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SIMULTANEOUS WBVR OBSERVATIONS AND INTERPRETATIONS OF THE LIGHT CURVES OF TT ARI AND V603 AQL

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Four-colour photometric observations of TT Ari and V603 Aql in 1994–1995 are presented. Both stars show photometric periodicities in their light curves, 3.2 h and 3.5 h respectively. But their colours sometimes also vary with spectroscopic periods for both stars equal to 3.3 h, and W–B of TT Ari varies with half the photometric period. In the TT Ari light curves quasi-periodic oscillations (QPO) are found in a wide range of periods, from 47 to 16 minutes, and they changed from night to night. The 60 minutes oscillations and their harmonics are presented on V603 Aql light curves. A new model of the oblique precessing accretion disk together with reflection from a secondary or hot spot is suggested to allow for the photometric variability of these stars. The theoretical light curves of TT Ari in the framework of this model are calculated. It is proposed that QPO is connected with orbiting blobs in the disk.

KEY WORDS Cataclysmic variables, individuals: TT Ari, V603 Aql, photometry, theoretical light curves, interpretation

1 INTRODUCTION

TT Ari (BD+14°341) and V603 Aql (Nova Aquilae 1918) are ones of the brightnest ($V \sim 10^{\rm m}_{.}5$ and $V \sim 11^{\rm m}_{.}3$ respectively) and well-known cataclysmic variables. Both stars have photometric variability at the level of about $0^{\rm m}_{.}2$–$0^{\rm m}_{.}3$ with periods 3.2 h (TT Ari; Smak and Stepien, 1975) and 3.5 h (V603 Aql; Haefner and Metz, 1985). However these photometric periods are inconsistent with the spectroscopic ones: 3.3 h (TT Ari; Cowley *et al.*, 1975) and 3.3 h (V603 Aql; Kraft, 1964). Such a distinction between photometric and spectroscopic periods is usually connected with precessing the accretion disk: an elliptical one as in SU UMa stars (Whiterhurst, 1988) or an oblique one as in HZ Her/Her X-1 (Crosa and Boynton, 1980). The period of precession is a few days and the photometric period is a beat period of the precession and spectroscopic periods. The photometric variabilities with precession periods of TT Ari (4 d, Semeniuk *et al.*, 1987) and V603 Aql (2.5 d, Udalsky and Schwarzenberg-Czerny, 1989) were found too.

In addition to the 3 h variability TT Ari and V603 Aql show quasi-periodic oscillations (QPO) on time scales between 14 and 27 minutes (TT Ari, Semeniuk *et al.*, 1987) and between 15.6 and 61 minutes (V603 Aql, Haefner and Metz, 1985; Udalsky and Schwarzenberg–Czerny, 1989). These binaries were also detected as ones of the brightness X-ray sources between cataclysmic variables (TT Ari: Jensen *et al.*, 1983; V603 Aql: Becker and Marshall, 1981). QPO in X-ray with periods close to optical ones were revealed too (TT Ari: Jensen *et al.*, 1983; V603 Aql: Udalsky and Schwarzenberg–Czerny, 1989).

All of these features led to classification of TT Ari (Semeniuk *et al.*, 1987) and V603 Aql (Udalsky and Schwarzenberg–Czerny, 1989) as intermediate polars (IP). But their QPO periods vary too fast to be white dwarf rotation periods as in another IP. This is why Hollander and van Paradijs (1992) suggested the beat-frequency model of Alpar and Shaham (1985) for explanation of the changes of QPO periods in TT Ari from 27 minutes in 1962 to 15 minutes in 1988 (Semeniuk *et al.*, 1987; Hollander and van Paradijs, 1992).In this case the QPO period would be connected with the luminosity of the star, but such a dependence has not been found in X-ray (Baykal *et al.*, 1995). Some problems may be related to V603 Aql 60 min oscillations too, in any case Patterson *et al.* (1993) did not found QPO with this period in 1991.

It is obvious that further observations and theoretical investigations of these binaries are necessary. As a result the four-colour photometry and interpretation of light curves are presented in this work.

2 OBSERVATIONS

Multicolour photometric observations of TT Ari and V603 Aql were obtained during 7 nights in October 1994 and August 1995. The observations were carried out with the 60-cm reflector of Special Astrophysical Observatory on Pastukhova Mt. (about 2000 m over the sea level) near stanitsa Zelenchukskaya on North Caucause. The Log of observations is given in Table 1.

Table 1. **Log of observations**

Date	*Run Start (UT)*	*Duration*	*Star*
6.10.94	$21^h\ 40^m$	$4^h\ 16^m$	TT Ari
7.10.94	19 47	6 10	TT Ari
8.10.94	19 45	6 15	TT Ari
27.08.95	20 00	2 56	TT Ari
28.08.95	21 10	2 30	TT Ari
29.08.95	18 55	6 15	TT Ari
7.10.94	16 20	3 00	V603 Aql
8.10.94	16 20	3 00	V603 Aql
9.10.94	16 55	2 40	V603 Aql

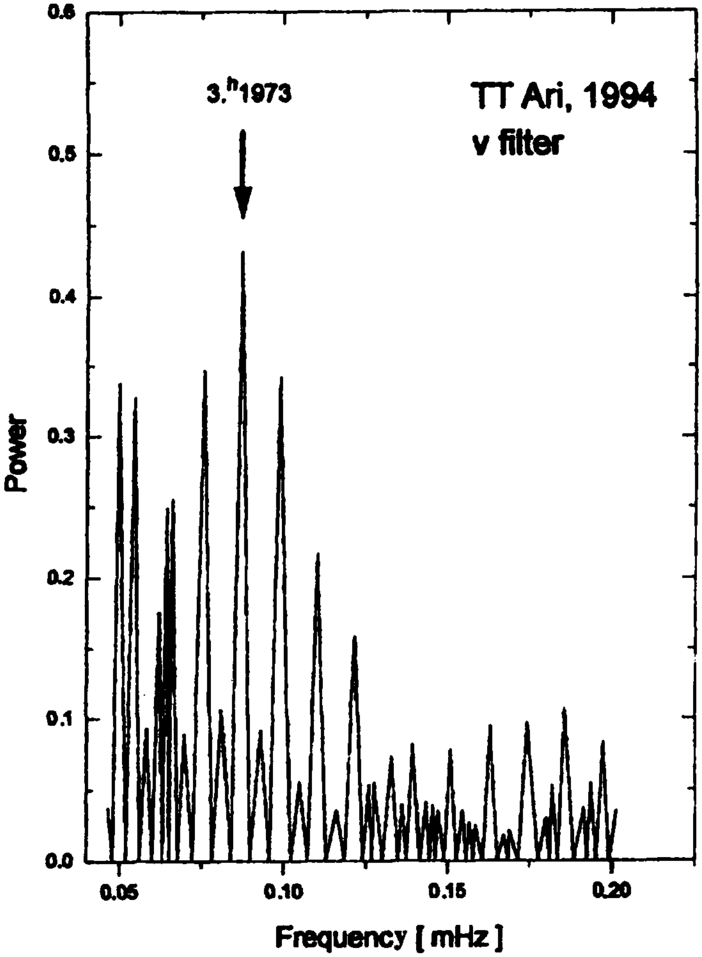

Figure 1 The power spectrum of TT Ari light curve in 1994.

The telescope was equipped with 4-channel photometer of Kazan State University. This photometer allows one to obtain simultaneous observations of any object in four bands, which are close to the bands of WBVR system (Straižys, 1977). Data acquisition is controlled by microcomputers IBM PC XT (Zhukov *et al.*, 1996).

The duration of individual runs was different and varied from more than 6 hours to 2.3 hour. The integration time was 10 s in all cases. Object observations were interrupted by observations of background and comparison stars every 15–20 minutes. The adopted comparison stars were d for TT Ari (Gotz, 1985) and S880-A (Lasker *et al.*, 1988) for V603 Aql.

The observations were processed conventionally: after background subtraction the object counts were divided by the corresponding counts of the comparison star.

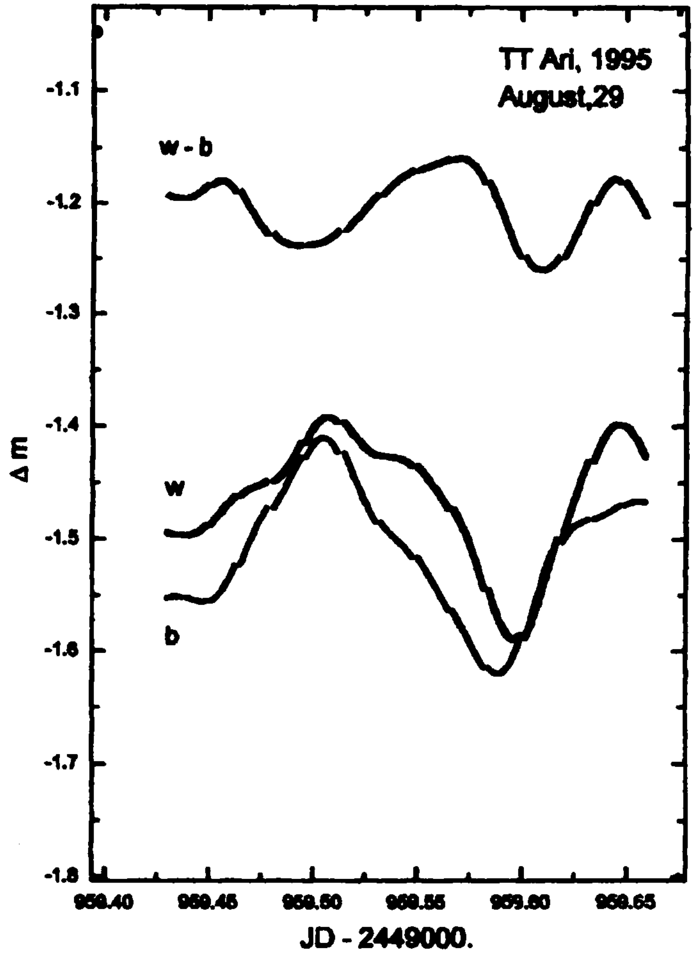

Figure 2 The light curves of TT Ari avereged over 200 points in August 29, 1995.

Consequently all values were instrumental magnitudes. The error of individual observation did not exceed $0\overset{m}{.}01$ in the B and V bands and $0\overset{m}{.}03$ in the W band. Red observations were not analysed because signal in the R channel was low. The processing of the observations was performed with the software written by D. Senio.

The periodogram analysis was performed using the programme (based on Fourier analysis) written by Yu. Kolpakov (SAI).

3 RESULTS

In 1994–1995 TT Ari and V603 Aql were in "high (bright) states" ($V \sim 10.8$ and $V \sim 11.3$ respectively). Below the results of period search are given separately for TT Ari and V603 Aql.

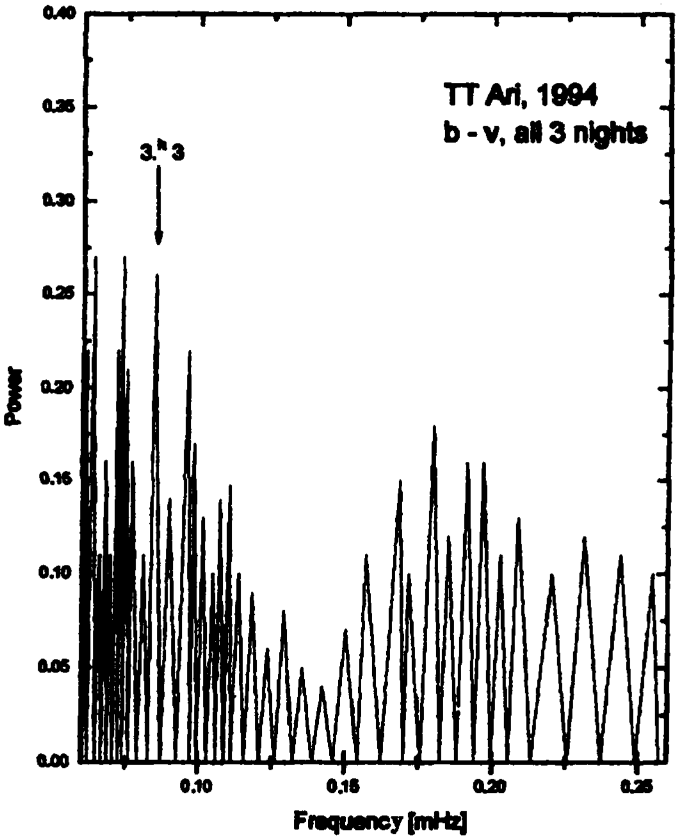

Figure 3 The power spectrum of TT Ari colour (b–v) curve in 1994.

3.1 TT Ari. 3.2 Hour Photometric Period

The searches of 3 hour photometric period close to the orbital one were performed separately in 1994 (October 6,7,8) and in 1995 (August 27,28,29). Periodogram analysis was carried out for light curves in the w, b and v filters and w–b and b–v colour curves. The peaks corresponding to the 3.2 hour period and its one-day aliases are strongest features in the power spectra of these curves (Figure 1). The obtained periods are summed in Table 2. In addition full amplitudes of approximated light curves are given too. The greatest amplitudes are in the w filter.

The photometric behaviour of colours are more interesting. So, in 1994 the w–b colour demonstrated more likely half-photometric period, and in 1995 it was obvious. That was due to a more wide w hump than the b hump, as seen from the light curves averaged over 200 points (Figure 2). The variation of the b–v colour have period rather close to the spectral period than to the photometric one in 1994. But in 1995 any detectable photometric variability in this colour was not found. The power spectrum of the b–v colour in 1994 is shown in Figure 3.

Table 2. The photometric periods of TT Ari in 1994, 1995

1994

Filter	*Period*	*Amplitude*
w	$3^{h}.2$	$0^{m}.2$
b	3.2	0.15
v	3.2	0.15
w–b	3.18, 1.6(!)	0.08, 0.06
b–v	3.28(!), 1.65	0.09, 0.07

1995

Filter	*Period*	*Amplitude*
w	$3^{h}.2$	$0^{m}.17$
b	3.2	0.15
v	3.2	0.15
w–b	1.68(!)	0.09
b–v	–	0.01

3.2 TT Ari. QPO period

The QPO periods were sought separately for every night of observation. The obtained periods are given in Table 3. The power spectrum for the QPO period equal to 20 min (August 29, 1995) is presented in Figure 4. It should be noted that there are some features in these results. The presented periods varied from 47 to 8 minutes from night to night, and there was a night without significant oscillations (e.g. October 8, 1994). In the selection nights there are harmonics of the basic oscillation periods, in particular, all of the 8 min periods are harmonic (e.g. on August 27 and 28, 1995). The amplitude of oscillation is the largest in the **w** filter.

The most interesting change of QPO periods was during 3 consecutive nights on August 1995. The QPO period decreased from 47.5 min on August 27 to 36 min on August 28, and to 20 min on August 29 (see Figure 5).

The QPO periods have been found in colour light curves too. They, as a rule, are the same as the QPO periods obtained from separate filter light curves. But so-

Table 3. The QPO periods of TT Ari (v filter)

Data	*Period*	*Amplitude*
6.10.94	10 min	$0^{m}.03$
7.10.94	17, 8.5 min	0.05,0.03
8.10.94	17 min	0.06
27.08.95	47.5, 24.5 min	$0^{m}.1$, 0.05
28.08.95	36, 18 min	0.08, 0.03
29.08.95	20 min	0.06

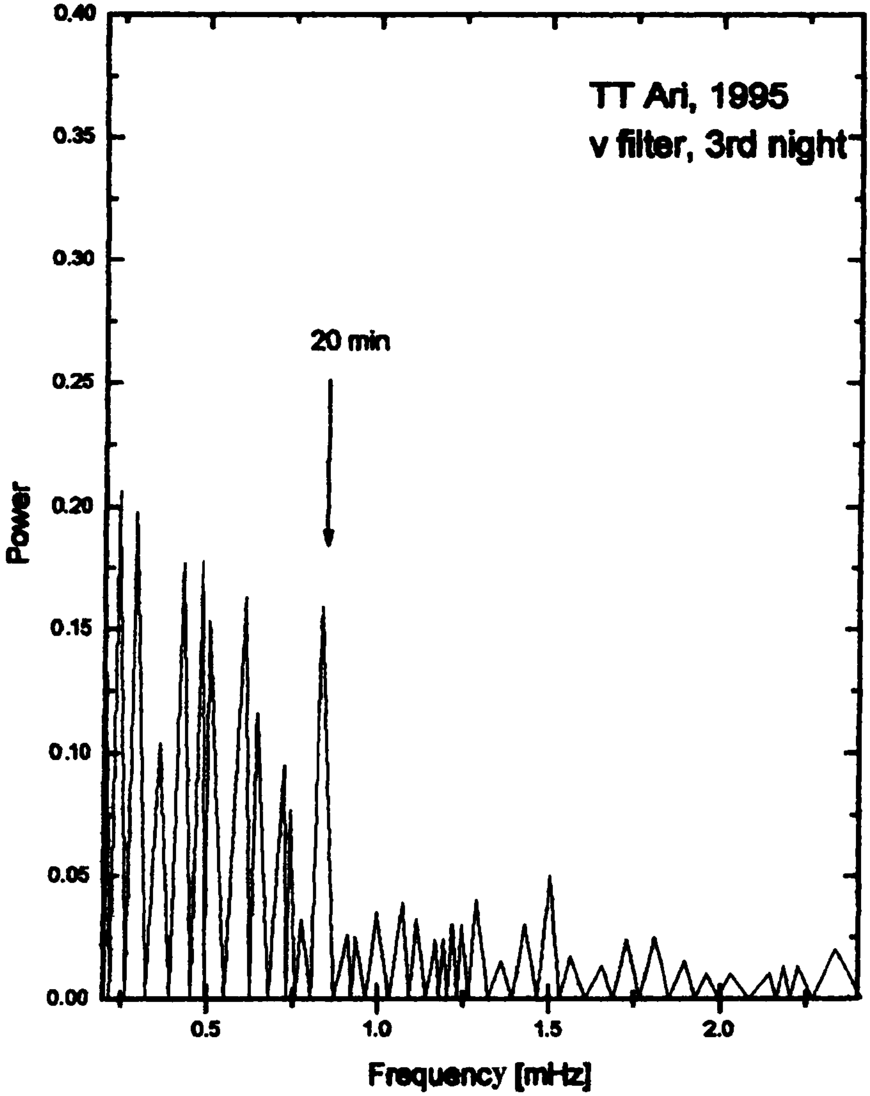

Figure 4 The power spectrum of TT Ari v curve QPO periods in August 29, 1995.

metimes the beat period between half the orbital period and the QPO period are more significant. It will be exemplified by the b–v QPO period on October 7, 1994 and the w–b QPO period on August 29, 1995.

It should be stressed that the most significant QPO period in 1995 (20 min) is a beat period between the more significant QPO period in 1994 (16.7 min) and the half-orbital period (1.7 h). Moreover, the 16.7 min period mentioned above is a more significant in the power spectrum of w–b light curve on August 29, although seen in the filters w and b the 20 min period.

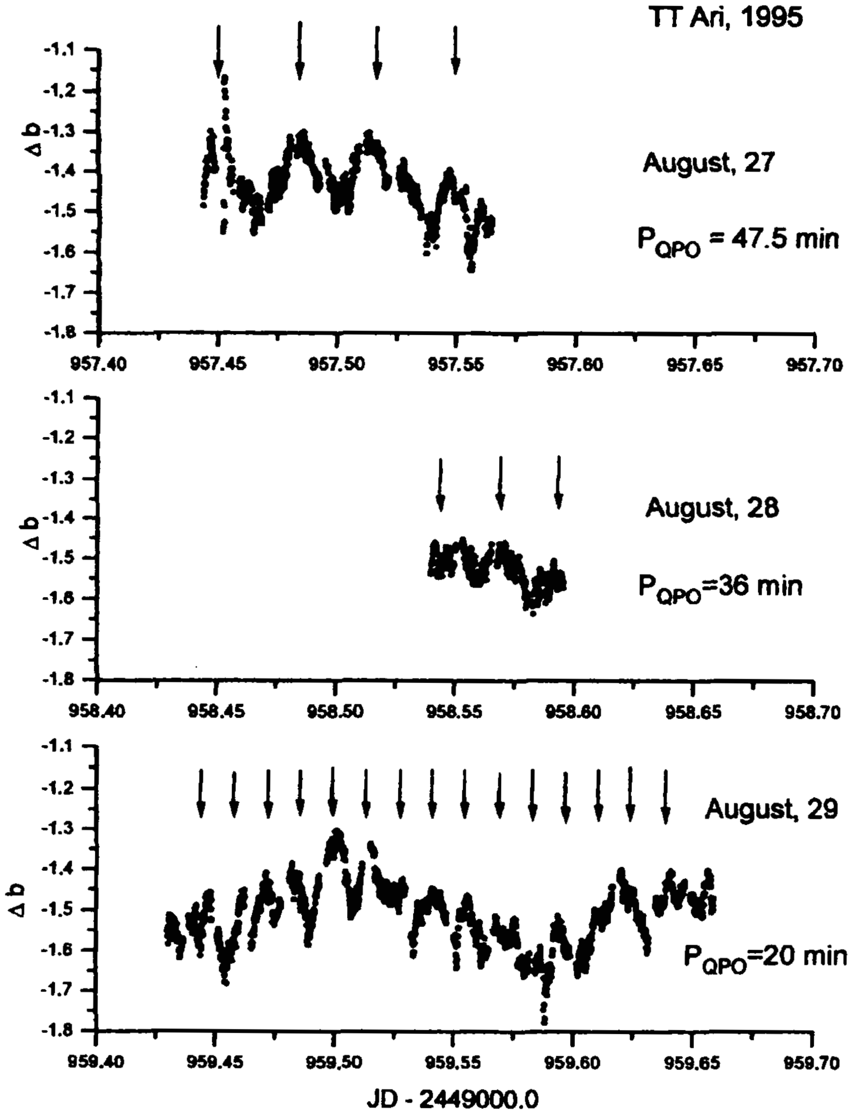

Figure 5 The light curves of TT Ari in August 27, 28, 29, 1995.

3.3 V603 Aql

The results of periodogram analysis are presented in Tables 4 and 5. The obtained photometric period has the value 3.65 h which is the significantly larger period than the period found previously by another authors ~ 3.5 h. The change of V603 Aql photometric was noted by Patterson *et al.* (1993), but this variation was less. Therefore our photometric period needs to be verified. The amplitude of variability is large in the **w** filter as for TT Ari.

Table 4. The photometric periods of V603 Ari in 1994

Filter	*Period*	*Amplitude*
w	$3^{\mathrm{h}}.65$	$0^{\mathrm{m}}.33$
b	3.65	0.25
v	3.6	0.25
w–b	3.65, 3.3	0.06, 0.05
b–v	3.65, 3.3	0.16, 0.08

Table 5. The QPO periods of V603 Ari in 1994 (v filter)

Data	*Period*	*Amplitude*
7.10	20, 39, 58 min	$0^{\mathrm{m}}.1$
8.10	16, 32, 47, 62.2 min	0.1
9.10	16, 30, 59 min	0.07

The photometric variations in colours show a period close to the spectral one, not only photometric, and corresponding peaks are found in power spectra.

The quasiperiodic oscillations are found in a wide range from 62 min to 16 min, but all periods less than 60 min are harmonics of the basic period close to 60 min, although it varied from night to night too.

4 INTERPRETATIONS AND DISCUSSIONS

4.1 Photometric Period

At present the commonly accepted model of photometric variability with a period different from the spectroscopic one is that of precessing accretion disk.

In the SU UMa type of cataclysmic variable superhump photometric variability during a superoutburst have periods by several percent longer than orbital ones. As a consequence of the elliptical accretion is the disk precession stretched by second star tidal forces (Whitehurst, 1988). The mass-ratio of a binary should be less than 0.25 for this effect to be possible (Whitehurst and King, 1991). But the mass-ratios of V603 Aql and TT Ari are greater than 0.25, approximately 0.5 (Ritter, 1987). Moreover, the photometric period of TT Ari is shorter than the orbital one. These features give a strong evidence of the absence of SU UMa type disk in our systems.

In astrophysics oblique precessing accretion disks are also known, for example in HZ Her/Her X1 and SS 433 (Schwarzenberg-Czerny, 1992). The model of retrograde oblique precessing accretion disk was suggested for intermediate polar TV Col by Barrett *et al.* (1988). They assume that the disk tilt arose from magnetic field of the secondary. But this model alone cannot explain the beat photometric variability of TT Ari and V603 Aql.

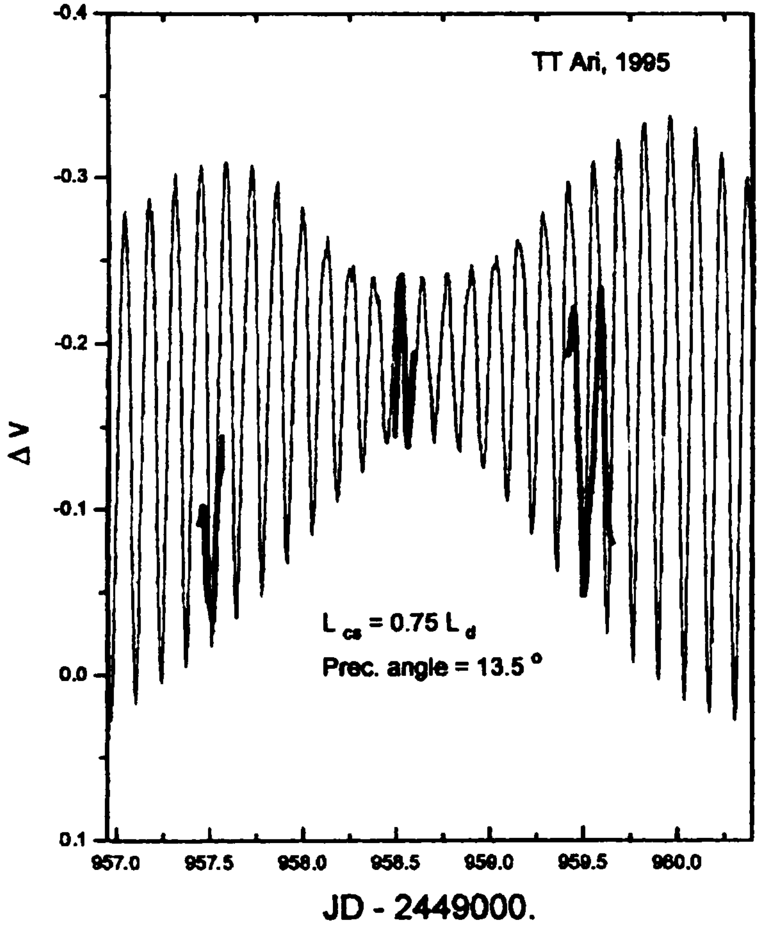

Figure 6 The theoretical and observed light curves of TT Ari.

Here we suggest an improved model of the precessing oblique accretion disk completed by the reflection effect from a secondary or a hot spot. There are two arguments to support our hypotheses. First of all, the intermediate polars such as AO Psc and V1223 Sgr have optical pulses with beat periods between the X-ray pulse periods and orbital periods. Therefore, these optical pulses appeared to be due to the reflection effect. The X-ray luminosities of these IPs ($L_x \sim 10^{31}$ erg s^{-1}) and TT Ari and V603 Aql are very close, and this effect may be significant for our stars too. The second observational argument is connected with the obtained colour variations with spectral periods in TT Ari and V603 Aql.

To illustrate the possibilities of this model we calculate theoretical light curves of TT Ari in the framework of the precessing oblique accretion disk model together with the reflection effect from the secondary. The parameters of binary TT Ari were taken from Ritter (1987), and the accretion disk model parameters were found previously (Suleimanov and Andrianov, 1994) from ultraviolet fluxes (Verbunt, 1987). The following parameter values were taken: the white dwarf mass $M_{\rm wd} = 0.8M_{\odot}$, the secondary mass $M_{\rm rd} = 0.4M_{\odot}$, the accretion rate $\dot{M} = 1.7 \times 10^{17}$ g s^{-1}, the outer disk radius $R_d = 2.9 \times 10^{10}$ cm, the inner disk radius $R_{\rm in} = 6.7 \times 10^8$ cm, the radius of the secondary $R_{\rm rd} = 2.6 \times 10^{10}$ cm, the binary separation $a = 8.6 \times 10^{10}$ cm and the inclination angle $i = 23°$.

The theoretical light curves were calculated in effective wavelengths of the W, B and V filters. The radiation flux from the disk has been calculated following Suleimanov (1996). The radiation reflected from the secondary has been calculated in the black body approximation (Suleimanov and Shakura, 1994).

The example of such theoretical light curve in V filter together with light curves averaged over 200 points observed in 1995 is shown in Figure 6. A general view of the theoretical light curve depends on the accepted TT Ari parameters and another two parameters: a central source luminosity $L_{\rm cs}$ and an inclination angle of the disk to the orbital plane $i_{\rm prec}$.

The most common feature of these theoretical light curves is a dependence of variability amplitude on the beat period phase. Namely, while the mean brightness of system is maximal, the amplitude of variability is minimal and vice versa. If this dependence is found, it will be a strong argument in favour of our model.

4.2 Quasi-Periodical Oscillations

The reason for the QPO in TT Ari have not been found. Hollander and van Paradijs (1992) considered, in some detail, possible reasons for QPO, and they suggested the beat-frequency model of Alpar and Shaham (1985). In this model the QPO period is a beat period between the white dwarf rotation period and is connected with its magnitosphere and the Kepler orbital period at the inner edge of the disk. The boundary between the magnitospheric radius and the disk depends on the accretion rate and magnetic moment of the white dwarf. Hence, the beat frequency depends on the accretion rate:

$$\nu_{\rm QPO} = K(\dot{M}_{16})^{3/7} - \nu_{\rm rot}, \tag{1}$$

where $\dot{M}_{16}$ is the accretion rate in units of 10^{16} g s^{-1}, and $\nu_{\rm rot}$ is the spin frequency of the white dwarf, and K is the constant at a given magnetic moment and mass of the white dwarf. Hollander and van Paradijs (1992) connected the decrease in the QPO period from 27 min in 1962 to 15 min in 1988 (Semeniuk *et al.*, 1987) with the increase of optical luminosity of TT Ari by 10–15 percents during this time. But such a dependence has not been found in the X-rays by Baykal *et al.* (1995). The QPO period in X-rays ($\sim$ 17 min) remained constant with 25 percents changes in the X-ray luminosity.

An another argument against the beat frequency model is a significant variability of the QPO period in TT Ari from night to night, although the mean brightness of binary varies only slightly. In partucular the most interesting change was during 3 nights in August, 1995 described above. It would appear reasonable to connect such a decrease of the QPO period with a diffusion of any blob along the disk radius.

It means that the QPO would be connected with the Kepler period of the blobs in the disk. These periods depend on the mass of the white dwarf and the radius of the blob orbit:

$$P = 9\ \mathrm{min}\left(\frac{M}{M_\odot}\right)^{-1/2}\left(\frac{R}{10^{10}\ \mathrm{cm}}\right)^{3/2} \tag{2}$$

Then the longest QPO periods should be close to the Kepler period at the outer edge of the disk: $P_{\mathrm{max}} = 47$ min $(M/M_\odot)^{-1/2}$ if $R_{\mathrm{out}} = 3 \times 10^{10}$ cm and that is the case. The QPO period of V603 Aql equals ~ 60 min, and the theoretical one is 58 min for a given mass of the white dwarf: $M_{\mathrm{wd}} = 0.66 M_\odot$ (Ritter, 1987). The maximal QPO period of TT Ari equals 47.5 min, and this is in accordance with our hypothesis too.

If our hypothesis is true, observations of QPO period decrease can give an important information about the α-parameter and the half-thickness of the disk z_0. The diffusion time through disk can be evaluated as (Pringle, 1985):

$$t_\nu \sim \alpha^{-1}\left(\frac{z_0}{R}\right)^{-2}\omega^{-1}, \tag{3}$$

where ω is the Kepler frequency at a given radius R. The ratio z_0 (R) to R is evaluated approximately as 0.05–0.1, and (3) may be rewritten as follows:

$$t_\nu \sim (0\overset{\mathrm{d}}{.}1 - 1^{\mathrm{d}})\alpha^{-1}\left(\frac{M}{M_\odot}\right)^{-1/2}\left(\frac{R}{10^{10}\ \mathrm{cm}}\right)^{3/2} \tag{4}$$

It means that the blobs really can propagate through the disk with a typical time ~ 1 d, as observed on August 27 to 29, 1995.

It is necessary to note a high stability of the QPO period TT Ari in X-ray. Jensen *et al.* (1983) in 1981 and Baykal *et al.* (1995) in 1991 found almost the same QPO periods in X-ray – 1000 s (~ 17 min). This period, most likely, is a rotation period of the white dwarf. Therefore, a complicated picture of the optical QPO in TT Ari can arise from an interaction rotation period of the white dwarf with the orbital period and the Kepler periods of the blobs.

In this picture a secular decrease of the optical QPO period (Semeniuk *et al.*, 1987) remains a mystery. If we decide that the periods 16.7 min and 20 min are the mean periods in 1994 and 1995 respectively, then it will be necessary to infer that the period QPO of TT Ari begins to increase. But a high variablity from night to night of the TT Ari QPO period casts some doubt that the secular change of this period is real.

5 CONCLUSION

In this paper simultaneous WBV observations of TT Ari and V603 Aql during 7 nights in 1994–1995 are presented. The periodogram analysis of the light and colour curves of these binaries allows one to obtain new photometric periods: 3.2 h and

3.65 h respectively. It is shown that the W–B colour of TT Ari changes with half the photometric orbital period, and that the B–V colour of this star changes with a spectral period in 1994. In the power spectra of V603 Aql colour curves there are peaks corresponding both to the photometric period and the spectral one.

These are the observational arguments in favour of the model of the oblique precessing accretion disk together with the reflection effect from the secondary. This model is suggested in this work to explain a photometric variability of TT Ari and V603 Aql. The theoretical light curves of TT Ari are calculated in the framework of our model. The detection of the photometric amplitude decrease during the phases of maximum brightness of the beat (between spectral and photometric) period of TT Ari or V603 Aql would be a verification of our model.

The investigation of the QPO in TT Ari shows a change of the QPO period from night to night. These periods vary from 48 min to 16 min, although the brightness of TT Ari was almost constant. This seems contrary to the beat frequency model for QPO of TT Ari proposed by Hollander and van Paradijs (1992). At the same time the consecutive decrease of the QPO period during 3 successive nights in August 1995 was observed. This suggests that QPO are connected with the Kepler periods of any inhomogeneities (blobs) in the disk and that the change of the QPO period is connected with a diffusion of these blobs along the radius of the disk. If this hypothesis is true, it will open possibilities for obtaining the values of α-parameter and the half-thickness – radius ratio along the disk radius.

In V603 Aql the QPO with the period $\sim$ 60 min and its harmonics were found.

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