]cite.pat81DNOhtcasPatterson(1981); 000 [cite]cite.woo95htcasXrayWood et al.(1995)). The profile of eclipses strongly varies. The orbital humps are absent in low-state quiescence [a representative collection of low-state orbital light curves can be seen in te[cite]cite.woo95htcasXrayWood et al.(1995) (cite)cite.woo95htcasXrayWood et al.(1995)), which also presents an example of the presence of orbital humps in high-state quiescence]. Eclipse mapping of flickering shows a strong concentration toward the inner disk (000 [cite]cite.wel95htcasWelsh, Wood(1995); 000 [cite]cite.bru00htcas2051ophipepeguxumaflckeringBruch(2000)) in contrast to the classical example of U Gem, whose flickering is known to be strongly concentrated in the bright spot (000 [cite]cite.war71ugemWarner, Nather(1971)).

4. HT Cas shows moderately strong X-ray emission relative to the optical flux ($f_X/f_{opt}$) among non-magnetic dwarf novae (000 [cite]cite.ver97ROSATVerbunt et al.(1997); see also 000 [cite]cite.woo95htcasXrayWood et al.(1995) and 000 [cite]cite.muk97htcasMukai et al.(1997) for the detailed analysis of ROSAT pointed observation).

IR Com exhibits a number of similarities with HT Cas. We examine them in more detail in the following subsections.

4.1. Outburst cycle length

tecite.wen95ircomWenzel et al.(1995) ([cite]cite.wen95ircomWenzel et al.(1995)) and tecite.ric97ircomRichter et al.(1997) ([cite]cite.ric97ircomRichter et al.(1997)) suggested that the recurrence time of major outbursts is $8/N$ yr, where $N(>0)$ is a small integer. Although more recent observations by the VSNET Collaboration suggest a higher frequency of outbursts, only five outbursts (table 4) are known between 1996–2001, in spite of intensive monitoring. All of them were short outbursts, lasting less than a few days. No clear periodicity can be found from these data, supporting the finding by tecite.ric97ircomRichter et al.(1997) ([cite]cite.ric97ircomRichter et al.(1997)). This irregular, infrequent occurrence of short outbursts (normal outbursts) is very reminiscent of the irregular behavior of HT Cas (000 [cite]cite.wen87htcasWenzel(1987)). The 1988 outburst reaching mag 13.5 reported by tecite.ric97ircomRichter et al.(1997) ([cite]cite.ric97ircomRichter et al.(1997)) lasted at least two days, and showed a relatively slow rise. Although the available information is very limited to draw a firm conclusion, this outburst may have been a superoutburst. The overall characteristics of outbursts of IR Com closely resembles those of HT Cas (item 1).

4.2. High and low states in quiescence

IR Com is known to show both high and low states in quiescence (000 [cite]cite.ric95ircomRichter, Greiner(1995); 000 [cite]cite.ric97ircomRichter et al.(1997)). The quiescent observation of the present work was mainly done in high state (at $V=16.9– 17.2$). However, the system was reported to show an excursion to a low state ($V=19$) in 1996 June (000 [cite]cite.kro96ircomalert428Kroll(1996)), only two month after our final observation in 1996. The intermediate faint observation ($V=17.5$) on 1996 February 27 may be a suggestion of an ongoing excursion to a faint state. The existence of high and low states in quiescence, and the time-scales of transitions between them (a hundred to several hundreds days), are similar to those (000 [cite]cite.rob96htcasRobertson, Honeycutt(1996)) observed in HT Cas (item 2).

4.3. Orbital humps

As shown in 3.4, we did not detect significant orbital humps during our quiescent observations. This is unusual for an eclipsing dwarf nova, and more resembles the quiescence of HT Cas. Since most of our observations were done during high-state quiescence of IR Com (subsection 4.2), further observations of eclipses and humps in IR Com in low quiescent state are therefore highly wanted in order to establish the similarity with HT Cas.

4.4. X-ray observations

As originally selected in X-ray surveys, IR Com emits relatively strong (and likely hard) X-rays (000 [cite]cite.ric95ircomRichter, Greiner(1995)). Table 5 shows the comparison of IR Com with HT Cas. Although direct comparison is difficult, because of different interstellar absorption and poorly determined X-ray spectrum in IR Com, it is evident both systems have a very similar $f_X/f_{opt}$, which is higher than the average dwarf nova. Both systems are apparently non-magnetic, from the absence of coherent modulations either in X-rays or optical (000 [cite]cite.ric95ircomRichter, Greiner(1995) for IR Com). Since most of the known X-ray luminous CVs are magnetic CVs (000 [cite]cite.ver97ROSATVerbunt et al.(1997)), the high $f_X/f_{opt}$ in IR Com, an apparently non-magnetic dwarf nova, may require a similar explanation to HT Cas: to effectively produce X-ray emissions from the boundary layer.
(e.g. 000 [cite.woo95htcasXrayWood et al.(1995); 000 [cite.muk97htcasMukai et al.(1997)). Future phase-resolved X-ray observations of IR Com will be valuable in testing the similarity of processes of X-ray emission, as well as the accretion processes in the quiescent disk, between IR Com and HT Cas.

5. Conclusion

We observed an X-ray selected, deeply eclipsing cataclysmic variable IR Com (=S 10932) in outburst and quiescence. The light curve of the outburst, which occurred on 1996 January 1, was indistinguishable from that of a normal outburst of an SU UMa-type dwarf nova. Time-resolved photometry during outburst showed that the evolution of the eclipse light curve is a typical one for a dwarf nova outburst. Full-orbit light curves in quiescence show little evidence of orbital humps or asymmetry of eclipses. In addition to the presence of high–low transitions in quiescence, the overall behavior of outbursts and characteristics of the eclipse profiles suggest that IR Com can be best understood as a twin of HT Cas, an eclipsing SU UMa-type dwarf nova with a number of peculiarities.

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Table 5. Comparison of X-ray properties between IR Com and HT Cas from the ROSAT 1RXS Catalogue.

| Object | ctr* | V mag† |
|--------|------|--------|
| IR Com | 0.061 | 17.0 |
| HT Cas | 0.099 | 16.4 |

*Total count rate (s^{-1}).
†Typical quiescent V magnitude.