**ABSTRACT**

We present charge-coupled device (CCD) photometry, light curve and time-series analysis of the classical nova V2275 Cyg (N Cyg 2001 No. 2). The source was observed for 14 nights in total in 2002 and 2003 using an $R$ filter with the 1.5-m Russian–Turkish joint telescope (RTT150) at the TUBITAK National Observatory in Antalya, Turkey, as part of a large programme on the CCD photometry of cataclysmic variables. We report the detection of two distinct periodicities in the light curve of the nova: (a) $P_1 = 0.31449(15)$ d [7.6 h], and (b) $P_2 = 0.017079(17)$ d [24.6 min]. The first period is evident in both 2002 and 2003 whereas the second period is only detected in the 2003 data set. We interpret the first period as the orbital period of the system and attribute the orbital variations to aspect changes of the secondary irradiated by the hot white dwarf (WD). We suggest that the nova was a supersoft X-ray source in 2002 and, perhaps, in 2003. The second period could be a quasi-periodic oscillation originating from the oscillation of the ionization front (due to a hot WD) below the inner Lagrange point or a beat frequency in the system as a result of the magnetic nature of the WD if steady accretion has already been re-established.

**Key words:** accretion, accretion discs – binaries: eclipsing – stars: individual: V2275 Cygni – novae, cataclysmic variables – stars: oscillations – white dwarfs.

1 INTRODUCTION

Classical novae are a subset of cataclysmic variables that are interacting binary systems hosting a main-sequence secondary (sometimes a slightly evolved star) and a collapsed primary component, a white dwarf (Warner 1995). An outburst on the surface of the white dwarf as a result of a thermonuclear runaway in the accreted material causes the ejection of $10^{-3}$ to $10^{-7} M_{\odot}$ of material at velocities up to several thousand kilometres per second (Shara 1989; Warner 1995). The classical nova V2275 Cyg (N Cyg 2001 No. 2) was discovered at a magnitude 7.0–8.8 on 2001 August 18 simultaneously by Nakamura, Tago & Abe (2001) and Nakano et al. (2001). Early optical spectroscopy showed hydrogen Balmer lines with P Cygni profiles and Hα lines indicating expansion velocities of 1700 km s$^{-1}$ (Ayani 2001). At later stages, high-energy coronal lines were found to dominate the spectrum (e.g. [Si x], [Si ix] and [Al ix]). The nova was found to belong to the ‘He/N’ subclass of novae defined by Williams (1992), because of the broad lines of H, He and N in its spectrum (Kiss et al. 2002). In addition, Kiss et al. (2002) measured $t_2 = 2.9 \pm 0.5$ d, $t_3 = 7 \pm 1$ d and $M_V = -9.7 \pm 0.7$ mag, which were used to derive a distance of 3–8 kpc for the nova. An USNO star of $R = 18.8$ mag and $B = 19.6$ mag was suggested as a possible progenitor star (Schmeer 2001).

This paper is on the charge-coupled device (CCD) photometry of V2275 Cyg covering years 2002 and 2003 obtained with the 1.5-m Russian–Turkish joint telescope (RTT150) at the TUBITAK (Scientific and Technical Research Council of Turkey) National Observatory (TUG) in Antalya, Turkey. We present the discovery of a distinct period reported by Balman et al. (2003) (which we mark as $P_1$) and the detection of a highly coherent quasi-periodic oscillation (QPO) on six different nights in 2003 (using $V$, $R$ and $I$ filters). Fast variations from V2275 Cyg similar to this second period (which we mark as $P_2$) were also reported by Garnavich et al. (2004) derived from a data set of two nights obtained with a $V$ filter.

2 OBSERVATIONS AND DATA REDUCTION

V2275 Cyg was observed during eight nights in 2002 and six nights in 2003 using the standard $R$ filters (Johnson and Cousins) at TUG (see Table 1 for a timetable of observations). The data were obtained with the imaging CCD (a Loral LICK3 2048 $\times$ 2048 pixel...
Table 1. The timetable of the observations. (All observations are obtained with standard V, R and I filters.)

| UT date | Time of start (HJD − 245 000) | Run time (h) | Number of frames | Filter |
|---------|-----------------------------|-------------|-----------------|--------|
| 020610  | 436.484518                  | 1.8         | 30              | R      |
| 020612  | 438.486060                  | 1.9         | 29              | R      |
| 021001  | 549.246533                  | 7.1         | 88              | R      |
| 021002  | 550.248770                  | 5.3         | 68              | R      |
| 021003  | 551.256457                  | 5.9         | 99              | R      |
| 021005  | 553.293507                  | 5.4         | 80              | R      |
| 021201  | 610.238175                  | 1.5         | 40              | R      |
| 021222  | 631.188612                  | 2.9         | 68              | R      |
| 030825  | 877.367836                  | 5.8         | 136             | R      |
| 030826  | 878.376911                  | 4.1         | 114             | R      |
| 030827  | 879.299621                  | 7.5         | 204             | R      |
| 031101  | 945.196586                  | 6.2         | 81, 82          | R, I   |
| 031102  | 946.208050                  | 5.6         | 65, 64          | R, V   |
| 031228  | 1002.221443                 | 2.0         | 23, 23          | I, V   |

back-illuminated CCD chip at 0.26 arcsec pixel\(^{-1}\) resolution) on 2002 June 10 and June 12, and an Ap47p CCD (1024 \(\times\) 1024 pixels with 13 µm pixel\(^{-1}\) resolution) on 2002 October 1–5, December 1 and December 22. The rest of the data are taken with the ANDOR CCD (2048 \(\times\) 2048 pixels at 0.24 arcsec pixel\(^{-1}\) resolution) on 2003 August 25–27, and the imaging CCD on 2003 November 1–2. The exposure time is 90 s for each frame. A total of 1149 images were obtained in the \(R\) band and reduced using standard procedures calibrating the frames with the bias/dark current frames and dome flat fields. In addition, a total of 105 frames in the \(I\) band and 87 frames in the \(V\) band have been compiled for comparison (in 2003 November 1–2, and 2003 December 28). After the raw data were cleaned and calibrated, the instrumental magnitudes of the nova were derived by the point spread function (PSF) fitting algorithms DAOPHOT (Stetson 1987) and ALLSTAR in the MIDAS software package (version 02FEBpl1.0 and 03FEBpl1.0) using 25 stars as PSF stars. Also, another reference group of four constant stars close to the nova in the same field was formed in order to reduce the scintillation effects and to derive the relative magnitudes. The calibrated apparent magnitude of the nova in the \(R\) band varied in the range from 15.1 to 16.2 mag in 2002. The fading of the nova continued, changing this range to 17.3–19.0 mag in 2003.

3 ANALYSIS AND RESULTS

Using our reduced and calibrated \(R\)-band data, we constructed light curves for the nights given in Table 1. A collection of normalized light curves obtained from runs that are longer than 5 h is displayed in Fig. 1. The top panel is of 2002 October 1–5, the middle panel is of 2003 August 25–27 and the bottom panel is of 2003 November 1–2. A deep modulation of the light curve can be seen in Fig. 1. Fig. 2 shows the data obtained in the longest run (7.5 h) on 2003 August 27. This figure reveals not only the long period that is causing the deep modulation (which we mark as \(P_1\)), but also the other superimposed faster variations (which we mark as \(P_2\)) and humps that are observed in the system. We have also accumulated data using the standard \(I\) filter on 2003 November 1 and \(V\) filter on 2003 November 2 together with the \(R\) filter observations (see Fig. 3). The short time-scale variations (which we mark as \(P_2\)) are apparent in the figure. Subtraction of a linear trend from the \(V\)- and \(I\)-band light curves in Fig. 3 suggests that the long-period variations (i.e. \(P_1\)) are larger in amplitude in the \(I\) and \(R\) bands than the \(V\) band, which can be expected (see Discussion). We have performed Fourier analysis of the time series obtained from the data in order to derive the periods of these modulations. In general, several standard programs have been used, like the Scargle algorithm (Scargle 1982) and discrete Fourier analysis using Leahy normalization (Leahy, Elsner & Weisskopf 1983). Fig. 4 shows the power spectrum of the data for the year 2002 and Fig. 5 for the year 2003 where the Scargle algorithm is used to calculate the power spectra. The detection limit of a period at the 3σ confidence level (99 per cent) is a power of 14.2 in Fig. 4 (2002 data) and 15.6 in Fig. 5 (2003 data) (see also Scargle 1982). In order to correct for the effects of windowing and sampling functions on power spectra, synthetic constant light curves are created and a few very prominent frequency peaks that appear in these light curves are pre-whitened from the data in the analysis. Before calculating the power spectra, the individual or consecutive nights are normalized by subtraction of the mean magnitude. Moreover, when necessary, the red noise in the lower frequencies is removed by detrending the data.

Figure 1. The normalized differential light curve of V2275 Cyg observed on 2002 October 1–5 (top panel); the light curve obtained on 2003 August 25–27 (middle panel); and the light curve obtained on 2003 November 1–2 (bottom panel). All data are taken with the TUG 1.5-m telescope using the standard \(R\)-band filters (Johnson and Cousins). The epochs of the observations are noted on the x-axis. The average magnitude errors are ±0.0083, ±0.0065 and ±0.0095 for the top, middle and bottom panels, respectively.

Figure 2. The light curve of the longest observing run (7.5 h) on 2003 August 27. The data are taken with the ANDOR CCD using a standard \(R\)-band filter (Cousins). The average magnitude error is ±0.0063.
Irradiation-induced variations in V2275 Cyg

The light curve of V2275 Cyg obtained with the standard I and R filters on 2003 November 1, and with the V filter on 2003 November 2. The data are taken with the imaging CCD. The average magnitude errors are ±0.015, ±0.008 and ±0.011 for the V, R I light curves, respectively.

The power spectrum of V2275 Cyg obtained from the 2002 data set (eight nights), using the Scargle algorithm. The new period is indicated as \( P_1 \) and its weak (but significant) second harmonic is also noted.

We find a prominent period at \( P_1 = 0.31449(15) \) d using the whole data set. The power spectra in Figs 4 and 5 show the highest peak at this period and the group of peaks around it are some of the ±1/3, ±1/2, ±1 and ±2 d aliases of the detected period. In Fig. 4 (2002 data), a weak second harmonic of \( P_1 (P_1/2) \) is present (it is significant). In Fig. 5 (2003 data), the third harmonic of \( P_1 (P_1/3) \) is also present, but the second harmonic is not significantly detected.

The period \( P_1 \) shows an amplitude variation of 0.42 ± 0.06 mag in 2002 (measured by fitting a sine wave). The amplitude of the variations is decreased significantly in 2003 to 0.22 ± 0.12 mag. The decrease in modulation depth is about 50 per cent (in magnitude).

The ephemeris for \( P_1 \) determined by fitting a sine curve is

\[ T_{\text{min}} = \text{HJD} 245 2549.4163(±0.0154) + 0.31449(±0.00015) \times E. \]

We also detect a second periodicity at \( P_2 = 0.01709(17) \) d with an amplitude of 0.03 ± 0.01 mag. These rapid variations are revealed in all the nights in 2003 with varying intensity. They are also clearly seen in Figs 2 and 3 (in the V, R and I bands). We do not recover the beat period between \( P_2 \) and \( P_1 \) in the 2003 data set.

Figs 6 and 7 display the mean light curves folded on \( P_1 \) using the 2002 and 2003 data set, and \( P_2 \) using the 2003 data set, respectively.

4 DISCUSSION

We present 14 nights of data on V2275 Cyg obtained with the TUG 1.5-m telescope using mainly standard R filters in 2002 and 2003. We discover large modulations \( \Delta m_r = 0.42 \) at \( P_1 = 0.31449(15) \) d in the light curve of the classical nova in 2002, the amplitude of...
is the source of the light and the colour variation rather than a hotspot 
yields a secondary mass of about $0.83 M_\odot$.

Panel is the normalized colour magnitude ($I - R$) curve versus photometric bands as well. Since the periodicity $P_1$ detected in 2002–2003 is another indication of the changing conditions in the ionization front. The strong third harmonic of $P_1$ detected in 2003 could support the existence of several hot zones over the total surface of the secondary along with the significantly heated inner face resulting in the higher harmonics becoming prominent.

We also detected another periodicity $P_2 = 0.017079(17)$ d in the light curve of 2003. We suggest that this is a highly coherent QPO from the system. The power of the signal varies on different nights (independent of length of the observation) together with the small changes of the periodicity, which differ according to the colour (i.e. filter). The characteristics of the oscillations revealed in 2002 does not strongly support a WD spin period as the origin. The time-scale and characteristics of the QPOs ($\sim 1475$ s) resemble flickering, or reprocessing from blobs orbiting within the inner regions/magnetosphere of the accretion disc in accreting CVs. It could also be the beat period between the spin period and the orbital period of the system ($P_1$). However, since the nova is still in its early outburst stage during the TUG observations, it is not clear whether the disc is completely disrupted, or if re-established, the accretion is steady, sporadic or unstable. For example, the existence of an accretion disc was revealed in V1974 Cyg two years after the outburst (Rettter, Leibowitz & Ofek 1997), which was long after the discovery of the variations due to irradiation of the secondary. The total light curve is folded on $P_1$ using 10 phase bins. The right-hand panel shows $I - V$ colour variation over the photometric phase of $P_1$. The total light curve is folded on $P_1$ using 15 phase bins.

Figure 7. The light curve of the 2003 data set, folded on the period $P_2$ [0.017079(17)]. The first data point in time (start mid-HJD in 2003) is taken as the reference and a grouping (averaged over) of 20 phase bins is used for the folding process. The average error of a phase bin is $\pm 0.0015$ mag. The small oscillations superimposed on the mean light curve are due to the time windows of the data.

Figure 8. Colour variations of the detected periodicities. The left-hand panel is the normalized colour magnitude ($I - R$) curve versus photometric phase of $P_2$. The total light curve is folded on $P_2$ using 10 phase bins. The right-hand panel shows $I - V$ colour variation over the photometric phase of $P_1$. The total light curve is folded on $P_1$ using 15 phase bins.

time as observed for some other novae (e.g. V838 Her, Leibowitz et al. 1992; V1494 Aql, Kato et al. 2004). A recent search for variations/periodicities in the light curve of faint cataclysmic variables (CVs) (including old novae) reveals that irradiation yields larger amplitude for modulations (Woudt & Warner 2003a,b) as detected in our study.

After a nova explosion, the hot WDs are candidates for heating their cooler companion. Some classical nova systems were recovered to show this irradiation effect like: (1) V1500 Cyg (N Cyg 1975), which showed an unperturbed temperature of 3000 K for the secondary and 8000 K for the heated side (Schmidt, Liebert & Stockman 1995; Somers & Naylor 1999); (2) DN Gem (N Gem 1912) (Rettter, Leibowitz & Naylor 1999); (3) WY Sge (N Sge 1783), which indicated that the accretion luminosity from the disc could be ruled out because the modulation amplitude would be larger in
These oscillations are attributed to expected WD pulsations (i.e. non-radial, non-adiabatic modes) from the $\sim 1.5 \times 10^7$ K and $L \sim 2000 L_{\odot}$ hot WDs (Starrfield et al. 1985). The $P_2$ detected in V2275 Cygni is similar to these in time-scale. However, it is expected that the higher luminosity (a factor of 10) and the temperature (a factor of 4–5) of the WDs, as the hydrogen is burned over the surface, should decrease the pulsational time-scale (Starrfield et al. 1985), which makes this scenario unfavourable for V2275 Cyg. In addition, the 2002 data set should have revealed the same oscillations, if they were solely due to WD pulsations.

A more plausible explanation for the origin of $P_2$ is, yet again, the effect of an ionization front (IF) resulting from an alleged SSS phase and the radiative winds of the WD in the outburst stage. If the IF reaches well into the photosphere of the secondary, favourable conditions could result in ionization over the face of the secondary (the IF penetrates the photosphere) resulting in ‘boiling off’ (may be ‘rippling off’) material from a dense static/neutral medium, which could be the case in 2002. If the IF does not reach as far as the photosphere, it could still reach out below the inner Lagrangian point (L1, a sonic point) where conditions cannot be steady and the IF then oscillates on a time-scale of the order of the dynamical time-scale of the secondary near L1, which could result in QPOs as suggested by King (1989). This oscillation time-scale is proportional to $t_{qpo} \sim H/c_s$ (scaleheight/sound speed), which is equivalent to $t_{qpo} \approx (R^3/GM)^{1/2} \sim 176 P_{hr}$, Given the orbital period derived in this paper ($P_1$), the predicted oscillation period of L1 is similar to $P_2$ (assuming the size $R$ of the secondary will be larger on the equatorial plane). By late 2003 the IF could be withdrawn towards the WD, irradiating only the inner Lagrangian point (L1), which yields the QPOs.

CONCLUSIONS

We detected two periodicities in the light curve of the classical nova V2275 Cygni (2001). The first one is $0.314 \pm 0.015$ d, which we attribute to the orbital period of the binary system. The modulation depth of the mean light curve folded on this period indicates a change from $0.42 \pm 0.06$ mag to $0.22 \pm 0.12$ mag over the course of one year. We propose that these variations are due to the illumination of the secondary by the hot WD where the aspect variations of the heated/irradiated secondary reveals the binary period of the system. The reduction in the modulation depths indicates the changing conditions in the ionization front at the location of the secondary. This highly ionizing radiation could originate from a hot WD which went through a supersoft X-ray phase while burning hydrogen on its surface. We also detect a second period of $0.017 \pm 0.001$ d in the year 2003, which we interpret as a QPO from our data in 2002–2003. For the origin of this period we propose either a magnetic cataclysmic variable scenario (e.g. the interaction of blobs with the magnetosphere) or a scenario where the QPOs are a result of oscillations of the inner Lagrangian point (L1) due to irradiation from a cooling hot WD. Both scenarios indicate that some form of accretion is being established in the nova system after the outburst. Our preliminary analysis reveals that both periods exist in 2004 data and the modulation depth of the first period is further reduced. The photometric observations of V2275 Cyg in 2004 (still being conducted at TUG) should reveal the changing shape and depth of the orbital modulations and QPOs which will, in turn, portray the evolution of the WD itself.

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