

SU URSAE MAJORIS: THE PERFECT PROTOTYPE OF SU UMa SUBCLASS OF DWARF NOVAE

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ABSTRACT

Photometric observations of the April 1989 superoutburst of SU UMa are presented. The periodic light variation—the superhumps—were discovered proving that SU UMa is indeed a typical star of the SU UMa-type of dwarf novae and a good prototype of the class. The superhump period is equal to 113.4 min and is about 3% longer than the orbital one. It decreases during the superoutburst with the rate $dP/P \approx 6 \times 10^{-5}$. Photometry obtained during the late stages of the superoutburst suggests the presence of so-called “late superhumps.” The superhump profile has an evident, two-component structure which can be explained in the simplest way by the mass-transfer model.

1. INTRODUCTION

Dwarf novae are close binary systems consisting of a late-type main-sequence star (the secondary) and a white dwarf companion. The secondary fills its critical Roche surface and transfers material to the primary. The transferred material cannot fall directly upon the primary because of its angular momentum and forms an accretion disk surrounding the white dwarf. Additionally, the bright spot is formed on the outer rim of the disk where the mass stream impacts the disk.

SU Ursae Majoris has been selected as a prototype of a small subgroup of dwarf novae which display several distinct properties, distinguishing them from other dwarf novae. First, in addition to normal dwarf nova eruptions, they also undergo longer-lasting and brighter outbursts called superoutbursts or supermaxima. The intervals between superoutbursts tend to be more regular than the intervals between the normal eruptions, but supermaxima are much rarer than the normal outbursts. The second characteristic property is the presence of well-defined, periodic brightness changes called superhumps. The superhumps occur only during superoutbursts and their amplitudes can be more than 0.3 mag, in some cases. They are also present in systems with low orbital inclination which suggests that the phenomenon is not a simple geometric effect. The period of the superhumps is a few percent longer than the orbital one in all cases when both periods are determined (Warner and Livio 1987).

All SU UMa type dwarf novae are ultrashort period binaries. All orbital periods, except that of TU Men, fall below 2.1 hr, i.e., below the short time boundary of the “period gap” in the orbital period distribution of cataclysmic variables. It is quite possible that all unmagnetized dwarf novae with periods below this boundary are, in fact, of the SU UMa type.

Although the mechanism of the normal eruptions of dwarf novae seems to be well explained by the disk instability model (Mineshige 1988a and references therein), the mechanism causing superoutbursts and superhumps is still poorly understood. So far, several models have been proposed for superhumps; however, none is entirely satisfactory. Below, we summarize the more important ones:

(a) The eccentricity of the binary’s orbit (Papaloizou and Pringle 1979) leading to a mass-transfer modulation as the

separation of the components changes. Precession of the lines of apsides gives the period a few percent longer than the orbital one.

(b) The superhump source (bright spot) on the non-synchronously rotating surface of the secondary component (Whitehurst, Bath, and Charles 1984).

(c) The “intermediate polar model” (Warner 1985). The magnetized white dwarf rotates slowly with the period equal to the beat period between the orbital and the superhump periods. The beam from the magnetic pole illuminates part of the disk and during any orbital revolution asymmetries on the disk (like the bright spot) fall into the beam and become brighter by reprocessing. The interaction between the spin and the orbital periods gives the longer superhump period.

(d) The elliptical disk models (Vogt 1982; Osaki 1985). A precessing elliptic disk (created only during superoutburst) is the cause of the superhumps. Two mechanisms can be taken into account: the varying amount of energy released from the bright spot because of different gravitational potential around the elliptical disk (Vogt 1982) and the modulated mass transfer (Osaki 1985). The latter is caused by the varying shadow of the outer disk which modulates irradiation of the secondary from the primary, and from the inner disk.

From the aforementioned models, the latter class seems to be the most promising. Model (a) cannot explain the observed range of the orbital and superhump periods differences, (b) does not provide explanation of many superhump features, (c) assumes very slow rotation of the white dwarf which is difficult to understand theoretically, and contradicts observations (SW UMa Robinson *et al.* 1987). However, although Osaki’s model explains many properties of the superhumps, it is not clear how the elliptic disk actually forms. Whitehurst (1988) performed simulations of an accretion disk showing that, for extreme mass ratios ($q > 4$), tidal instabilities lead to creation of the precessing and elliptical disk. Because the SU UMa group is characterized by extreme mass ratios, his calculations explain why the superhump phenomenon is limited to this group of dwarf novae only. An elliptic disk created in these simulations can be the basis of the Osaki’s (1985) model. However, Whitehurst’s calculations also show that the disk is deformed by the tidal influence of the secondary during every orbital cycle. These stresses can be, in fact, a source of superhumps which would become, in this case, a tidal property of the accretion disk. A

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combined mechanism of the normal disk instability and the tidal instability can also be a cause of superoutbursts (Osaki 1989).

SU UMa itself is a relatively bright dwarf nova. It reaches a brightness of 12.0 mag during the normal outbursts, lasting typically 4 days. In superoutbursts, it can even reach 11.2 mag, and it can stay at this level for longer than 14 days (Szkody and Mattei 1984).

Although SU UMa has the typical pattern of normal and superoutbursts, and for this reason it has been chosen as the prototype of a whole class, the superhump phenomenon has not been observed in this star. Barwig and Schoembs (1981) obtained photometry of the star at the beginning of a superoutburst, but they did not find any periodic features resembling superhumps. Lack of superhumps in SU UMa raised questions concerning homogeneity of the SU UMa group as a whole. Are superhumps always present during superoutbursts? Is the presence of a longer eruption sufficient to classify the star as a SU UMa-type? (Note that some of the normal U Gem dwarf novae also have longer eruptions.) Is SU UMa a good prototype of the class?

Only detailed observations of an SU UMa superoutburst could give an answer to these questions. Unfortunately, the superoutbursts of the star stopped for 3 yr after the Barwig and Schoembs (1981) observations. Then they reappeared, but occurred less frequently than before 1980, typically once per year. Meanwhile, Thorstensen, Wade, and Oke (1986) derived the orbital period of SU UMa using spectroscopic data. Its value turned out to be typical for SU UMa type stars and equal to 109.9 min. The photometric observations of the star during a normal eruption (Udalski 1988) did not show any similar periodicities.

As usual, the April 1989 superoutburst was detected by observers of the AAVSO. Notified about the phenomenon by the Director of the AAVSO (Dr. J. A. Mattei), we were able to collect photoelectric light curves of SU UMa during the eruption. The preliminary results have already been reported (Udalski 1989). Here, we present the full details of our observations.

II. OBSERVATIONS

The photoelectric photometry of the April 1989 superoutburst of SU UMa was carried out during 6 nights between 21/22 and 27/28 April 1989. The observations were obtained with the 61 cm/48 cm telescope twin photometric system of the David Dunlap Observatory, University of Toronto in Richmond Hill, Ontario, Canada (Ferne 1986). The system consists of two almost identical, single-channel photometers attached to 61 cm and 48 cm telescopes. Each photometer contains a chopping system with which light can be measured from two diaphragms alternately. The measured star is located in one of these diaphragms, whereas the second one measures nearby sky background. The difference of the two measurements gives the net count from the object. The chopping frequency is set to 60 Hz. This value has been found to give the best results in subtracting fast, short time-scale changes of the sky background.

The system also provides the capability to remove slower scale atmospheric transparency changes. Two photometers allow simultaneous monitoring of an object and of a nearby comparison star. Extinction changes of up to several percent can be removed by dividing the simultaneous measurements

of the variable by those of a constant comparison star (e.g., Grauer and Bond 1981).

We collected a total of 25 hr of SU UMa superoutburst photometry. Because we concentrated mainly on searching for possible periodicities, we observed the star in "white" light to assure reasonable count statistics. The broadband was defined by the spectral response of an EMI 9658R photomultiplier. We did not attempt color photometry because of the small size of the telescopes and the faintness of the star. One integration consisted of 1250 added chopping cycles which corresponded to the integration time of 10 s for both object and sky diaphragms. The effective system time resolution was then about 30 s. We estimate the statistical uncertainty of a single measurement to be about 0.02 mag. The last two runs, when SU UMa was about 0.4 mag fainter, were binned into 60 s bins (i.e., two consecutive observations) to preserve this accuracy.

BD 63°769 served as a comparison star which was observed simultaneously with the 48 cm telescope. It was also observed from time-to-time with the 61 cm telescope, to check the stability of the gain differences of both telescopes. We did not find any gain variations greater than 0.003 mag. At least twice per night BD 63°765 was observed as a secondary comparison. Again, we did not find any magnitude differences between the primary and secondary comparisons larger than 0.012 mag. Each night, we also obtained several measurements to derive corrections for non-equal sizes of diaphragms in the chopping system in each photometer. These small corrections were negligible in the case of the much brighter comparison stars, but were taken into account for the variable star.

The data were reduced in the following way. First, the variable star measurements were corrected for diaphragm-size correction by adding empirically obtained values. They were then divided by the averaged comparison-star counts. For two nights, with nonphotometric conditions (24/25 and 26/27 April), the variable counts were divided by the simultaneous comparison counts, without averaging. The data were then crudely corrected for the small differential extinction (always smaller than 0.015 mag) and left in arbitrary magnitude units. Table I gives the observing log.

III. THE APRIL 1989 SUPEROUTBURST

Figure 1 presents the visual light curve of the April 1989 SU UMa eruption. The data were obtained by members of the AAVSO and were kindly provided by Dr. J. A. Mattei. The eruption started on 15 April 1989. It probably began as a normal outburst. SU UMa stopped at the typical normal outburst magnitude of $V \approx 12.0$ for at least one day. Unfortu-

TABLE I. Log of observations.

No.	Date	Start Time (JD - 2447600)	Length (hr)
1	1989 Apr 21/22	38.5868	5.74
2	1989 Apr 22/23	39.5674	6.02
3	1989 Apr 23/24	40.5661	5.72
4	1989 Apr 24/25	41.6116	1.00
5	1989 Apr 26/27	43.5794	1.50
6	1989 Apr 27/28	44.5593	5.72

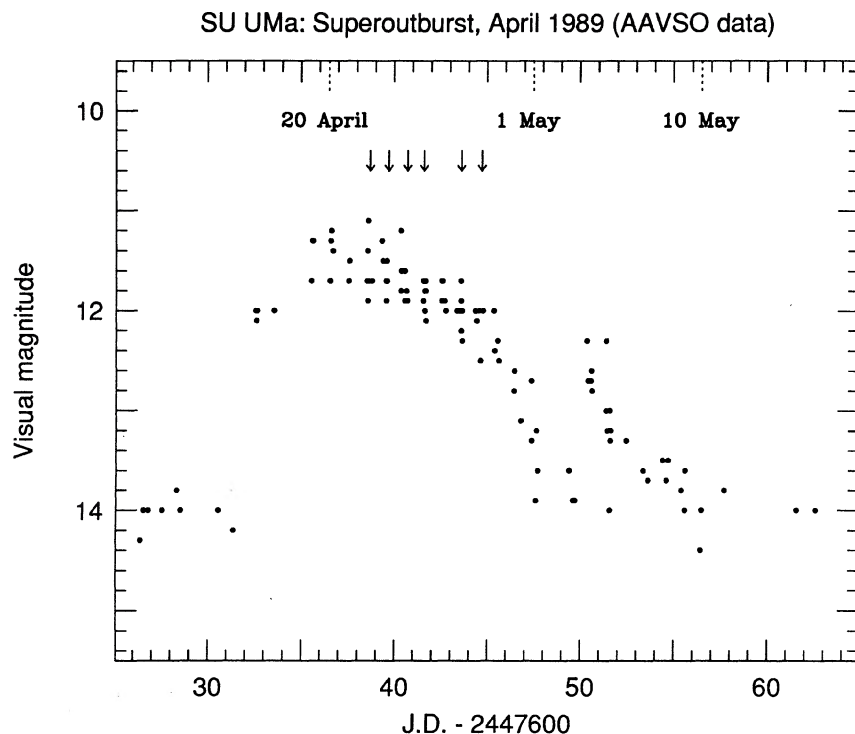


FIG. 1. Visual light curve of the April 1989 superoutburst of SU UMa obtained by observers of the AAVSO. The arrows mark moments when photoelectric runs were obtained.

nately, the AAVSO data file lacks information on the crucial moment of triggering the superoutburst which took place on 18 April. On the next night, the superoutburst was already clearly developed because SU UMa brightened about 0.5 mag. The maximum of light was reached around 20 April ($V \approx 11.4$). Then the star began to fade slowly down to $V \approx 12.5$ on 29 April. The final decline took place around 1 May. However, three days later, SU UMa evidently underwent another short, normal outburst.

Figure 2 shows photoelectric light curves of SU UMa collected during the superoutburst. The very short run from 24/25 April, obtained in bad photometric conditions and interrupted by complete cloudiness, has not been included there. Our first observations took place on 21/22 April, when the superoutburst was well developed. Very soon, we discovered the periodic light variations (superhumps). They had an amplitude of up to 0.15 mag. We were able to observe three consecutive maxima on this first night. During the following nights, we observed 11 more superhumps. Their amplitude gradually increased, reaching 0.2 mag on 22 and 23 April. The shape of the superhumps remained almost the same during the superoutburst. Clearly, the main hump was followed by a smaller, secondary hump shifted about 0.35 in phase (see Sec. VI).

The situation changed during the last, almost 6-hr-long run, on 27/28 April. The maxima became less regular and their shape changed from cycle to cycle. Two days later, SU UMa began its final decline to quiescence.

IV. THE PERIOD OF SUPERHUMPS

The photometric coverage of almost the whole superoutburst allowed us to determine a precise value of the super-

hump period. The timings of the moments of the superhump maxima are listed in Table II. We also include a moment derived from the very short run on 24/25 April which is not shown on Fig. 2. The shape of this run clearly showed a maximum which we interpret as a superhump.

We tried to establish a linear ephemeris for the data in Table II. However, it turned out that the moments for the last night (27/28 April) were shifted about 0.5 in phase and it was not possible to fit all moments with the single linear ephemeris. Therefore, we exclude these maxima from the period determination and we discuss their possible nature in Sec. V.

The best linear fit to the superhump maxima can be described by the following elements:

$$\text{JD hel.} = 2447638.645 + 0.078773 P \pm 0.001 \pm 0.000045. \quad (1)$$

We also considered the 1 day aliases of this period, but we have excluded them as they gave much greater O - C residuals.

The well-studied SU UMa stars reveal an apparent decrease of the superhump period during superoutbursts (Warner 1985). Because our data spread over 65 cycles it was possible to check if this was also the case for SU UMa. The best second-order fit gives an ephemeris:

$$\text{JD hel.} = 2447638.643 + 0.079042 P - 4.6 \times 10^{-6} P^2 \pm 0.001 \pm 0.000095 \pm 1.5, \quad (2)$$

where we again excluded the moments from 27/28 April. Table II contains the O - C residuals for the linear and quadratic ephemeris.

As can be seen, there is a decrease of the superhump peri-

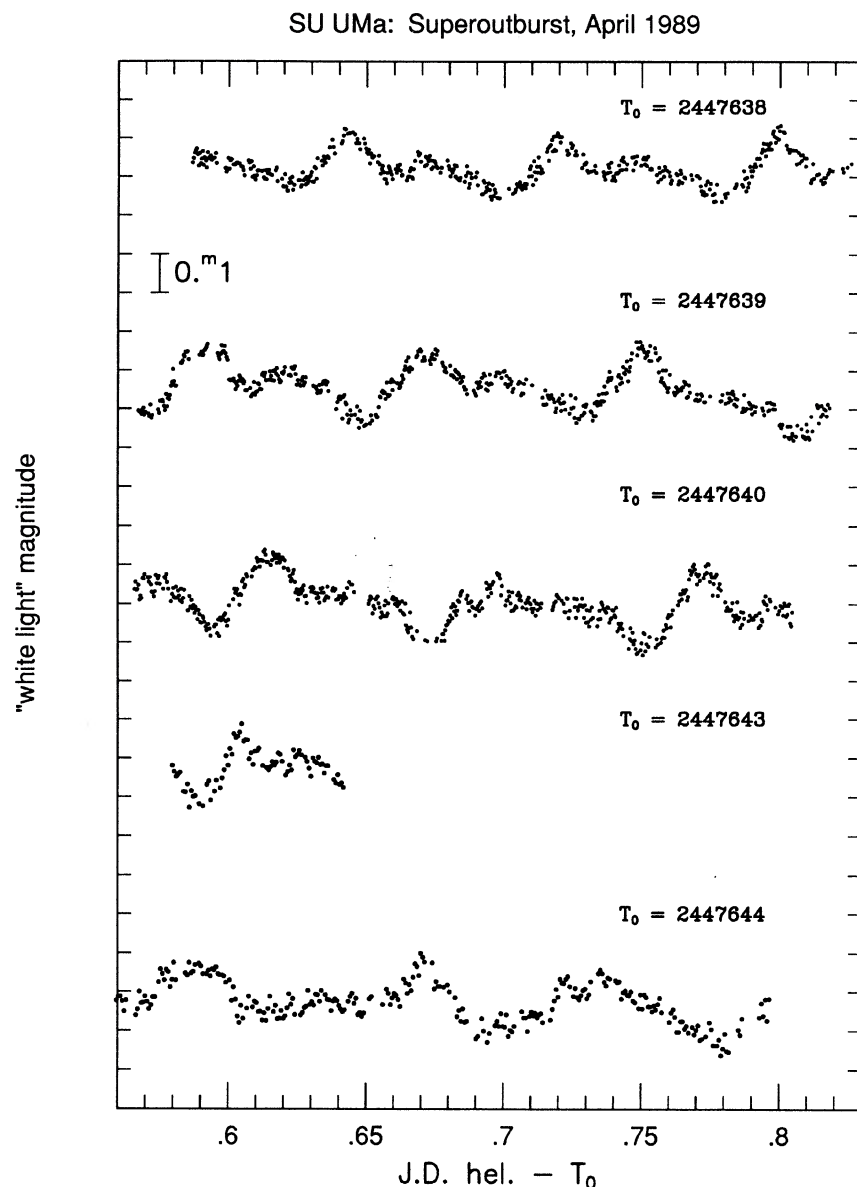


FIG. 2. "White-light" photoelectric light curves collected during the April 1989 superoutburst of SU UMa.

od during the superoutburst. We checked the statistical significance of the quadratic term using the method described by Pringle (1975). Application of the method to our data gives the quadratic term significance at the level 98.3%. Additional evidence supporting decrease of the superhump period is discussed in Sec. V. SU UMa is then the seventh star showing this property (Warner 1985). Therefore, we can strengthen Warner's conclusion that the decrease of the superhump period is a common phenomenon among the SU UMa-type dwarf novae.

We also checked the possibility of the existence of other periodicities in our data. Some dwarf novae are known to reveal periodic or quasiperiodic oscillations on timescales of minutes to seconds. We performed a periodogram analysis of the data prewhitened by subtracting the fundamental superhump period and its harmonic components. However, we

did not find any significant period. In particular, periodicities of 13, 19, or 38 min, which were observed during normal outburst and at quiescence (Barwig and Schoembs 1981; Udalski 1988), were not present during the superoutburst.

V. SU UMa AS A SU UMa TYPE DWARF NOVA

Evidently, SU UMa is a typical member of the SU UMa subgroup of dwarf novae. Discovery of the superhumps during the superoutburst proves that this main, distinguishing property of SU UMa-type stars is present in SU UMa as well.

The presence of the superhumps in SU UMa gives us an opportunity to compare the orbital and the superhump period. Except for four eclipsing SU UMa type stars, the orbital period is known only in a few cases derived either from the orbital hump (visible in quiescence) or from radial-velocity

TABLE II. Moments of superhump maxima.

No.	Time of Maximum (JD - 2447600)	O-C* (phase)	O-C** (phase)
1	38.644	-0.013	0.013
2	38.720	-0.048	-0.025
3	38.799	-0.045	-0.026
4	39.592	0.022	0.015
5	39.672	0.037	0.029
6	39.751	0.040	0.030
7	40.615	0.008	-0.014
8	40.696	0.037	0.014
9	40.772	0.001	-0.022
10	41.638	-0.005	-0.024
11	43.605	-0.035	0.009
12	44.588	0.445	0.547
13	44.672	0.511	0.619
14	44.737	0.336	0.449

* - linear elements.

** - square elements.

measurements. For all SU UMa type stars with known orbital period, the superhump period turns out to be a few percent longer than the orbital one (Warner and Livio 1987).

The orbital period of SU UMa was first derived by Thorstensen *et al.* (1986) from radial-velocity measurements of emission lines. However, because of the moderate inclination of the system ($i \approx 45^\circ$), determination of the period was not an easy task. Based on three runs separated by a few hundred days, Thorstensen *et al.* (1986) gave a value of 0.076351 day (109.9 min) as the most probable orbital period. A small number of possible aliases falls in the range of 109.8–110.1 min.

The mean superhump period derived from the superhump maxima is equal to 113.4 min (Sec. IV). Therefore, also in the case of SU UMa, it is about 3.0%–3.3% longer than the orbital one. Again, the widely accepted feature of the SU UMa-type stars, the superhump period longer by a few percent than the orbital one, finds one more independent confirmation. Stolz and Schoembs (1984) first noted that the ratio of the superhump to orbital period increases with the orbital period. Comparing the appropriate ratio for SU UMa, one can find that it conforms to this relation (see Fig. 10, Robinson *et al.* 1987). However, it should be noted that the relation still lacks objects with longer periods to establish it beyond any doubt. The discovery of superhumps, with the period 5% longer than the orbital one, in the very short-period dwarf nova, T Leo (Slovak, Nelson, and Bless 1988), seems to contradict the existence of the Stolz–Schoembs relation.

As was discussed in Sec. IV, the maxima observed on 27/28 April did not follow the linear or second-order elements. As can be seen from Table II, they occurred more or less around the phase 0.5. Observations of VW Hyi (Vogt 1983) show that the so-called “late superhumps” develop at the final phases of superoutburst. They have a period similar to the normal superhumps, but their distinguishable feature is a phase shift by about 0.5 with respect to the normal superhumps. Warner (1983) reanalyzed Semeniuk’s (1980) observations of another SU UMa star, V436 Cen, and found that superhumps observed there in the final stages of the

superoutburst may be in fact the “late superhumps.” The “late superhumps” were also observed in OY Car (Schoembs 1986).

The 0.5 phase shift of SU UMa maxima observed on 27/28 April strongly suggests that we see here the same phenomenon which was observed in VW Hyi and V436 Cen. Examination of Fig. 1 supports this explanation—the observations from that night were carried out only two days before the final decline to normal low state. Therefore, we are convinced that the maxima observed on 27/28 April were in fact the “late superhumps” and this phenomenon is also present in SU UMa. The star would then be the next object showing this feature. We suppose that the “late superhumps” are common among the SU UMa-type stars, and that lack of a good photometric coverage of superoutbursts has prevented discovery of them in more systems.

It is believed that the phase shift of the “late superhumps” is 0.5. If so, the timings of the late superhumps in SU UMa give an additional support for the decrease of the superhump period in SU UMa (Sec. IV). Adding 0.5 to the respective O – C residuals in Table II, one finds that moments of the “late superhumps” match the quadratic ephemeris better than the linear one. The rate of decrease of the superhump period in SU UMa is then of the order of $dP/P \approx 6 \times 10^{-5}$ and is comparable to that observed in a few other SU UMa type stars (Warner 1985).

SU UMa turned out to be a typical SU UMa-type star, sharing all known properties of stars in this class. As such, it can now be considered as a good prototype of the SU UMa class not only because of its pattern of normal and superoutbursts, but also because of its photometric superhump behavior.

VI. THE SUPERHUMP PROFILE

One of the potentially powerful tests to distinguish between superhump models is modeling of superhump profiles. Mineshige (1988b) examined the response of an accretion disk to rapid modulations of mass transfer, taking into account two sources of light: the spot and the outer disk component. The presence of the latter is suggested by observations of the high-inclination SU UMa-type stars. In spite of many approximations, he was able to reproduce, at least qualitatively, the superhump profiles and color changes of VW Hyi, providing a strong support for the models predicting varying mass transfer as a mechanism of superhumps (Osaki 1985).

As was described in Sec. III, the SU UMa superhump shape remained very stable during the April 1989 superoutburst. The main, sharp superhump peak was followed by a broader and lower amplitude secondary hump. Such a shape is evidently different from that observed in higher inclination systems like VW Hyi (van Amerongen, Bovenschen, and Paradijs 1987), OY Car (Krzeminski and Vogt 1985), or Z Cha (Warner 1985). To examine it closer, the mean superhump profile was derived. First, we rescaled the data for the nights of 21/22–26/27 April to the same mean intensity level and then folded them with the linear elements (1). The folded data were then once again renormalized to the intensity at the minimum of brightness. The mean superhump profile was obtained by binning the folded data into 0.05 phase bins. On average, about 90 points fell into each bin. Figure 3(a) shows the mean profile where, for clarity, the phases are repeated twice.

Figure 3(a) confirms our earlier conclusions. The super-

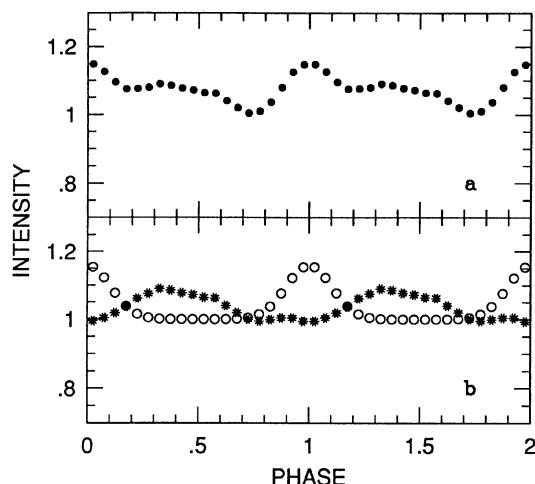


FIG. 3. (a) The mean profile of the superhump during the April 1989 SU UMa superoutburst. (b) Two components of the superhump profile: open circles and asterisks denote the compact hot spot source and the broad, outer disk component, respectively.

hump evidently consists of two components: the sharp peak around phase 0.0 with the FWHM of about 0.2 and the amplitude of 15% and the broad hump with the amplitude about 9% and the maximum around phase 0.35–0.40. We extracted the both components by subtracting the sharp peak from the observed profile, approximating it by the Gaussian. Figure 3(b) shows both components separately. Added, they give the total superhump profile from Figure 3(a).

Unfortunately, we only have the “white” light profile of the superhump (corresponding approximately to the blue band). Therefore, we do not have any information about color changes of the superhump with phase and we cannot draw any conclusions about temperatures of both peaks. We can only speculate that the brighter sharp peak is probably hotter than the broad second component. Moreover, our light curve cannot be absolutely calibrated which would allow us to estimate the size of the emitting area. However, it seems logical to associate the sharp peak with a bright compact object, and the second maximum with the more extended cooler area.

What can cause the two components of the superhump? Obviously, the observations rule out models assuming one source of the superhump. The modulated mass-transfer model seems to give the most promising and natural explanation. Calculations of Mineshige (1988b) show that, in response to the modulated (with the superhump period) mass transfer, the outer disk heats itself and can produce large modulations of the disk brightness with the superhump period. These changes are delayed with respect to the mass-transfer modulations. Having two light components (the bright compact spot and delayed extended disk source) both varying with the superhump period, Mineshige (1988b) was able to reproduce the superhump shape and color changes for VW Hyi.

Although we can only extrapolate the results of Mineshige’s calculations for VW Hyi (whose parameters like

components masses, accretion disk size, temperature and inclination differ from those of SU UMa), similarity of his result to our observations is striking. In particular, his Fig. 3 shows that the delay of the brightness of the disk component can reach phases 0.2–0.3 which is comparable with the observed range of 0.35–0.40 in SU UMa. The disk component is also much wider and has a lower amplitude than the sharper spot component. However, one should remember that our comparison has only a very qualitative meaning, and that more accurate calculations should be performed to reproduce the profile of the SU UMa superhump.

The observations of the SU UMa superoutburst seem to support the mass-transfer model for superhumps. Mineshige (1988b) discusses the possible origin of modulated mass transfer suggesting the elliptical disk as the most promising mechanism. On the other hand, although his explanation of two light components of the superhump seems to be the simplest, a much more complicated situation cannot be excluded. For instance, the Whitehurst (1988) model predicts a roughly elliptical shape of the disk during the superoutburst. In addition to his tidal stresses mechanism for superhumps, the modulated mass-transfer mechanism, which requires an elliptical disk, might work then as well.

VII. CONCLUSIONS

The results of the first observations of the SU UMa superoutburst can be summarized as follow:

- (1) The light curves show superhumps indicating that SU UMa is a typical SU UMa-type star.
- (2) The superhump period is equal to 113.4 min and is about 3% longer than the orbital one.
- (3) The superhump period decreases during the superoutburst.
- (4) The “late superhumps” are present during the final stages of the superoutburst.
- (5) The superhump has an interesting, two-component structure which can be explained in the simplest way on the basis of the mass-transfer superhump model (Mineshige 1988b).

Conclusions (1)–(4) prove that from the observational point-of-view, SU UMa is the perfect prototype of the SU UMa-class of dwarf novae.

The next obvious observational steps should include:

- (1) Photometry of the next superoutbursts of SU UMa to check if the two-component structure of the superhump is always present, or if it was only a transient feature of the April 1989 superoutburst.
- (2) Multicolor observations of the SU UMa superhump to check the temperature, and areas of both components of the superhump.

We would like to express our gratitude to all observers of the AAVSO for their excellent and valuable work. We acknowledge the AAVSO observations sent by the Director AAVSO, Dr. J. A. Mattei, and we also thank her for notification about the April 1989 superoutbursts. We are very grateful to Dr. D. Fernie for making it possible to use his scheduled telescope time. We wish to thank Dr. S. M. Rucinski and Dr. N. R. Evans for their reading of the manuscript and useful comments.

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