The Recurrent Nova U Scorpii in the 1999 Outburst: the First Detection of a Significant Orbital-Period Change

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Abstract

In this paper we present and discuss our time-resolved photometry of an eclipsing recurrent nova, U Sco, during an outburst in 1999, which was conducted from immediately after the optical maximum to the final fading toward the quiescence. In the first-ever complete light-curve, a few primary and secondary eclipses of the binary system were detected, and the timings of the minima were determined. We found that the eclipses showed no totality during the outburst. The depth of the primary eclipses was 0.4–0.8 mag, much shallower than that in quiescence. In the plateau phase, very little irradiation (≤0.1 mag) was observed in the orbital light curve, which implies the existence and a large flaring rim of the accretion disk during the outburst. The minima of the eclipses were detected at earlier orbital phases for the predicted ephemerides. Thus, we obtained an orbital period change of the binary system as \( \frac{P}{P_0} = 1.7(\pm0.7) \times 10^{-6} \) yr\(^{-1}\) from the \( O-C \). Assuming that this period change is a result of the conservative mass transfer between the component stars, its mass-transfer rate reaches \( \dot{M} = 2.4(\pm1.0) \times 10^{-6} \) \( M_\odot \) yr\(^{-1}\) for a 1.37\( M_\odot \) white dwarf and a 2.0\( M_\odot \) mass-donor companion, which is too high to cause shell flashes, even on a massive white dwarf. Therefore, this large rate of the period change strongly indicates a non-conservative mass transfer in the binary system.

Key words: accretion: accretion disks — stars: individual: U Scorpii — stars: novae, cataclysmic variables

1. Introduction

It is widely accepted that recurrent novae are binary systems in which mass is transferred to a white-dwarf primary from a main-sequence or red-giant secondary over-flowing its Roche lobe. The transferred matter gradually accumulates on the surface of the white dwarf. When it reaches a critical mass, hydrogen ignites to trigger a thermonuclear-runaway outburst (Starrfield et al. 1988) with recurrence periods from one decade to one century. Recurrent novae are classified as a kind of cataclysmic variables (e.g., Warner 1995 for a review); at present, we firmly know only nine systems in our galaxy, i.e., CI Aql, V394 CrA, T CrB, IM Nor, RS Oph, T Pyx, U Sco, V745 Sco, and V3890 Sgr, and one system in the LMC (e.g., see table 1 of Hachisu, Kato 2001b).

Although classical novae share many aspects of the outburst nature with recurrent novae as a subclass of cataclysmic variables, because the former erupt every ten thousand years or so, their outburst has been recorded only once in human history. The white dwarf accumulates hydrogen-rich matter much slower than that for recurrent novae. As a result, because a part of the hydrogen diffuses into the white dwarf before ignition, a very surface layer of the white dwarf is dredged up into the hydrogen-rich envelope and blown off in the outburst wind (e.g., Prialnik 1986; Kato, Hachisu 1994). Therefore, the ejecta of classical novae contain much of the white-dwarf matter (carbon, oxygen, or neon), and the white dwarf is gradually eroded.

Recurrent novae, on the other hand, show characteristics clearly different from classical novae: 1) heavy elements, such as carbon, oxygen, and neon, are not enriched in ejecta, but are similar to the solar values (for U Sco, e.g., Barlow et al. 1981; Williams et al. 1981), indicating that the white dwarf is not eroded; 2) very short recurrence periods from a decade to a century theoretically require a very massive white dwarf close to the Chandrasekhar mass limit, \( \sim 1.4 M_\odot \) (e.g., figure 9 of Nomoto 1982). These two arguments indicate that the mass of the white dwarf in recurrent novae increases toward the Chandrasekhar mass limit. We expect that, if the white dwarf is made of carbon and oxygen, it ignites carbon at the center, and explodes as a type Ia supernova, or collapses to form a neutron star when it reaches a critical mass of 1.378\( M_\odot \) (Nomoto et al. 1984; Nomoto, Kondo 1991).
U Sco is a unique member of recurrent novae; among them, U Sco is characterized by 1) the fastest decline rate of the light curve in the past outbursts (∼0.6 mag d⁻¹), 2) the shortest recurrence period of about 11 yr (Schaefer 2001), and 3) extremely helium-rich ejecta of He/H ∼ 2 by number (Barlow et al. 1981; Williams et al. 1981). The decline rates of the outbursts of recurrent novae are mainly determined by the white-dwarf masses (e.g., Kato 1999b), the rate of which increases as the white-dwarf mass is approaching the Chandrasekhar mass. Precise photometry of a recurrent nova in outburst is therefore necessary to determine the mass of the white dwarf with sufficient accuracy, especially near the Chandrasekhar limit. Once the mass is determined, the mass-accretion rate of the white dwarf can be determined from the recurrence period (e.g., figure 9 of Nomoto 1982). We are then able to theoretically determine the growth rate of the white dwarf toward the Chandrasekhar limit. In the current subject, it is almost certain that U Sco corresponds to an extreme case of very massive white dwarfs from its fastest decline rate and shortest recurrence period. We expect that the recurrent nova U Sco is an immediate progenitor of a type Ia supernova (Hachisu et al. 1999a).

Type Ia supernovae are one of the most luminous explosive events of stars. Recently, they have been used as good distance indicators, which provide a promising tool for determining cosmological parameters based on their almost uniform maximum luminosities (Riess et al. 1998; Perlmutter et al. 1999). Both of these authors derived the maximum luminosities ($L_{\text{max}}$) of type Ia supernovae completely empirically from the shapes of the light curve (LCS) of nearby type Ia supernovae, and assumed that the same $L_{\text{max}}$–LCS relation holds for high red-shift ($z$) type Ia supernovae. In order for this method to work, the nature of type Ia supernovae and their progenitors should be the same between high-$z$ and low-$z$ ones. Therefore, it is necessary to identify the progenitor binary systems, thus confirming whether or not type Ia supernovae “evolve” from high-$z$ to low-$z$ galaxies (e.g., Umeda et al. 1999).

It is generally accepted that the exploding star of type Ia supernova, itself, is a mass-accreting white dwarf in a binary system (e.g., Nomoto 1982; Nomoto et al. 1984), while the companion (and thus the observed binary system) is not known. Several candidates have been proposed, which include merging double white dwarfs (e.g., Iben, Tutukov 1984; Webbink 1984), recurrent novae (e.g., Starrfield et al. 1985; Hachisu, Kato 2001b), symbiotic stars (e.g., Munari, Renzini 1992), supersoft X-ray sources (e.g., Rappaport et al. 1994), etc (e.g., Livio 2000 for more details of these candidate systems). If U Sco is confirmed to be as massive as or very close to the critical mass of $M_{\text{crit}} = 1.378 M_\odot$, and also now growing in mass, it is the first strong candidate for type Ia supernova progenitors.

U Sco is also known as an eclipsing binary system with an ephemeris for timings of mid-eclipses of HJD 2447717.6061 + 1.23056 × E (Schaefer 1990; Schaefer, Ringwald 1995). The orbital phase duration of the primary eclipses, $\approx 0.1$, indicates the inclination angle, $i \approx 80^\circ$ (e.g., table 4.2 of Warner 1995). The origin of binary systems with a very massive white dwarf and a slightly evolved main-sequence star having a helium-rich envelope is naturally understood in the context of a binary evolutionary scenario of type Ia supernovae (Hachisu et al. 1999a; 1999b). Thus, we had been anxiously awaiting the next eruption of U Sco, since the previous outburst in 1987, in order to obtain a detailed transition of the nova-outburst, and thus to clarify the physical nature of the object.

The past outbursts of U Sco were recorded in 1863, 1906, 1936, 1945, 1979, and 1987. At last, this object underwent its seventh recorded outburst in 1999, which was detected by Schmeer (1999) on February 25.194(UT) when the object was about 9.5 mag. It is noted that the object had been fainter than at least 14.3 mag on February 25.04(UT) (Monard 1999), and also that there had not been any positive detection before it (Kato 1999a). The fast circulation of Schmeer (1999) provided us rare opportunities for prompt studies of eruption in the very early phase. Several optical and infrared spectroscopic studies in such a phase and for later evolution were successfully made by some authors (Munari et al. 1999; Lépine et al. 1999; Amlpama, Dewangan 2000; Ikeda et al. 2000; Evans et al. 2001; Thoroughgood et al. 2001).

We started intensive time-resolved photometry of the outburst immediately after detection on February 25 in order to understand the detailed behavior of the progress throughout the event, and then to probe into its nature. In the observation, we detected eclipses and revealed that the orbital period has significantly shortened year by year. In the following part, details of the observation are described in section 2, the results are presented in sections 3, and discussions follow in section 4.

2. Observation and Data Reduction

The optical photometric observation of U Sco was carried out for a total of 30 nights between February 25 and May 20 in 1999, using an unfiltered CCD camera equipped with a Kodak KAF-0400 chip (SBIG ST-7) in the 2×2 binning mode, attached to a 0.25-m Schmidt–Cassegrain telescope (Meade LX200) installed on the rooftop of the Department of Astronomy, Kyoto University. The exposure time for the object was set to 10 s on February 25, 20 s on February 27, and 30 s on the other nights, depending on the conditions. The obtained frames were dark-subtracted, flat-fielded with a normalized sky flat, and then analyzed using a Java-based aperture and PSF photometry package developed by one of the authors (TK).

We performed relative photometry using GSC 6206.372 [RA = 16h22m27.64s, DEC = −17°48′57.7′′ (J2000)] as a local comparison star, whose constancy was confirmed by GSC 6206.266 [RA = 16h22m45.79s, DEC = −17°51′52.7′′ (J2000)]. Although the observational error varied even in an intraday observation, the typical probable errors for the object were determined to be ∼0.1 mag or greater for observations made on March 2, 5, 9, 11, and 27, which were under poorer conditions, and on and after March 28.
The light curve made with the past outbursts superposed on those in the current outburst (e.g., Rosino, Iijima 1988).

We divided the whole light curve of the present outburst into three stages of 1) fast decline phase, 2) mid-plateau phase, and 3) final fading phase toward quiescence, according to the decline rates (figure 1). In the fast decline stage, the object showed an extremely rapid decline of $\sim 0.59$ mag d$^{-1}$ until March 13, i.e., about 16 days after the optical maximum. Such a fast decay is known as to be one of the characteristic features seen in outbursts of U Sco. The light curve was momentarily flatten to around 14 mag on March 11–13 at the end of this first stage. The declining rate then turned to be gradual ($\sim 0.095$ mag d$^{-1}$) between March 16 and 28 (plateau phase). The object finally entered into the last decline stage with a declining rate of $\sim 0.19$ mag d$^{-1}$ about 32 days after the maximum (final fading phase). At that time we could not perform time-resolved photometry due to the faintness of the object, and therefore the data points were averaged each night from the start of this third stage (and also on March 9 due to an extremely bad sky condition), as shown in figure 1. After the final fading phase, the object returned to quiescence around the end of 1999 April.

3.2. Primary and Secondary Eclipses

In the early part of the fast decline phase, we obtained almost linear declining trends on each night, especially on February 25 and March 1 with longer coverages with continuous $\sim 0.13$ orbital phase durations and better qualities with typical probable errors of $\leq 0.01$ mag. In the fast decline phase, however, we detected a secondary eclipse of the binary system in the observation on March 3. The light curve on that night showed a clear intraday modulation digressing from a linear declining trend, and no similar features were seen in the other nightly light curves during this phase (figure 2). Note that the linear trend which involves all affectable factors for the observation,

### Table 1. Journal of the observation.*

| Date (1999) | N | Time coverage (HJD–2451000) | Orbital phase coverage |
|------------|---|-----------------------------|------------------------|
| Feb. 25    | 939 | 235.2124–235.3780          | 0.53–0.67              |
| 27         | 240 | 237.2038–237.3695          | 0.15–0.29              |
| 28         | 91  | 238.2988–238.3578          | 0.04–0.09              |
| Mar. 1     | 303 | 239.2124–239.3712          | 0.78–0.91              |
| 2          | 60  | 240.2461–240.3660          | 0.62–0.72              |
| 3          | 337 | 241.2275–241.3681          | 0.42–0.54              |
| 5          | 167 | 243.1873–243.3662          | 0.01–0.16              |
| 9          | 7   | 247.2181–247.3573          | 0.29–0.40              |
| 11         | 6   | 249.2529–249.3523          | 0.94–0.02              |
| 12         | 435 | 250.1754–250.3622          | 0.69–0.85              |
| 13         | 187 | 251.2384–251.3567          | 0.56–0.65              |
| 16         | 472 | 254.1679–254.3592          | 0.94–0.09              |
| 17         | 410 | 255.1645–255.3359          | 0.75–0.89              |
| 22         | 40  | 260.2791–260.3545          | 0.90–0.97              |
| 23         | 191 | 261.2753–261.3505          | 0.71–0.77              |
| 27         | 109 | 265.3026–265.3446          | 0.99–0.02              |
| 28         | 14  | 266.3182–266.3435          | 0.81–0.83              |
| 31         | 217 | 269.2315–269.3350          | 0.18–0.26              |
| Apr. 2     | 106 | 271.3025–271.3438          | 0.86–0.90              |
| 3          | 174 | 272.2692–272.3373          | 0.65–0.70              |
| 4          | 226 | 273.2596–273.3429          | 0.45–0.52              |
| 5          | 12  | 274.2452–274.2470          | 0.25–0.25              |
| 6          | 63  | 275.3168–275.3402          | 0.12–0.14              |
| 8          | 319 | 277.2089–277.3361          | 0.66–0.77              |
| 11         | 198 | 280.2595–280.3357          | 0.14–0.22              |
| 16         | 102 | 285.3011–285.3384          | 0.24–0.27              |
| 29         | 72  | 298.1201–298.1415          | 0.65–0.67              |
| 30         | 55  | 299.1138–299.1344          | 0.46–0.48              |
| May 1      | 100 | 300.0980–300.1365          | 0.26–0.29              |
| 20         | 15  | 319.0657–319.0708          | 0.68–0.68              |

* N is the number of data points used in the analyses. The orbital phase was calculated using the ephemeris given in Schaefer and Ringwald (1995).
such as extinction, is not identical to the fast declining trend of the outburst denoted by the dashed line in figure 1. It should also be noted that the curvature for the local light curve is extremely small, i.e., the quadratic term around 10 days is about \(-0.03\) mag d\(^{-2}\), indicating that the influence of the curvature, about 0.0014 mag for the 0.2 d duration, should be safely negligible. We confirmed no significant change in the counts of the comparison star, GSC 6206.372, other than the quite normal slow variation caused by changing airmass throughout the entire run. The differential photometry using the check star, GSC 6206.266, also yielded no significant variation larger than the observational error.

The detrended light curve on March 3 revealed that the minimum occurred at HJD 2451241.298 along with the depth of the eclipse being about 0.05 mag, and its duration was at least 0.1 d, i.e., 0.08 orbital phase. This detection was only one week after the optical maximum, which is the earliest example of eclipses among those after optical maxima in the past nova eruptions have ever been observed.

The secondary eclipse observed is theoretically expected in a numerical model of Hachisu et al. (2000a) as being the consequence of an irradiation effect by the expanded photosphere of the white dwarf in the nova outburst. In the fast decline phase, the photosphere of the white dwarf is as large as, or larger than, the size of the binary system. On March 3, because its photospheric radius was still as large as \(1.8R_\odot\) (the binary separation of \(\sim 6R_\odot\)), the irradiation of the companion star was large enough to make a secondary eclipse with a depth of 0.1 mag, from a theoretical model of a thermonuclear runaway event.

In addition to the secondary eclipse, we detected a minimum and ensuing egress of a primary eclipse of the binary system at HJD 2451254.2 in the observation on March 16; also, an ingress of the next primary eclipse was observed after the 1.23 d orbital period on the next night. In figure 3 the primary eclipse observed on March 16 corresponding to an orbital phase coverage of 0.9–0.1 is shown. The timing of the minimum occurred at HJD 2451254.211. The expected orbital phase given in the light curve in figure 3 is based on the ephemeris determined by Schaefer and Ringwald (1995), and the data points are averaged by each phase bin of 0.02 for clarity, after removing the internight linear decline of 0.095 mag d\(^{-1}\) for the plateau phase. The light curves on March 11–17, 22, 23, and 27 are also presented in order to depict the features outside the primary eclipse. Note that only data points outside of eclipse are shown for the data on March 11 in figure 3 because of the poor sky condition. Since no other nights fall on a range of 0.9–0.1 orbital phase during the interval of March 11–17, the profile of the eclipse minimum on March 16 is not influenced by the detrending process among the different nights. The orbital phase between 0.1 and 0.5 was unfortunately not covered during this plateau phase.

The object was observed as being somewhat below the declining trend-line on a few nights. The light curves on March 5 and 22 are such cases, as can be seen from figure 1. The scatter of the data on March 5 was mainly caused by larger observational errors, and no systematic variation was observed in the light curve. However, the orbital phase corresponded to 0.01–0.15, which is consistent with the fact that the object really showed a primary eclipse at that time. Because the observed duration on March 22 corresponded to an orbital phase of 0.90–0.97, it is also probable that the light curve could be related to a primary eclipse, and the observation on March 23 corresponded to an orbital phase of around 0.75. Hence, the light curves are consistent with the binary phases and the difference of the averaged magnitudes between March 22 and 23 is therefore reasonably explained. Nevertheless, it would be better that we reserve our conclusion about whether these two sets really display the primary eclipses or not, and therefore we have not given a clear discussion for these nights. We also briefly mention that the number
The orbital light curve also provided us the physical states of the binary system during the outburst. An extremely small reflection effect (≤ 0.1 mag) is suggested from the light curve during the orbital phase of ~ 0.55–0.9, which indicates that irradiation of the companion star by the white dwarf is shielded during the plateau phase. Thus, we can reasonably conclude that the accretion disk should have been remaining after the nova explosion (see also Sekiguchi et al. 1988) and that the rim of the disk was largely flaring-up in the plateau phase to shield the light from the white dwarf.

We divided the whole light curve of the outburst into three stages in subsection 3.1. The secondary eclipse detected on March 3 occurred in the first decline phase, during which the photosphere of the white dwarf was still expanded up to 1.8R⊙ which was comparable to the size of the binary system (Hachisu et al. 2000a). As a result, the companion (mass-donor star) could be strongly irradiated by the white-dwarf photosphere. In the plateau phase, however, the white-dwarf photosphere shrunk to 0.1R⊙, or smaller. Therefore, it could be blocked by the flaring-up rim of the accretion disk. In the final decay phase, the white-dwarf photosphere returned to its almost original radius in quiescence.

It is noted that no significant variation, like flickering reported by Schaefer (1990), was observed in the light curves of the individual nights.

4. Discussion

4.1. Non-Conservative Mass Transfer and the Orbital-Period Change

The timing of the minimum observed in the secondary eclipse on March 3 was centered at HJD 2451241.298, while the predicted ephemeris was HJD 2451241.324 based on the orbital ephemeris of Schaefer and Ringwald (1995). In addition, a significantly advanced timing of the eclipse was also detected in the primary eclipse observed on March 16. The center occurred at HJD 2451254.211, which was also detected in the primary eclipse observed on March 22 and 23 is reasonably explained by the eclipsing feature on the each occasion based on the ephemeris. The vertical axis represents the relative magnitudes. The declining trend during the primary eclipse was removed prior to combining each light curve.

Fig. 3. Orbital light curve of U Sco during the plateau phase of the 1999 outburst, which was constructed from the fragmentary light curves on March 11–13, 16, 17, 22, 23, and 27. Each data point was averaged by each of about 60 points on March 11–17 and each of about 20 points on March 22–27 for clarity. The data on March 16 and 27 corresponding to the primary eclipses are separately presented from the compiled light curve. The horizontal axis represents the orbital phases based on the orbital period and the ephemeris of the minimum of the primary eclipse of U Sco defined by Schaefer and Ringwald (1995). The contrast between the data on March 22 and 23 is reasonably explained by the eclipsing feature on the each occasion based on the ephemeris. The vertical axis represents the relative magnitudes. The declining trend during the plateau phase was removed prior to combining each light curve.

of data points on March 28 was small due to the poor sky condition on that night; we thus conclude that the data are not sufficient to discuss the intraday variabilities during that night.

3.3. Orbital Variability during the Outburst

The light curve shown in figure 3 demonstrates the shape of the primary eclipse of U Sco in an outburst. The primary eclipse on March 16 had a depth of about 0.4 mag in the early plateau phase of the outburst, which is much shallower than ∆B ∼ 1.5 mag determined in quiescence (Schaefer 1990; Schaefer, Ringwald 1995). The light curve also showed no totality of the minimum and, accordingly, indicates that the primary eclipse was a partial occultation. In figure 3 the data on March 27 are also presented as an example of the shapes of the primary eclipses during the later plateau phase of the outburst. This additional data set revealed that the primary eclipse of U Sco was deeper and steeper in the later plateau phase. We conclude that the amplitudes of the primary eclipses are 0.4–0.8 mag in the plateau phase, and that we were observing a growth of the eclipsing depth as the outburst was fading away. The data during May 11–17 suggest that the duration of the eclipse extended to 0.3–0.4 orbital phase, which is wider than the ~ 0.2 orbital phase determined in quiescence.
the possibility that their variation might be the orbital-period modulations given by Schaefer (1990). However, the 0.053 d periodicity cannot be applied to our cases, because it is too short and deep to explain our minima lasting for at least 0.1 orbital phase. The possibility of an apparent period change observed in a fading object is known in dwarf-nova outbursts (Krzeminski 1965). It is safely excluded for the present case because of the non-total eclipse shapes and the dominance of the disk in the optical range instead of a hotspot usually observed in dwarf novae. Thoroughgood et al. (2001) have argued that the minimum which occurred at HJD 2451286.2 was consistent with the ephemeris of Schaefer and Ringwald (1995), but their sampling in the photometry was not sufficiently accurate to detect the minimum. The direct use of the individual minima in table 1 of Schaefer and Ringwald (1995) might have introduced a large uncertainty in the calculation of the \(O-C\) fit. According to the error values of the timings, it is more secure that the minima in each season are treated as representatives for the three seasons in evaluations of \(O-C\).

We therefore conclude not only that the minima detected in our observation were surely consequences of eclipses, but also that the timings of the minima had advanced relative to the expected ones. These shifts of the timings imply that the orbital period of the binary system had significantly shortened, likely due to mass transfer, during the last quiescent state. Accordingly, the orbital-period change of the binary system obtained by a least-squares fitting among the available data of Schaefer and Ringwald (1995) and the present result is derived as

\[
\frac{\dot{P}}{P} = -1.7(\pm0.7) \times 10^{-6}\,\text{yr}^{-1}. \quad (1)
\]

where \(P\) is the orbital period.

If this period change is the result of a conservative mass transfer between the components of the binary system, the mass-transfer rate is given by

\[
\dot{M}_2 = -\frac{\dot{P}}{P} \frac{M_2}{3(1-q)}, \quad (2)
\]

where \(M_2\) is the mass of the secondary star and \(q \equiv M_2/M_1\). This yields

\[
\dot{M}_2 = -2.4(\pm1.0) \times 10^{-6}\,\text{M}_\odot\,\text{yr}^{-1} \quad (3)
\]

for a white dwarf with \(M_1 = 1.37\,\text{M}_\odot\) and a slightly evolved main-sequence star with \(M_2 = 2.0\,\text{M}_\odot\). However, this mass-accretion rate is too high to cause shell flashes, and it results in steady hydrogen-shell burning on very massive white dwarfs instead (e.g., figure 9 of Nomoto 1982).

Hachisu et al. (2000a) estimated the envelope mass at the optical maximum as being \(\sim 3 \times 10^{-6}\,\text{M}_\odot\). If this is the present case, the mass-accretion rate should be smaller than \(\sim 2.5 \times 10^{-7}\,\text{M}_\odot\,\text{yr}^{-1}\) in the quiescence between 1987 and 1999, because a part of the helium-layer mass may have been dredged up (e.g., Kovetz, Prilnik 1994; Prilnik, Kovetz 1995). The mass-transfer rate of \(\sim 2.4 \times 10^{-6}\,\text{M}_\odot\,\text{yr}^{-1}\) derived from equation (3) above, which resulted in an envelope mass of \(\geq 10^{-5}\,\text{M}_\odot\) during the previous quiescence, is again too high to be compatible with the envelope mass derived by Hachisu et al. (2000a).

Hence, we are forced to consider the possibility of non-conservative mass transfer in the U Sco system.

Assuming that a part of the transferred matter was lost from the binary system through the outer Lagrangian points, Hachisu et al. (2000b) derived a mass-transfer rate of \(\dot{M}_2 \sim -5.5 \times 10^{-7}\,\text{M}_\odot\,\text{yr}^{-1}\) for a 0.8–2.0 \(\text{M}_\odot\) mass-donor star during the previous quiescence. This implies that a part of the transferred mass, i.e., \(\sim 3.0 \times 10^{-7}\,\text{M}_\odot\,\text{yr}^{-1}\), was being lost from the binary system. The outflowing matter carried away the orbital angular momentum effectively, and caused a shrink of the orbital separation.

4.2. U Sco as a Progenitor of Type Ia Supernovae

Together with the ephemeris of Schaefer and Ringwald (1995), we detected a significant change in the orbital period for the first time. A brief summary of our theoretical analysis for the present study was published in Hachisu et al. (2000a). Their main results are summarized as follows: 1) The mass of the white dwarf was determined as \(M_1 = 1.37 \pm 0.01\,\text{M}_\odot\) by fitting their model light curves with the early 10 days of optical data. Because the fast decline rate of the light curve during the early 10 days is very sensitive to the mass of the white dwarf, but almost independent of the mass of the companion, the configuration of the accretion disk, or the hydrogen content of the envelope, this determined mass is rather stiff. 2) The envelope mass at the optical maximum was \(\sim 3 \times 10^{-6}\,\text{M}_\odot\) and 3) the hydrogen content of the envelope was \(X = 0.05\) by assuming a solar metallicity of \(Z = 0.02\). Therefore, the mass-accretion rate of the white dwarf was \(\sim 2.5 \times 10^{-7}\,\text{M}_\odot\,\text{yr}^{-1}\) during the quiescent phase between 1987 and 1999, if no white-dwarf
matter was dredged up into the envelope. 5) About 60% \((\sim 1.8 \times 10^{-6} M_{\odot})\) of the envelope was blown off in the outburst wind, but 40% \((\sim 1.2 \times 10^{-6} M_{\odot})\) was left and added to the helium layer on the white dwarf. 6) As a result, the white dwarf can grow in mass at a rate of \(\sim 1.0 \times 10^{-7} M_{\odot} \text{yr}^{-1}\). Thus, they concluded that U Sco is a strong candidate for a progenitor system of the type Ia supernova, because the white dwarf is very close to the critical mass for type Ia supernova explosion, and will be able to reach the critical mass of \(M_{\text{c}} = 1.378 M_{\odot}\) long before the mass-donor is exhausted.

Thoroughgood et al. (2001) independently estimated the mass of the white dwarf by means of radial velocity studies of the optical spectra obtained in the final fading phase of the 1999 outburst. The mass which they determined, based on the mass function of the binary system, was extremely close to the Chandrasekhar limit \((M_1 = 1.55 \pm 0.24 M_{\odot})\); they concluded that U Sco is the best candidate binary system growing to a type Ia supernova. Their result supports our conclusion about the nature of U Sco, described above, except for the slightly lighter estimation of the mass of the secondary star.

4.3. Relation to Supersoft X-Ray Sources

In the 1999 outburst of U Sco, the object was observed as a supersoft X-ray source by the BeppoSAX satellite on March 16–17, which was about 19 days after the optical maximum (Kahabka et al. 1999). It was an observational confirmation of a theoretical prediction based on the thermonuclear runaway of recurrent novae (Kato 1996), and the first definite case of recurrent novae, implying a similarity to supersoft X-ray sources. We have recently come to know a second possible case, the eclipsing recurrent nova CI Aql, which underwent the second recorded eruption in 2000 (Kiss et al. 2001; Matsumoto et al. 2001; Lederle, Kimeswenger 2003; Matsumoto et al. 2003). Although a firm confirmation has still not been made, CI Aql is expected as to be a recurrent nova related to supersoft X-ray emissivity, according to a theoretical model for the light curve of the 2000 outburst of that object (Hachisu, Kato 2001a; Hachisu et al. 2003).

Supersoft X-ray sources are characterized by luminous and extremely soft X-ray emissions (e.g., Kahabka, van den Heuvel 1997 for a review). Part of those sources are plausibly accreting binary systems containing a relatively massive white dwarf with nuclear burning of accreting matter on the surface (van den Heuvel et al. 1992; Rappaport et al. 1994); several systems have been identified in our Galaxy and the Magellanic clouds at present (Greiner 2000). We discuss here similarities of U Sco to supersoft X-ray sources.

CAL 87 is a typical example of supersoft X-ray sources to understand the photometric characteristics of U Sco, since CAL 87 is also an eclipsing binary system (e.g., Hutchings et al. 1998 and references therein). A light-curve analysis for CAL 87 has suggested a flared accretion-disk rim and irradiations of the disk and secondary star (Schandl et al. 1997). In the case of U Sco, the primary eclipse which we observed on March 16 just corresponds to that in the supersoft X-ray state. Taking into account both a flaring-up effect of the accretion-disk rim and an expansion of the accretion-disk radius, which exceeds the Roche lobe size, Hachisu et al. (2000a) successfully reproduced the shallow depth of the primary eclipse (figure 3 of Hachisu et al. 2000a).

Recently, several systems of cataclysmic variables have also been identified as supersoft X-ray sources, which are the so-called V Sge-type stars (Steiner, Diaz 1998; Patterson et al. 1998; Greiner, van Teeseling 1998) and VY Scl-type stars (Greiner, Di Stefano 1998; Greiner et al. 1999). An observationally interesting and remarkable fact concerning those systems is that supersoft X-rays are commonly detected only during faint states in optical wavelength. Such a fact was first observed in the supersoft X-ray source RX J0513.9–6951 (Reinsch et al. 1996; Alcock et al. 1996; Southwell et al. 1996). The same matter is also suggested for other members of supersoft X-ray sources, showing such switches of bright/faint states in relatively long-term light curves, such as RX J0019.8+2156 (Greiner, Wenzel 1995; Simon et al. 2001) and RX J0527.8–6954 (Greiner et al. 1996).

These features indicate a self-absorption effect of supersoft X-rays, which only appears during optically bright states. In the case of U Sco, an optically thick wind should cease before the detection of supersoft X-rays in the plateau phase. This feature can be understood by a massive wind produced by the white dwarf during the optically bright state, i.e., the early phase of the outburst. Hachisu et al. (2000a) have shown that the strong wind stops 17 days after the optical maximum, and that the duration of the optically thick wind is consistent with the supersoft X-ray detection.

We detected the growth of the eclipse depth, from about 0.4 mag to 0.8 mag, in the plateau phase of the outburst; interestingly, these depths in the bursting phase are much shallower than \(\sim 1.5\) mag in \(B\)-magnitude obtained in quiescence (Schaefer 1990). It is well known that the eclipse in bright states of V Sge is much shallower than that in the faint states (e.g., Herbig et al. 1965; Patterson et al. 1998). The present detection of a new example of the shallow primary eclipse implies that, although its physical mechanism is not yet clear, such a shallower depth is not special in the 1999 outburst of U Sco, but common in supersoft X-ray sources when they are in a bright state or in a bursting state.

5. Summary

We obtained a complete light curve of the 1999 outburst of U Sco, including a few detections of eclipses of the binary system. The decline of the outburst showed three trends, and the light curve generally traced those of the past recorded ones. The most substantial result in this study was the detection of a significant advance of the timings of the eclipse minima, which should be a consequence of an orbital-period change of the binary system during the previous quiescence. We established the orbital-period change for the first time; the mass-transfer
rate derived from the observed $P/P$ strongly indicates the occurrence of a non-conservative mass transfer in U Sco. The behavior of the orbital light curve observed in the outburst suggests a common configuration in the optical high state of the supersoft X-ray sources (including transient sources).

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