EARLY SUPERHUMPS IN THE "KING OF THE SUPEROUTBURSTS" SYSTEM WZ SGE

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ABSTRACT. Time series analysis of 6 nights of CCD observations of WZ Sge after it's unexpected superoutburst on July 23, 2001 has shown highly asymmetric periodic variations with a period $0.^d0566513(22)$, full amplitude $0.^m218(4)$ and a very high asymmetry $M-m = 0.670(9)$, a secondary minimum $0.38P$ after the main one. The initial epochs are $T_{max} = BJD2452118.7483(3)$ and $T_{min} = BJD52118.7670(2)$. The characteristics of the phase light curve are listed. In addition, we have found superhumps with a semi-amplitude of $0.^m021(2)$ and an ephemeris $T_{max,sh} = BJD2452117.6830(8) + 0.^d057435(45)\,E$. Other peaks at 21 and 25 minutes possibly correspond to quasi-periodic oscillations with an effective semi-amplitude of $0.^m014$.

Key words: Stars: variable: cataclysmic: UG SU: WZ Sge

1. Introduction

WZ Sge was known as a cataclysmic variable (CV) exhibiting outbursts every 33 years. Previous ones were detected in 1913, 1946, 1978 with a recurrence time of 11876^d (Ritter and Kolb, 1998), and the next one, achieved from this short sequence, could be predicted for 2011. However, it occurred on July 23, 2001, as was reported by T.Watanabe based on observations by M.Oshima. The extending story of recent studies of this object is presented at the VSNET page www.kusastro.kyoto-u.ac.jp/vsnet/DNe/wzsge01.html. At the figure taken from this site, one may see "evolution of early superhumps". Their period is equal to the orbital one, and there is a hump at the ascending branch.

G.Masi (*www.bellatrixobservatory.it*) presented numerous individual light curves obtained at the Bellatrix Observatory, often revising his site to add new results.

E.Kuulkers presented an outburst light curve which is compiled from the data obtained during previous three outbursts (*http://saturn.sron.nl/ -erikk/wzsge/wzsge_1913_1946_1978.gif*).

D.Steeghs (www.astro.soton.ac.uk/ ds/wzsge.html) presented a timetable containing dates of past and planed future observations of WZ Sge, which played an important role for coordinating research of various groups.

The object has become the CV target number one at the CBA (Center for Backyard Astrophysics) network supervised by J.Patterson (*cba.phys.columbia.edu*) and AAVSO (*www.aavso.org*, director J.Mattei). At these pages, one may find a list of runs obtained by the CBA and AAVSO members.

2. Basic information

Since the first two detected outbursts in 1913 and 1946, the star was classified as a recurrent nova, which contains a white dwarf (Greenstein, 1957). Krzeminski (1962) had found, that the star is an ultra-short period binary star with a period of 82 minutes. Krzeminski and Kraft (1964), while searching for " Binary Stars among Cataclysmic Variables", have published the paper on this star as the fifth one in these series. Thus the star was one of the key objects leading to a current paradigm, that all cataclysmic variables are close binaries.

Faulkner (1971) propose a model for ultrashort-period binaries with an example of WZ Sge, according to which, the mass transfer is powered by gravitational radiation, determining the evolution. This model was developed in detail by Tutukov and Yungelson (1979).

Warner and Nather (1972) reported on rapid variability of WZ Sge while searching for it in blue stars. The coherent 27.87s oscillations, which are often detected, argue for a presence of magnetic white dwarf (Patterson et al., 1998). Sometimes the periods are slightly larger, corresponding to beat periods.

However, the nature of outbursts was believed to be similar to the Novae, i.e. the thermonuclear outburst after gaining of the critical mass of hydrogen on a white dwarf. The situation has changed drastically during the subsequent outburst in 1978, when the star was intensely observed photometrically and spectroscopically. Despite the light curve is very similar to that of Novae, the outburst is caused by a distinctly other mechanism similar to the SU UMa-type dwarf novae, and thus the subclass of WZ Sge-type stars was separated from the recurrent novae.

Gilliland and Kemper (1980) pointed out a formation of a circumbinary disk and discussed the origin of superhumps - photometric wave with a period P_{sh} slightly exceeding the orbital one P_{orb}. Patterson et al. (1981) studied the observational appearance of the superhump during the outburst in 1978. In the case of WZ Sge, the period excess $E_p = (P_{sh} - P_{orb})/P_{orb} =$ 0.8%. Current models of superhumps have been discussed by Osaki (1995), O'Donoghue (2000) and Patterson (2001).

Thus the star is still among the first few ones, which lead to the present knowledge of cataclysmic variables.

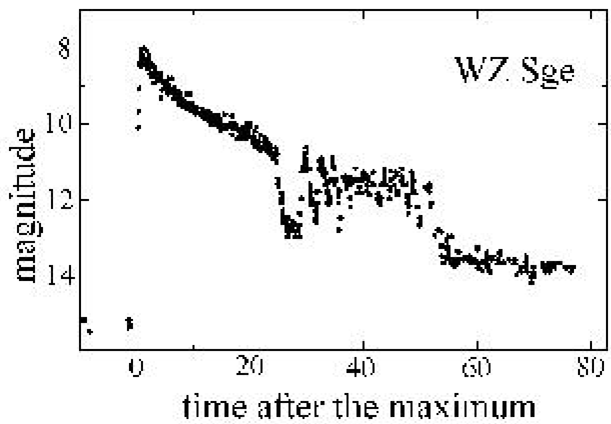

Figure 1: Long-term light curve based on the orbit-average magnitudes of WZ Sge compiled by D.Steeghs (*http://www.astro.soton.ac.uk/~ds/wzsge2001.gif*) using the VSNET and AFOEV data. Our data were obtained after 1...7 days after the maximum (complete interval shown by a horizontal line) during a stage of significant nonlinearity of the decay.

3. Observations

The object was also observed during 6 nights at the 40cm reflector of the University of Athens Observatory by using a CCD SBIG ST-8 camera by K.G., A.Y., P.N. in the Bessel R filter. The comparison star is GSC 1621:1830 (="C") with R=8.663 (Henden 2001). Altogether 1109 data points have been obtained from July 24 to July 31 (BJD 2452115.503-2452121.614). The time series analysis was made by I.L.A.

Our light curves for 6 runs show a nearly linear trend only for intermediate 4 nights from JD 2452116 to 2452119, whereas the first and last nights lie significantly above this line. This conclusion is also justified by the outburst light curve obtained during the international campaign (Fig. 1). Thus, for further analysis, we have used extracted 653 data points obtained during 4 subsequent nights on BJD 2452116.332–9.364.

The individual light curves are shown in Fig.2. They show a composite structure with two minima and two maxima during the period. This is also consistent with the "rise to the outburst" data from the VSNET (Fig.3).

The study of individual runs and of evolution of characteristics is planed to be done elsewhere.

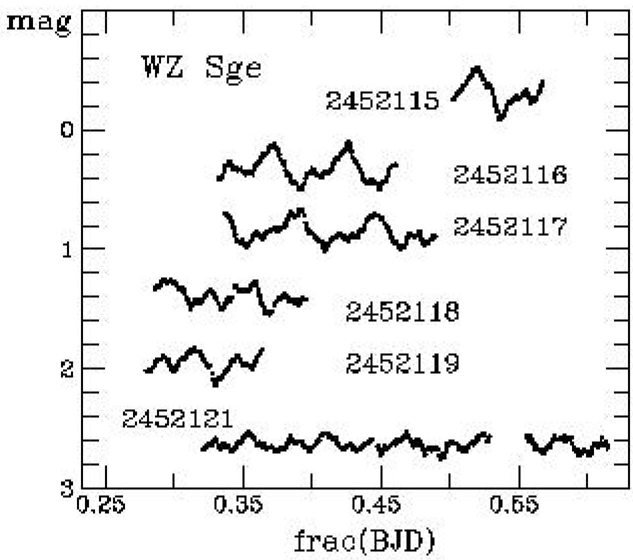

Figure 2: Light curves of WZ Sge for individual nights. The abscissa is a fractional part of barycentric Julian date. The integer part is shown near corresponding curves. The magnitude is expressed as "variable-comparison". The magnitude shift between the subsequent curves is $0.^m4$.

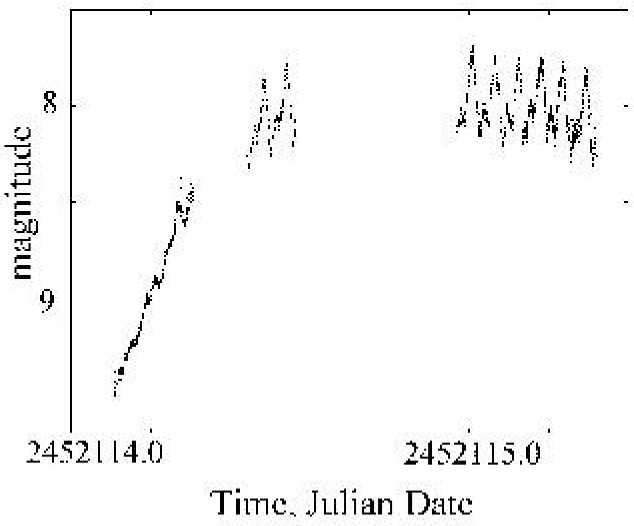

Figure 3: Rise to the maximum and the early evolution of the light curve from the VSNET observations *(www.kusastro.kyoto-u.ac.jp/vsnet/DNe/wzsge01.html)*. Our observations started 4 hours after these data, when the night moved from Japan to Europe.

4. Multi-harmonic analysis with a linear trend

Because of fast non-linear variations of the mean brightness and the light curve, the periodogram analysis for all data gives us some "effective" values of the parameters, which are highly biased by such instability. The preliminary analysis shows, that, the decrease of the interval allowed to decrease systematic errors owed to non-linear variations of the mean brightness. Thus we have used a trigonometric polynomial of order s superimposed onto the polynomial trend of order p. The mathematical model is

$$x_C(t) = C_1 + \sum_{k=1}^{s}(C_{2k}\cos(k\omega\bar{t}) + C_{2k}\sin(k\omega\bar{t})) + \sum_{k=1}^{p} C_{2s+1+k}\bar{t}^k, \qquad \bar{t} = t - \bar{t}, \qquad (1)$$

where $\bar{t}$ is the mean value of the times of observations, and $\omega = 2\pi/P$ is an angular frequency corresponding to the trial period P. The corresponding computer code extends the programs for separate multi-harmonic and polynomial approximations described by Andronov (1994). The preliminary value of the period is then changed to the value optimal for given degrees s and p for trigonometric and ordinary polynomials, respectively, using the method of differential corrections. The optimal values of s and p are determined using analysis of variances (the Fischer's criterion).

For the "shortened" data set, the values $s = 3$ and $p = 1$ are statistically significant. The "false alarm probability" of obtaining the wave at a period P/s of given amplitude, assuming the signal is white noise, is only $2 \cdot 10^{-4}$. The mean slope $C_{2s+2} = d\langle m\rangle/dt = (0.1481 \pm 0.0007)$ mag/days corresponds to a characteristic decay time $\tau = (d\langle m\rangle/dt)^{-1} = (6.75 \pm 0.03)$ days/mag. Here

$$\langle m\rangle = C_1 + \sum_{k=1}^{p} C_{2s+1+k}\bar{t}^k \qquad (2)$$

is a time-dependent zero-point of variations (trend value). For $p = 1$, it coincides with the orbit-average of the fit.

The time of the exponential decay $\tau_e = 2.5\tau/\ln 10 = 1.0857\tau = 7^d.33 \pm 0^d.03$ is well consistent with the range 4...12 days/mag over the first 15 days of the outburst estimated by Cannizzo (2001). The mean brightness $v - c = 0^m.2433 \pm 0^m.0014$ at the mean time of observations $\bar{t} = 2452118.77$. The best fit frequency $P^{-1} = 17.6518 \pm 0.0007$ cycles/day corresponds to the period $P = 0^d.0566513 \pm 0^d.0000022$. The light curve is highly asymmetric with a mean maximum at BJD 2452118.7483$\pm 0^d.0003$ with a trend-corrected value $v - c = 0^m.130 \pm 0^m.004$ and minimum at BJD 2452118.7670$\pm 0^d.0002$ with $v - c = 0^m.348 \pm 0^m.004$. Thus the total amplitude of the fit $\Delta m = 0^m.218 \pm 0^m.004$, asymmetry 0.670 ± 0.009.

Often the coefficients of trigonometric polynomial are studied instead of the real brightness values for variable stars of various types (e.g. Kukarkin and Parenago, 1937; Niarchos, 1978; Kopal, 1986; Petersen, 1986). In this case, the term

$$C_{2k}\cos(k\omega\bar{t}) + C_{2k}\sin(k\omega\bar{t}) = -r_k\cos(k\omega(t - T_0) - 2\pi k\varphi_k) \qquad (3)$$

Here T_0 is initial epoch (we use that corresponding to the brightness maximum, i.e. the minimum of the magnitude fit), and φ_k is the phase of maximum of the contribution. These characteristics are listed in the following table:

Table 1. The amplitudes r_k and phases φ_k of the contributions with a period P/k.

k	r_k	φ_k
1	0.0746±.0020	-0.051± 0.004
2	0.0538±.0020	0.055± 0.006
3	0.0087±.0020	-0.417± 0.037
	r_k/r_1	$\varphi_k - k\varphi_1$
1	1.000± .000	0.000±0.000
2	.722± .033	0.158±0.010
3	.117± .027	-0.263±0.039

The phase light curve and the best fit are shown in Fig.4. Despite the scatter of the individual curves is rather small, there are physical variations of the shape of the light curve.

5. Superhumps

The scatter in the phase curves is caused by real variability of the shape. One mechanism is the luminosity dependence of the phase curve, which could be studied separately. Another important mechanism is a possible of superhumps - periodic waves with a period larger than the orbital one.

Kato et al. (2001) reported that superhumps become dominating over the orbital variability on Aug.4.53 with an amplitude 0.10 mag and a period $0.^d057143 \pm 0.^d000046$. Their later observations during next two nights "have shown further development of superhumps up to 0.23 mag and give a mean period of 0.058876±0.000025 day". They called these superhums as "genuine", contrary to the "early superhumps" which they called the prominent hump structure of the orbital variations.

To look for possible "genuine" superhumps at the beginning of outbursts, we have made a periodogram analysis of the residuals "O−C" of the data from the fit (1). The periodogram shows three distinct groups of peaks caused by daily aliases. The most prominent peak occurred at the period $0.^d0611$, far from the value achieved for "genuine" superhumps. However, the second peak with a height differing from the first one by only one per cent. The corresponding period is $0.^d057435 \pm 0.^d000046$, in an excellent agreement with the superhumps. The initial epoch $T_{max,sh}$ =BJD $2452117.6830 \pm 0.^d0008$, and a semi-amplitude $0.^m208 \pm 0.^m0018$. Thus one may conclude that "genuine" superhumps started at least two days after the outburst.

Two other groups of peaks correspond to frequencies 57.88 and 67.80 cycles/day (21-25 minutes) and equal semi-amplitudes of $0.^m014 \pm 0.^m02$. The frequency difference between the highest peaks from these groups, $\sim$ 10 cycles/day does not correspond to the orbital frequency of the system (17.65 cycles/day). These frequencies are also much larger than the frequency 3100 cycles/day of the coherent 27.87-second oscillations. Thus possibly this variability is caused by some quasi-periodic oscillations and needs additional study.

6. Results

Our observations started $\sim 1^d$ after the outburst, where the mean light curve behaved non-linearly. Such a decrease of dm/dt was interpreted by Cannizzo (2001) as a consequence of increase of viscous time scale with decreasing mass of the accretion disk. He interpreted the outburst as a consequence of the sudden accretion of 10^{24} g of gas onto the white dwarf.

We present results of the "multiharmonic+trend" fit of the orbital variation, report on the presence of superhumps much before their amplitude became dominating. An interesting phenomenon are 21-25 minute waves.

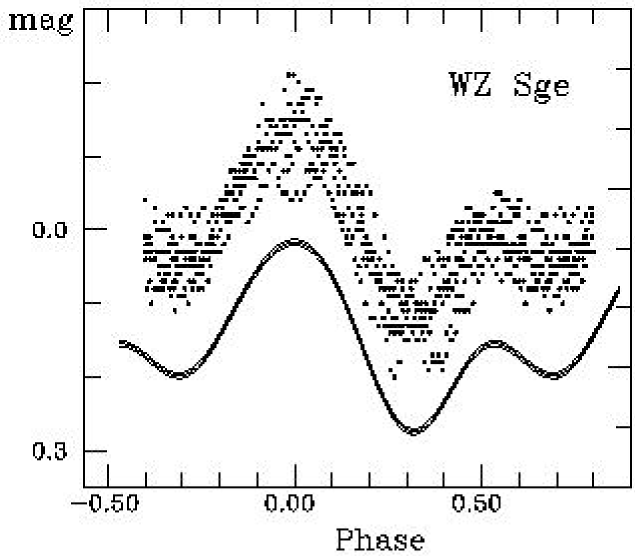

Figure 4: Phase light curve of WZ Sge for 4 nights used for the fit. The data are trend-corrected. The 3^{rd}−order trigonometric fit and its $\pm 1\sigma$ limits are shown as solid lines shifted by $0.^m15$ from the data points.

Acknowledgements. The authors are thankful to Profs. F.Meyer and Y.Osaki for helpful discussions. This work was partially supported by the grant 02/07/451 of the Ukrainian State Fund of Fundamental Research.

References

Andronov I.L.: 1994, *Odessa Astron. Publ.*, **7**, 49.
Cannizzo J.K.: 2001, *ApJ*, **561**, 175.
Faulkner J.: 1971, *ApJ*, **170**, L99.
Gilliland R.L., Kemper E.: 1980, *ApJ*, **236**, 854.
Greenstein J.L.: 1957, *ApJ*, **126**, 23.
Kato T. Ohashi H., Ishioka R., et al.: 2001, *IAUC*, **7680**.
Kopal Z.: 1986, *Vistas in Astronomy*, **29**, 295.
Krzeminski W.: 1962, *PASP*, **74**, 66.
Krzeminski W., Kraft R.P.: 1964, *ApJ*, **140**, 921.
Kukarkin B.W., Parenago P.P.: 1937, *AZh.*, 14, 337.
Niarchos P.G.: 1978, *Ap.Space Sci.*, **58**, 301.
O'Donoghue D.: 2000, *New Astr. Rev.*, **44**, 45.
Osaki Y.: 1995, *PASJ*, **47**, 470.
Patterson J.: 2001, *PASP*, **113**, 784, 736.
Patterson J., McGraw J.T., Coleman L., Africano J.L.: 1981, *ApJ*, **248**, 1067.
Patterson J., Richman H., Kemp J., Mukai K.: 1998, *PASP*, **110**, 746, 403.
Petersen J.O.: 1986, *As.Ap.*, **170**, 59.
Ritter H., Kolb U.: 1998, *As.Ap.Suppl.*, **129**, 83.
Tutukov A.V., Yungelson L.R.: 1979, *Acta Astr.*, **29**, 665.
Warner B., Nather E.R.: 1972, *MNRAS*, **156**, 297.