The Extended Deep Minimum and the Subsequent Brightening of RX And in 1996–1997

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Abstract

We discovered that RX And, one of prototypical Z Cam-type dwarf novae, underwent a deep, extended faint state in 1996–1997. Time-resolved photometry at the bottom of the fading revealed the presence of strong flickering, and the absence of detectable orbital modulation. This finding indicates that the mass-transfer remained even at the deepest minimum of the fading, contrary to what was observed in a deep minimum of a VY Scl-type star, MV Lyr. RX And subsequently underwent a brightening (outburst) during its recovery stage. The photometric and spectroscopic characteristics of the brightening significantly differed from those of ordinary outbursts of RX And, and are considered to resemble an inside-out type outburst of a long-period dwarf nova. An examination of historical visual observations revealed the possible presence of ~10-yr periodicity, which is close to what has been proposed for MV Lyr. The common observed features between RX And and VY Scl-type stars may suggest a common underlying mechanism for producing temporary deep stagings. The departure from the disk instability model, as observed in VY Scl-type stars, was not apparent in the present fading of RX And. In conjunction with the recently published Hubble Space Telescope observation during the same fading, we can conclude that the phenomenological difference from the VY Scl-type fading is understood as a smaller effect of irradiation on the accretion disk in RX And.

KeyWords: accretion, accretion disks — stars: binaries: eclipsing — stars: dwarf novae — stars: novae, cataclysmic variables — stars: individual (RX Andromedae)

1 Introduction

RX And is one of the best-known Z Cam-type dwarf novae (cf. Warner (1995)), which show standstills in addition to usual dwarf nova-type outbursts (for a review of dwarf nova outbursts, see Osaki (1996)). Although the exact origin of Z Cam-type phenomenon is not perfectly understood, it has been proposed that the changing mass-transfer rate $\dot{M}$ is most responsible for the dwarf nova–standstill alternations: the standstill is a state of an enhanced $\dot{M}$, which thermally stabilizes the accretion disk (e.g. Meyer, Meyer-Hofmeister (1983)). Meyer, Meyer-Hofmeister (1983) proposed that a normal outburst below the critical surface density can trigger a standstill, which is maintained by an enhanced mass-transfer caused by irradiation from the brightened accretion disk and white dwarf. Subsequent model calculations by Lin et al. (1985) and King, Cannizzo (1988), however, did not well reproduce the observed properties of Z Cam-type stars. Honeycutt et al. (1998) presented an observational test, and reported that some Z Cam stars were indeed brighter in standstill than the mean brightness in the outbursting phase, suggesting higher mass-transfer rates during standstills.

More recently, Buat-Ménard et al. (2001) claimed that the basic features are reproduced by correctly taking the heating of the disk by the tidal torque and the mass-transfer stream impact into account. Buat-Ménard et al. (2001) also claimed that large variation of mass-transfer rates are not necessary to reproduce the Z Cam-type phenomenon. However, the resultant light curve by Buat-Ménard et al. (2001) is different from the observation in some respects. Kato (2001) argued that there is a striking departure from the theoretical prediction when a system enters a standstill.

Several types of cataclysmic variables (CVs) show temporary reductions of $\dot{M}$, the best-known cases being VY Scl-type stars and AM Her-type stars (polars) (Warner (1995); Greiner (1998)). Indeed, Warner, van Cittert (1974) tried to explain the Z Cam-type and VY Scl-type phenomena in the same framework. However, observations suggest that there is a strong segregation of period distributions between Z Cam-type stars and VY Scl-type stars (Verbunt, 1997). Furthermore, past extensive studies on representative Z Cam-type stars (Honeycutt et al. (1998); Oppenheimer et al. (1998)), together with more theoretical discussion by Buat-Ménard et al. (2001), have shown little evidence for VY Scl-type strong temporary reduction of $\dot{M}$.

The nature of Z Cam-type phenomenon is thus still controversial; there still remain discrepancies between observations and theories. Even if we assume changing $\dot{M}$ as a cause of Z Cam-type phenomenon, the exact origin of changing $\dot{M}$ is still poorly understood, although star spots covering the L1 point (Livio, Pringle, 1994) would be a promising interpretation for the VY Scl-type
phenomena.

RX And had been known as a relatively typical Z Cam-type dwarf nova, with outbursts-standstill alternations, until the discovery of an extremely deep fading (also called deep quiescence by some authors) in 1996 September. The deep fading lasted until 1997 January.

2 Observation

2.1 Photometry

The time-resolved observations were acquired on three nights between 1996 November 15 and 19 (near the bottom of the fading), using a CCD camera (Thompson TH 7882, 576 × 384 pixels, on-chip 2 × 2 binning adopted) attached to the Cassegrain focus of the 60 cm reflector (focal length=4.8 m) at Ouda Station, Kyoto University (Ohtani et al., 1992). An interference filter was used which had been designed to reproduce the Johnson V band. The exposure time was 60 s. The frames were first corrected for standard debiasing and flat fielding, and were then processed by a microcomputer-based aperture photometry package developed by one of the authors (TK). The magnitudes of the object was determined relative to GSC 2807.1483 (V = 11.86, B − V = +1.05), whose constancy during the run was confirmed using GSC 2803.948. The magnitude of the comparison star is taken from Misselt (1996). Barycentric corrections to observed times were applied before the following analysis. We also obtained additional nightly snapshot photometry on 32 nights between 1996 September 10 and 1997 February 5. Table 1 lists the log of observations, together with nightly averaged magnitudes.

2.2 Spectroscopy

We took a low-resolution spectrum with a 1.88-m telescope and the New Cassegrain Spectrograph equipped with a 150 grooves mm$^{-1}$ at Okayama Astrophysical Observatory (OAO, a branch of the National Astronomical Observatory, an inter-university research institute operated by the Ministry of Education, Science, Sports and Culture of Japan) on 1997 February 5. The detector was a CI502AB CCD (512x512 pixels). The spectral coverage was 4600–7100 Å, and the wavelength resolution was 5.9 Åpix$^{-1}$. The exposure started at BJD 2450484.9111, and the exposure time was 600 s.

The reduction was done using the Spectronebula-graph reduction system (SNGRED) developed mainly by M. Yoshida at OAO on IRAF package. The aver-

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IRAF is distributed by the National Optical Astronomy Ob-

\[\text{Table 1: Nightly averaged magnitudes of RX And}\]

| Date      | Start$^*$ | End$^*$ | mean$^+$ | err$^+$ | N$^\dagger$ |
|-----------|-----------|---------|----------|---------|-------------|
| 1996 Sep 10 | 337.265   | 337.266 | 2.802    | 0.027   | 3           |
| 1996 Sep 15 | 342.175   | 342.176 | 3.146    | 0.025   | 3           |
| 1996 Sep 16 | 343.124   | 343.125 | 2.929    | 0.039   | 3           |
| 1996 Sep 17 | 344.099   | 344.100 | 3.333    | 0.036   | 3           |
| 1996 Sep 18 | 345.040   | 345.041 | 2.949    | 0.071   | 3           |
| 1996 Oct 20 | 377.141   | 377.144 | 3.313    | 0.028   | 5           |
| 1996 Oct 22 | 379.154   | 379.157 | 3.394    | 0.022   | 5           |
| 1996 Oct 29 | 386.204   | 386.210 | 3.290    | 0.017   | 8           |
| 1996 Nov 15 | 402.883   | 403.135 | 3.294    | 0.007   | 265         |
| 1996 Nov 16 | 403.899   | 404.200 | 3.304    | 0.006   | 320         |
| 1996 Nov 17 | 405.040   | 405.041 | 3.333    | 0.036   | 3           |
| 1996 Nov 18 | 405.899   | 406.200 | 3.386    | 0.025   | 3           |
| 1996 Nov 19 | 406.982   | 407.204 | 3.272    | 0.005   | 280         |
| 1996 Dec  8  | 425.870   | 425.875 | 2.825    | 0.045   | 4           |
| 1996 Dec  9  | 426.938   | 426.943 | 3.219    | 0.014   | 5           |
| 1996 Dec  11 | 428.896   | 428.898 | 3.315    | 0.022   | 5           |
| 1996 Dec  18 | 435.930   | 435.933 | 3.091    | 0.095   | 2           |
| 1996 Dec  21 | 439.010   | 439.011 | 3.346    | 0.140   | 3           |
| 1996 Dec  22 | 439.870   | 439.871 | 3.231    | 0.053   | 3           |
| 1996 Dec  23 | 440.858   | 440.858 | 2.908    | 0.173   | 2           |
| 1996 Dec  24 | 441.860   | 441.861 | 2.955    | 0.033   | 3           |
| 1996 Dec  25 | 443.007   | 443.008 | 3.267    | 0.056   | 3           |
| 1996 Dec  27 | 444.868   | 444.873 | 3.066    | 0.019   | 5           |
| 1996 Dec  31 | 448.865   | 448.866 | 3.067    | 0.168   | 3           |
| 1997 Jan  1  | 449.867   | 449.869 | 2.895    | 0.142   | 3           |
| 1997 Jan  2  | 450.912   | 450.918 | 2.763    | 0.017   | 12          |
| 1997 Jan  3  | 451.869   | 451.870 | 2.571    | 0.019   | 3           |
| 1997 Jan  4  | 452.927   | 452.929 | 2.185    | 0.013   | 5           |
| 1997 Jan  6  | 454.867   | 454.871 | 2.607    | 0.073   | 8           |
| 1997 Jan  8  | 456.865   | 456.869 | 1.296    | 0.015   | 6           |
| 1997 Jan  12 | 460.930   | 460.932 | 0.020    | 0.002   | 5           |
| 1997 Jan  13 | 461.867   | 461.869 | -0.333   | 0.004   | 5           |
| 1997 Jan  15 | 463.865   | 463.870 | -0.506   | 0.010   | 10          |
| 1997 Jan  19 | 467.907   | 467.909 | 1.537    | 0.008   | 5           |
| 1997 Jan  20 | 468.875   | 468.877 | 1.926    | 0.015   | 5           |
| 1997 Feb  3  | 482.906   | 482.909 | 0.813    | 0.005   | 5           |
| 1997 Feb  5  | 484.906   | 484.911 | 1.736    | 0.013   | 6           |

$^*$BJD−2450000.
$^\dagger$Relative magnitude to GSC 2807.1483.
$^\ddagger$Standard error of nightly average.
$^\S$Number of frames.
3 Result and Discussion

3.1 The Fading Episode in 1996–1997

The overall light curve, which is drawn from the present CCD observations and the visual observations reported to VSNET international variable star network\(^3\), is presented in figure 1. For comparison with the \(V=15\) mag reached during this extended low state, note that RX And is normally at \(V=14\) in quiescence.

Such a fading strongly resembles faint (or low) states observed in VY Scl-type novalike variables. The existence of such an extended, extremely faint state in a Z Cam-type star firmly established that a remarkable reduction of mass-transfer rates comparable to those of VY Scl-type stars indeed occurs in a Z Cam-type star. The faint state lasted for \(\sim 140\) d.

3.2 Short-Term Light Variation

In some VY Scl-type stars, a total cessation of mass-transfer is suggested from the disappearance of flickering (MV Lyr; Robinson et al. (1981)). We obtained

![Figure 1: Light curve of the extended faint state of RX And occurring in 1996. The light curve is drawn from visual observations reported to VSNET (dots) and present CCD \(V\)-band observations (filled squares with error bars). The vertical ticks and arrow represent the epochs of time-resolved photometry and spectroscopy, respectively.](image1)

![Figure 2: Time-resolved photometry of RX And during the deep fading in 1996. The error of individual measurements are smaller than 0.01 mag. Short-term irregular variations are clearly visible, which can be attributed to flickering.](image2)

...
Figure 3: Phase-averaged light curve of RX And during the deep fading. The upper limit of the amplitude of orbital modulations is 0.1 mag.

\( P = 0.209893 \text{ d}, \text{Kaitchuck (1989)} \). Although there is an indication of double-humped orbital variation with an amplitude of \( \sim 0.1 \text{ mag} \), the lack of coherent signal in the period analysis more strongly suggests that the variation in the averaged light curve is spurious. We therefore put the upper limit of the amplitude of orbital modulations as 0.1 mag.

One might expect a direct reflection effect from the hot white dwarf, if the accretion disk had disappeared or become optically very thin. The absence of such an effect also supports that a substantial amount of accretion disk remained even in the extended deep minimum of RX And. Future optical spectroscopic observations on similar occasions will be able to test the presence of a normal CV disk.

Sion et al. (2001) independently obtained far-UV spectra during the same deep fading with the Hubble Space Telescope. Sion et al. (2001) applied a synthetic spectral fitting to the UV spectra, and concluded that the accretion disk contributes to 25 \% of the far-UV light, corresponding to a mass-accretion rate of \( 10^{-10.52} M_\odot \text{ yr}^{-1} \). Although their estimate of the accretion rate may have suffered from some degree of ambiguities resulting from a fit using an optically thick disk, the unmistakable signature of the remaining mass accretion (close to the white dwarf) in the far-UV wavelengths strengthens our finding of the remaining mass-transfer from the secondary.

3.3 Brightening from the Minimum

There was a gradually brightening trend since JD 2450439 (1996 December 21). RX And brightened for the subsequent 14 nights at a mean rate of 0.037 mag d\(^{-1}\). Such a slow brightening is commonly observed in the early recovery stage from deep, long, fadings of VY Scl-type stars (cf. general light curves: Greiner (1998); MV Lyr: Krichva, Genkov (1992)). RX And then started brighten quickly (figure 4), attaining the maximum of \( V = 11.4 \) on 1997 January 14.

The light curve of the brightening more or less resembles that of a dwarf nova-type outburst, but is different from ordinary outbursts of RX And in many respects: 1) The entire duration of the brightening (outburst) was \( \sim 40 \text{ d} \), with multiple peaks. The duration is several times longer than those of ordinary outbursts of RX And (Szkody (1974); Szkody, Mattei (1984)). 2) The rise to the maximum was anomalously slow, accompanied by a short “stagnation” period in the rising branch (a temporary fading was particularly apparent near JD 2450460 = 1997 January 11). The duration of the “outburst” was similar to dwarf nova-like brightenings observed in a VY Scl-type star, MV Lyr (Pavlenko (1998); Shugarov, Pavlenko (1998); Pavlenko, Shugarov (1998)).

The slow rising branch also resembles those of long-period dwarf novae (Menzies et al. (1986); Kim et al (1992); Simon (2000)). Kim et al. (1992) interpreted this feature in GK Per as a result of slow inside-out propagation of the thermal instability starting at the inner region of the accretion disk. This condition is apparently achieved in long-period, low-\( \dot{M} \) dwarf novae, in which the critical surface density is more likely to be reached at the inner region (Kim et al., 1992).

The same condition was likely to be achieved in the recovery process of RX And from the very low state,
when the mass-transfer seems to have slowly recovered, as inferred from the slow rise from the deep minimum.

In the spectrum obtained on 1997 February 5 (figure 5), when RX And was declining from the third peak after recovery from the deep minimum and ∼1 mag above the deep quiescence, emission lines of the Balmer lines, Hα and Hβ, and HeI dominated. The equivalent widths, FWHM and FWZI are listed in table 2. The errors of FWHM and FWZI are 40 and 100 km s⁻¹, respectively. The instrumental width corresponds to 540 km s⁻¹. The Hβ equivalent width is ∼10% larger than that in normal quiescence and on one day before an outburst measured by Kaitchuck et al. (1988). While most dwarf novae, including RX And itself (cf. Clarke, Bowyer (1984); Kaitchuck et al. (1988)) are known to show reduced line strengths above quiescence, RX And in this stage showed relatively strong emission lines. This suggests that the accretion disk had an extra emission source, which can be naturally explained if the heating wave from the inner region had not reached the outer region of the accretion disk and the accumulated matter during the low quiescence was left from being accreted. The large values of FWHM and FWZI are consistent with formation of these lines in the outer disk.

In conclusion, we interpret that RX And mimicked a long-period, low-M dwarf nova in its recovery process from the deep minimum.

### 3.4 Frequency of Deep Fadings

The reason why such deep fadings of RX And had not been recognized before the 1996–1997 event was partly from the presence of a close V=14.3 mag companion, which may have been confused with RX And when the variable was exceptionally faint. This hypothesis is strengthened by the subsequent detections of (shorter) fading episodes occurring 1997 February to March and 2000 April to August. During both fadings, RX And was observed fainter than its “nominal” quiescent magnitude of 14.0. Such fading episodes may have been identified as “intervals without outbursts” in the past visual record. An examination of the data in VSOLJ (Variable Star Observers League in Japan) and AFOEV (Association Française des Observateurs d’Etoiles Variables) databases since 1970 has revealed at least two distinct such instances in 1977 and 1986. Although the frequency and periodicity should be confirmed future observations, there seems to be a quasi-period of ∼10 yrs, which is close to what is proposed for a VY Scl-type star, MV Lyr (Wenzel, Fuhrmann (1983); Rosino et al. (1993)).

### 3.5 Relation to VY Scl-Type Stars

The present extended fading episode strongly mimics the temporary fadings of VY Scl-type stars. Observations have suggested a number of similarities between the present phenomenon of RX And of VY Scl-type fadings. The presence of a similar periodicity between RX And and MV Lyr may further suggest a common underlying mechanism for producing temporary deep fadings, though the reason remains a mystery why there is no evidence of a similar phenomenon in other Z Cam-type stars.

Additional difference between the present fading of RX And and VY Scl-type fadings can be seen in the initial part of the fading episode (figure 5). The disk instability model predicts that a system should undergo dwarf nova outbursts (Honeycutt et al. (1994); King Cannizzo (1998)) in response to the temporary reduction of M. This is what was indeed observed in RX And, in the early stage of the fading. VY Scl-type systems, on the contrary, show little such evidence of dwarf nova-type outbursts (Honeycutt et al. (1994); Greiner (1998)). Leach et al. (1999) explained that such a departure of VY Scl-type stars from the disk-instability model is caused by the irradiation from the hot white

| Line  | E.W.* | FWHM† | FWZI† |
|-------|-------|-------|-------|
| Hα   | –30   | 940   | 2650  |
| Hβ   | –10   | 1130  | 2630  |
| HeI 5876 | –3    | 670   | ⋯     |

* Equivalent width in Å.
† Unit in km s⁻¹.

Table 2: Widths of emission lines.
dwarf, which can suppress thermal instability. More recent discovery of unique short-period mini-outbursts in a VY Scl-type star, V425 Cas (Kato et al., 2001) can be regarded as another support to this explanation. The detection of supersoft X-rays from V751 Cyg in low state (Greiner et al., 1999; Greiner, 2000) and the indirect evidence in BZ Cam (Greiner et al., 2001) also support this interpretation. The far-UV observation by Sion et al. (2001) during the deep fading yielded a white dwarf temperature of 34100±1000 K, which does not significantly differ from those measured in other quiescent dwarf novae. This observation provides strong support for the interpretation that what phenomenologically distinguishes temporary fadings of RX And from VY Scl-type fadings is the effect of heating from the white dwarf.

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