Detection of superhumps in the VY Scl-type nova-like variable KR Aur

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ABSTRACT

We report on the detection of negative superhumps in KR Aur, a typical VY Scl star. The observations were obtained with a multi-channel photometer over 107 h. The analysis of the data clearly revealed brightness variations with a period of 3.771 (±0.005) h. This is 3.5 per cent shorter than $P_{\text{orb}}$, suggesting that the observed oscillation is a negative superhump. Negative superhumps in VY Scl stars are widespread. The discovery of powerful soft X-rays from V751 Cyg suggests that VY Scl stars may contain white dwarfs, on to which nuclear burning of the accreted material occurs. If this suspicion is correct, it is possible that the powerful radiation emerging from the white dwarf may cause a tilt of the accretion disc to the orbital plane, and its retrograde precession may produce the negative superhumps seen in VY Scl stars.

Key words: stars: individual: KR Aur – novae, cataclysmic variables – stars: oscillations.

1 INTRODUCTION

Cataclysmic variables (CVs) are interacting binaries that consist of a white dwarf primary accreting matter from a low-mass secondary. In non-magnetic systems, this matter forms a bright accretion disc. Many CVs of short orbital period have light-curves with prominent humps, which reveal periods slightly longer than $P_{\text{orb}}$. These are called ‘superhumps’, as they are characteristic of SU UMa-type dwarf novae in superoutbursts. Some bright nova-like variables and nova remnants show superhumps during the normal brightness state. These are called permanent superhumps. Their periods can be either a few per cent longer than $P_{\text{orb}}$, in which case they are called ‘positive superhumps’, or a few per cent shorter, in which case they are called ‘negative superhumps’. Typical full amplitudes of permanent superhumps are about 5–15 per cent of the mean brightness, but they are highly variable and sometimes even disappear from the light-curve. The periods of the superhumps are unstable and usually show appreciable wobbling. A positive superhump is explained as the beat between the binary motion and the precession of an eccentric accretion disc in the apsidal plane. A negative superhump is explained as the beat between the orbital period and the nodal precession of a disc tilted to the orbital plane. A review of permanent superhumps is given in Patterson et al. (1993), and some recent data on permanent superhumps can be found in Patterson et al. (2002).

VY Scl stars are CVs with light-curves that are characterized by orbital drops from steady high states into low states lasting up to several hundred days. VY Scl stars often reveal positive and negative superhumps. The classical example is TT Ari, which alternates between showing positive and negative superhumps (Skillman et al. 1998). KR Aur is a typical VY Scl star. Spectroscopic observations revealed that it is a close binary system, consisting of a white dwarf (0.7 $M_\odot$) and a red dwarf (0.48 $M_\odot$) with an orbital period of 3.907 h (Shafter 1983). A historical light-curve for KR Aur has been compiled by Liller (1980). The brightness of KR Aur is usually between 12 and 14 mag, with occasional decreases to 15.5 mag, but it drops to 18 mag occasionally. Singh et al. (1993) detected large-amplitude quasi-periodic oscillations (QPOs) in this star, with periods in the range 500–800 s. There were also indications of a modulation with a period of about 4 h. This modulation might represent the orbital period or might be a type of superhump. However, Kato, Ishoka & Uemura (2002) conducted photometric observations of KR Aur and found no modulation with such a period. We decided to clarify whether a photometric signal near the orbital period is present in KR Aur, and the first observational night clearly showed such a modulation. This paper presents the results of our observations, spanning a total duration of 107 h.

2 OBSERVATIONS

In observations of CVs we use a multi-channel photometer that allows us to make continuous brightness measurements of two stars and the sky background. Photomultiplier tubes (PMTs) have a lower quantum efficiency than CCDs and are not advantageous in observations of faint stars. In observations of relatively bright stars (12–13 mag, metre-class telescopes), however, multichannel photometers with PMTs can attain the same or better accuracy under similar conditions (Abbott & Kleinman 1994). We verified this by performing the noise analysis of our observations according to the Transits of Extrasolar Planets (TEP) network (Kozhevnikov & Zakharova 2000). The TEP network was aimed at detecting planetary transits in CM Dra, a star of 11 mag. Our accuracy was nearly the same as the accuracy of the other TEP network observations with CCDs, although we used a smaller telescope located in unfavourable photometric conditions (see tables 1 and 3 of Deeg et al. 1998).
KR Aur was observed in 2004 January and February over 13 nights using the 70-cm telescope at Kourovka observatory, Ural State University. A journal of the observations is given in Table 1. The programme and comparison stars were observed through 16-arcsec diaphragms, and the sky background was observed through a 30-arcsec diaphragm. The comparison star was located in the direction NE, at a separation of 7.4 arcmin from KR Aur. This comparison star was chosen from nearby stars because its colour was close to that of KR Aur, and also because it was only slightly brighter than KR Aur, which minimized the influence of the variable sky background under non-photometric conditions. Data were collected at 8-s sampling times in white light (approximately 300–800 nm), employing a PC-based data-acquisition system. We used the CCD guiding system, which enables precise centring of the two stars in the diaphragms to be maintained automatically. This improves the accuracy of brightness measurements and facilitates the acquisition of long continuous light-curves. The design of the photometer is described in Kozhevnikov & Zakharova (2000).

The measurements of the sky background were subtracted from the programme and comparison star data, taking into account the differences in light sensitivity between the various channels. We then obtained differences of magnitudes of the programme and comparison stars. Because the angular separation between the programme and comparison star is small, the differential magnitudes were corrected for first-order atmospheric extinction and light absorption by the thin clouds that sometimes appeared during the observations. According to the mean counts, the photon noise (rms) of the differential light-curves is equal to 13 mmag. The actual rms noise also includes atmospheric scintillations and the motion of the star images in the diaphragms. We estimate that these noise components equal approximately 5 mmag each. The total white-noise component of the light-curves (rms) is then 15 mmag. Fig. 1 presents the longest differential light-curves of KR Aur, with magnitudes averaged over 40-s time intervals. The white-noise component of these light-curves is 7 mmag. Besides the white-noise components, each photometric system usually exhibits the 1/f noise component, which decreases the precision at frequencies below approximately 1 mHz (e.g. Young et al. 1991). When observing in white light, most of the 1/f noise component can be caused by differential extinction. In the following analysis, however, we use light-curves from which nightly low-frequency trends are removed by subtraction of a second-order polynomial fit. After such a procedure, the average level of the 1/f noise in the amplitude spectra at frequencies below 1 mHz is small and does not exceed 1 mmag.

During the main observations we carried out the measurements only in white light. A month later we found $B = 13.47$, $V = 13.35$ for KR Aur, and $B = 13.26$, $V = 12.70$ for the comparison star. This implies that in white light KR Aur was fainter than the comparison star by approximately 0.4 mag. As seen in Fig. 1, the differential magnitude of KR Aur was roughly the same. Hence the B magnitude of KR Aur was about 13.5 during our observations.

### 3 ANALYSIS AND RESULTS

As seen in Fig. 1, the light-curves of KR Aur are fairly typical of CVs in showing rapid flickering. QPOs on a time-scale of tens of minutes are also easily visible. In addition, the light-curves show prominent maxima and minima, which may indicate periodic oscillation on a time-scale of hours. Fourier amplitude spectra calculated for the longest de-trended light-curves show that the semi-amplitude of this oscillation is variable from night to night, with a range of 0.05–0.15 mag. Because the oscillation has only a few oscillation cycles in each individual light-curve, however, these spectra do not allow us to estimate the oscillation frequency with sufficient accuracy. Furthermore, when considered independently from each other, the individual light-curves cannot show whether this oscillation is coherent. For this reason we analysed the data incorporated into
common time series. These time series were composed from all
the de-trended individual light-curves and included the gaps arising
from daylight and poor weather during the observations.

To calculate the power spectra we first used the method of a fast
Fourier transform (FFT). The second method was an analysis of
variance (AoV) (Schwarzenberg-Czerny 1989). The AoV method
is usually applied to data folded and grouped into bins according
to the phase of a trial period. Here, however, we specify trial frequen-
cies at constant intervals of their change and then apply the AoV
method as before. Then, instead of an AoV periodogram, we obtain
an AoV spectrum, which can cover larger time intervals of variabil-
ity. In addition, such an AoV spectrum is easily comparable with
a Fourier power spectrum. However, the test statistic $\Theta_{AoV}$ is also
sensitive to oscillations with multiple frequencies, and this creates
additional noise. For this reason one more power spectrum was cal-
culated, with the aid of a sine-wave fit (SWF) to folded light-curves
using the method of least squares. Such a power spectrum can have
the large detection sensitivity of periodic signals that is inherent for
AoV spectra. In addition, it is not sensitive to multiple frequencies.
All these spectra are presented in Fig. 2. They show distinct pic-
tures of principal peaks and one-day aliases. The principal peaks
correspond to a period of 3.771 (±0.005) h. The width and location
in frequency of all the one-day aliases correspond exactly to the
window functions obtained from artificial time series consisting of

a sine wave and the gaps. This means that the observed oscillation
behaves like a strictly periodic oscillation and has coherent phase
during all the observational nights. It leaves no doubt as to the reality
of the detected oscillation.

As mentioned above, we analysed de-trended individual light-
curves. It is worthwhile to note that the subtraction of a poly-
nomial fit is a standard procedure used in time-series analyses for
de-trending (e.g. Bendat & Piersol 1986). As it is able to decrease
amplitudes of signals only at very low frequencies, this procedure
cannot introduce additional periodicities. The oscillations observed
in KR Aur have a rather low frequency, however, and we must there-
fore estimate the effect of this de-trending. By performing numerical
experiments with artificial time series, we found that the subtraction
of a second-order polynomial fit from the individual light-curves de-
creases the amplitude of the 3.771-h signal by only 20 per cent.

The period of the observed oscillation differs significantly from the
orbital period of KR Aur, which is obtained earlier by using rad-
ial velocity measurements and equals 3.907 h (Shafter 1983). The
large noise level visible between the principal peak and the one-day
aliases (Fig. 2) may denote the presence of another oscillation with
a similar frequency, and this oscillation may be the orbital period.
This signal can be hidden in the relatively large features of the win-
dow function that are caused by the large 3.771-h signal. To find this
oscillation, we excluded the main oscillation from the data. This is a
well-known technique that allows the removal of these features and
therefore makes visible smaller signals in the power spectra. Fig. 3
shows the results. Fig. 3(a) shows the SWF power spectrum of an
artificial time series in which two large peaks indicate the frequen-
cies of two oscillations with periods of 3.907 h and 3.771 h. The
presence of these two peaks also shows that the frequency resolution
of our data is sufficient to distinguish between these two periodici-
ies. Fig. 3(b) shows the SWF power spectrum of an artificial time
series consisting of a sine wave with a period of 3.771 h and with the
sampling of the observed data. This spectrum characterizes the

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Power spectra of KR Aur calculated by means of a FFT algorithm,
via the analysis of variance of folded light-curves and with the aid of a sine-wave
fit (SWF) to folded light-curves. The horizontal dotted line marks the
0.1 per cent significance level. The principal peaks are labelled with ‘F’ and
the one-day aliases are labelled with ‘A’. The bottom frame shows the SWF
power spectrum of the pre-whitened data.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** (a) Sine-wave fit (SWF) power spectrum of an artificial time series
consisting of two sine waves with periods of 3.907 h and 3.771 h and with
the gaps according to the observations. (b) SWF power spectrum of a sine
wave with a period of 3.771 h and with the gaps. (c) and (d) SWF power
spectra of the data of KR Aur and the pre-whitened data on a large scale.
The arc connecting the flickering level seems like an overestimate. In the second case the flickering level is the arc connecting the first and last points of the QPO hump (as shown in Fig. 5). This level seems more likely. We also need to know the noise of the data. At the highest frequencies, when the flickering power becomes negligible, the power spectrum must flatten out owing to the white noise in the data. Examining the high-frequency part of the average power spectrum, it can be seen that the flickering in KR Aur is detectable up to a frequency of 47 mHz. The noise level at higher frequencies corresponds to a white noise of 19 mmag. This is close to the white-noise component of the light-curves (15 mmag), which we evaluated directly (see Section 2). Thus, by excluding this white-noise level and integrating the power spectrum over frequencies higher than 0.2 mHz, we find that the relative power of the QPOs is on average 19 and 35 per cent of the flickering power for the first and second cases, respectively. This QPO power seems considerable.

4 DISCUSSION

Shafter (1983) found the orbital period of KR Aur to be equal to 3.9071 ± 0.0005 h. The detected period is 3.771 ± 0.005 h. This is 3.5 per cent shorter than $P_{\text{orb}}$. Such a small but clear discrepancy between the orbital and photometric periods is a feature of a permanent superhump system, and may therefore indicate that the observed oscillation is a negative superhump. Brightness variations with periods slightly shorter than the orbital period are also, however, typical of asynchronous polars (e.g. V1500 Cyg, Stockman, Schmidt & Lamb 1988). Unlike asynchronous polars, the superhumps usually show an appreciable instability in their periods. Power spectra of our data divided into two groups (January and February) hint at such an instability because the principal peaks are slightly displaced in frequency from each other (Fig. 6). This displacement is small, however, and could be caused by noise in the data. None the less, we must exclude the possibility that the observed oscillation is caused by a rotating magnetic white dwarf. Strong light polarization has never been found in VY Scl stars, and, therefore, they can contain only weakly magnetic white dwarfs similar to those of intermediate polars, the rotation periods of which are much shorter than $P_{\text{orb}}$.

Because different kinds of superhumps are detected in CVs depending on their brightness state, it is important to know the brightness state of KR Aur. During the main observations it was obvious...
that this star was in the bright state. Our 70-cm telescope does not allow us to observe stars fainter than 15 mag, and KR Aur was easily observable. As seen in Fig. 1, the average brightness of KR Aur was decreasing. This trend might denote the transition to the low state. A month later, however, we found the visible brightness of this star was in the bright state. Our 70-cm telescope does not maintain the disc tilt, but also causes the disc to precess, with the effect of radiation. This works well for luminous X-ray binaries, according to calculations made by Foulkes et al. (2005) it is sufficient to tilt the disc (see their table 2).

The basic properties of VY ScI stars correspond surprisingly well to an extension of the SSB class, and the conjecture that all VY ScI stars are SSBs seems viable (Greiner et al. 1999). Although luminous supersoft X-ray emission denoting nuclear burning is directly observed only in the VY ScI star V751 Cyg, various other VY ScI stars show indirect signs of nuclear burning. Strong UV radiation was found in the optical low state of TT Ari, and as far back as the early eighties it was suspected that this radiation might be caused by nuclear burning (Wagenaar et al. 1982). The VY ScI star BZ Cam is surrounded by a faint emission nebula. Photoionization by a canonical CV cannot account for the nebular excitation, and the emission-line ratios of the BZ Cam nebula and the nebula size are in agreement with the predictions of ionization by luminous ($10^{35–10^{36}}$ erg s$^{-1}$) supersoft X-ray emission (Greiner et al. 2001). Furthermore, because we do not see other plausible reasons for negative superhumps in VY ScI stars, nor in luminous nova-like variables, we can consider negative superhumps as one more indirect sign of nuclear burning of the accreted material.

5 CONCLUSIONS

(i) We found brightness variations with a period of 3.771 h in the optical light-curve obtained during 107 h of observations of the VY ScI star KR Aur in 2004 January and February.

(ii) The semi-amplitude of these variations was in the range of approximately 0.05–0.15 mag, and showed changes from night to night.
(iii) The observed period is 3.5 per cent shorter than the orbital period, suggesting that the observed oscillation is a negative superhump.

(iv) Like other superhump systems, KR Aur reveals QPOs on a time-scale of tens of minutes. The power of these QPOs is on average 19–35 per cent of the flickering power at frequencies higher than 0.2 mHz.

(v) Distinctive features of VY Scl stars, and especially the discovery of luminous soft X-rays from V751 Cyg, demonstrate that VY Scl stars may contain white dwarfs, on to which nuclear burning of the accreted material occurs. Then the large fraction of negative superhumpers among VY Scl stars suggests that the negative superhumps in such stars may be caused by the powerful radiation arising from nuclear burning.

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