On supercycle lengths of active SU UMa stars

M. Otulakowska-Hypka* and A. Olech

N. Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warsaw, Poland

Accepted 2013 May 7. Received 2013 May 4; in original form 2013 March 25

ABSTRACT

We performed a detailed analysis of extensive photometric observations of a sample of the most active dwarf novae, that is, SU UMa stars which are characterized by supercycle lengths shorter than 120 d. We found observational evidence that supercycle lengths for these objects have been constantly increasing over the past decades, which indicates that their mean mass-transfer rates have been decreasing during that time. This seems to be a common feature for this type of stars. We present numerical results in each case and estimate time-scales of future development of these systems. This study is important in the context of evolution of dwarf nova stars and perhaps other cataclysmic variables.

Key words: binaries: close – stars: dwarf novae – stars: evolution – cataclysmic variables.

1 INTRODUCTION

As it was pointed out in one of the papers of Paczyński (1997), massive professional photometric surveys are today sources of many, often unexpected, discoveries [e.g. the ASAS project of Pojmanski (1997) or the Kepler mission of Borucki et al. (2010)]. On the other hand, data bases collecting amateur photometric measurements are growing rapidly, as telescopes and CCD detectors are easily accessible nowadays (Patton 2011; Szkody et al. 2012; Waagen 2012). This gives us access to a number of valuable open astronomical archives, both professional and amateur, with a richness of data gathered during the past decades. We have now a great opportunity to trace photometric behaviour of a lot of variable objects, for instance dwarf nova stars.

Dwarf nova are cataclysmic binaries with a white dwarf as a primary and a low-mass main-sequence star, filling its Roche lobe, as a secondary. Due to the transfer of mass from the secondary on to the non-magnetic primary, an accretion disc is formed. Such a mass transfer leads to outbursts in dwarf novae, as they are caused by sudden gravitational energy release due to accretion of this material on to the white dwarf. Dwarf novae with shortest orbital periods ($P_{orb} < 2.5\, h$) are called SU UMa stars. They are characterized by the presence of superoutbursts, next to normal outbursts, which are about 1 mag brighter and about 10 times less frequent than normal outbursts (Hellier 2001; Warner 2003).

The length of the supercycle, i.e. the time between two successive superoutbursts, is one of the most fundamental properties of SU UMa stars and is specific for each of them. The nature of this feature is still uncertain. Nowadays there is an open debate about the cause of superoutbursts. The thermal–tidal instability (TTI) model (Osaki 1997) suggests that the supercycle length ($P_{sc}$) is set by the mass-transfer rate ($M_t$). According to this scenario, the observed $P_{sc}$ is inversely proportional to $M_t$. The TTI model predicts that normal outbursts remove less material from the disc than it has been accreted since the last normal outbursts. This makes the disc to grow during a number of normal outbursts. When the disc reaches the critical radius ($r \sim 0.46 a$, with $a$ being the binary separation), it becomes eccentric and tidal effects occur, which causes superoutburst, during which the disc is shrinking again. Although the TTI model is commonly accepted, it still seems to need some improvements. For instance, the TTI simulations which reproduced the light curve of one of the most active dwarf novae, the star ER UMa, required an artificial increase of the mass-transfer rate by the factor of 10 in comparison to values expected from the theory based on gravitational radiation (Osaki 1995). Another example is the fact shown by Cannizzo (2012, and references therein) that embedded precursors of superoutbursts are present also in systems with long orbital periods. This argues for a more general model, which is not restricted to the mass ratio of $q < 0.25$, as the TTI model. Recently, Osaki & Kato (2012) presented evidence in favour of this model. Although their analysis was based on variations of the negative superhump period of a single dwarf nova, V1504 Cyg, they claimed that the cause of superoutbursts is finally revealed. However, Smak (2013) showed that this object cannot be considered as a representative for all systems which show negative superhumps. He also presented a number of arguments which suggest that superoutbursts are caused by strongly enhanced mass-transfer rate (Smak 2008).

Recent observations (Otulakowska-Hypka et al. 2013) surprisingly showed that the supercycle length of one of the most active dwarf novae, IX Draconis, has been increasing with a constant rate since the last twenty years. This is interesting in the context of evolution of such systems. Encouraged by this fact, we decided to investigate the same issue for other well-observed active objects of the SU UMa type.

The paper is arranged as follows. In Section 2, we give information on the data used in this research. The analysis is presented in Section 3. Results together with discussion are given in Section 4. We summarize the main conclusions in Section 5.

*E-mail: magdaot@camk.edu.pl
Table 1. List of objects with information on the used data bases in this study.

| Object          | ASAS | MEDUZA | AAVSO | AFOEV | BAAVSS | Kepler | Extra data          |
|-----------------|------|--------|-------|-------|--------|--------|---------------------|
| DI UMa          | x    | x      | x     | x     | x      |        | Rutkowski et al. (2009) |
| ER UMa          | x    | x      | x     | x     | x      |        | Kato & Kunjaya (1995)   |
| RZ LMi          | x    | x      | x     | x     | x      |        | Olech et al. (2008)    |
| SS UMi          | x    | x      | x     | x     | x      |        | Olech et al. (2006)    |
| V1159 Ori       | x    | x      | x     | x     | x      |        |                     |
| V1504 Cyg       | x    | x      | x     | x     | x      |        |                     |
| V344 Lyr        | x    | x      | x     | x     | x      |        |                     |
| V503 Cyg        | x    | x      | x     | x     | x      |        |                     |
| YZ Cnc          | x    | x      | x     | x     | x      |        |                     |

2 DATA

We searched accessible archives of amateur astronomical observers and automatic professional surveys to create joint and as complete light curves as possible. In a few cases, we also have an additional data from our previous observational campaigns and from other observers. The relevant photometric data were obtained from the following data bases: the ASAS\(^1\) project (Pojmanski 1997), the MEDUZA\(^2\) project of the Variable Star and Exoplanet Section of the Czech Astronomical Society (Brá & Zejda 2010), the Kepler mission\(^3\) (Borucki et al. 2010) and the data bases with amateur observations: AAVSO\(^4\), AFOEV\(^5\) and BAAVSS.\(^6\)

At first, we intended to perform the analysis for most of the well-observed (which often means the brightest) active SU UMa stars. However, we did not find enough data for the following objects to reach any unambiguous conclusions: BF Ara, BK Lyn, BR Lup, CI UMa, IX Dra, MN Dra, NY Ser, SDSS J210014 and UV Gem. We selected only those targets which have really good time coverage of their light curves, i.e. those for which we were able to easily distinguish superoutbursts from the rest of the signal. The chosen objects have light curves spreading over at least twenty years. In Table 1, we present the final list of objects together with information on the used data bases for each star.

Although our selected objects are all of the SU UMa type and they are located below the period gap in the orbital-period distribution for dwarf novae, they are diverse in terms of the evolutionary status. Fig. 1 shows the relation between the orbital period–superhump period excess ($\epsilon$) and the orbital period ($P_{\text{orb}}$) for dwarf novae, noticed first by Stolz & Schoembs (1984), where we marked by squares positions of the selected objects. Thanks to the dependence between $\epsilon$ and the mass ratio ($q$) for dwarf novae reported by Patterson (1998):

$$\epsilon = \frac{0.23q}{1 + 0.27q},$$

we can use the relation between $P_{\text{orb}}$ and $\epsilon$ as an excellent plane to examine evolution of these stars, since the mass ratio decreases with time due to the mass-loss from the secondary. In Fig. 1, small points represent known dwarf novae, from Olech et al. (2011). It was impossible to mark the exact position of one of the stars, RZ LMi, since its orbital period is unknown.

\(^1\) http://www.astrouw.edu.pl/asas/
\(^2\) http://var2.astro.cz/
\(^3\) http://archive.stsci.edu/kepler/
\(^4\) http://www.aavso.org/
\(^5\) http://cdsarc.u-strasbg.fr/afoev/
\(^6\) http://www.britastro.org/vs/
of all the objects are not uniform. There is an yearly trend present in all of them, with the exception of the Kepler data, caused by the variable observational conditions. In addition, the density of observations increases with time, as the number of amateur observers is constantly growing.

For this unevenly sampled data, we decided to use the ANOVA software (Schwarzenberg-Czerny 1996) for the time series analysis. First, we divided each of these light curves into five bins of equal time range. For each of the bins, we searched for the most prominent peak in the corresponding power spectrum obtained from ANOVA. Despite the data suffered from yearly aliasing, we were able to derive values of $P_{sc}$ for vast majority of the time bins for all of the objects. These values correspond to the most dominant peaks in a reasonable range of frequencies of periodograms. An example of such a power spectrum is presented in Fig. 3.

The obtained value of supercycle length for a given time bin is naturally not exactly equal to each time period between each pair of successive superoutbursts during the time covered by the time bin, because not all of them are strictly regular. There are some subtle differences between the $P_{sc}$ measured on short time-scales, as was already shown many times in the literature, for instance by Antonyuk & Pavlenko (2005) and Zemko, Kato & Shugarov (2012). However, our analysis aimed at examination of the overall behaviour of the $P_{sc}$, i.e. on long time-scales of the order of decades. Thus, based on the ANOVA statistics, we derived one value of $P_{sc}$ for each time bin, which corresponds to the range of observation time from a few years to one decade, depending on the object. All the results are presented in the next section, and the exact ranges of time bins for all stars are given in Table 2.

### 4 RESULTS AND DISCUSSION

In Figs 4 and 5, we show the obtained evolution of supercycle lengths for all of the analysed objects. Unfortunately, the quality of the rest of the data did not allow us to investigate more objects, so the statistics is poor. Seven out of nine examined targets show clearly growing supercycle lengths during the past decades (Fig. 4). The only two examples which seem to have a constant value of $P_{sc}$ are the ones with the poorest time coverage of the observations, before the Kepler data, which could have influenced the results (Fig. 5).

The behaviour of the $P_{sc}$ of YZ Cnc (the last one in Fig. 4) is a puzzle. First of all, it has the highest value of its period among all of the objects. Secondly, there is a peculiar drop in the $P_{sc}$ between the third and the fourth time bin, which looks like a transition from the increasing to a constant supercycle length. It is possible that this is only a short time-scale fluctuation, like for instance in the case of V503 Cyg. However, this drop is significant in comparison to the rest of the objects, which have fluctuations of the order which is about 1 mag smaller. Since this effect is so strange and unique, we checked it twice, and we claim that this is certainly not an artificial result. Because of the fact that the value of the supercycle length for YZ Cnc is the highest one, we cannot exclude a possibility that there is some critical value for such a high $P_{sc}$ which could have caused the drop.

| Object      | $P_{sc}$ (d) | $P_{sc}^{min}$ (d) | $P_{sc}^{max}$ (d) | HJD range (yr) |
|-------------|--------------|-------------------|-------------------|----------------|
| DI UMa      | $4.3 \pm 9.6 \times 10^{-4}$ | 23.8              | 44.7              | 30             |
| ER UMa      | $(12.7 \pm 1.9) \times 10^{-4}$ | 42.7              | 51.5              | 20             |
| IX Dra      | $(17.5 \pm 0.3) \times 10^{-4}$ | 45.7              | 59.0              | 20             |
| RZ LMi      | $(5.0 \pm 1.9) \times 10^{-4}$ | 18.3              | 22.9              | 18             |
| SS UMi      | $(34.5 \pm 5.8) \times 10^{-4}$ | 56.5              | 108.3             | 29             |
| V1159 Ori   | $(11.0 \pm 4.9) \times 10^{-4}$ | 42.6              | 55.1              | 19             |
| V1504 Cyg   | $(0.3 \pm 5.4) \times 10^{-4}$ | 110.6             | 120.6             | 20             |
| V344 Lyr    | $(0.2 \pm 2.5) \times 10^{-4}$ | 112.9             | 123.9             | 30             |
| V503 Cyg    | $(0.6 \pm 1.7) \times 10^{-3}$ | 112.1             | 128.1             | 20             |
| YZ Cnc      | $(30.2 \pm 1.4) \times 10^{-4}$ | 90.5              | 149.5             | 51             |

**Figure 2.** Example of the final light curve of YZ Cnc used in the further analysis (top). Zoom-in of the most recent part of this light curve where superoutbursts are clearly visible (bottom).

**Figure 3.** An example of a resulting periodogram. This is the case for the last time bin of ER UMa star. The most prominent peak here corresponds to the $P_{sc} = 50.9 \pm 0.5$ d. The side lobes come from the yearly sampling and are separated by 1 c yr$^{-1}$.

**Figure 4.** An example of the final light curve of YZ Cnc used in the further analysis (top). Zoom-in of the most recent part of this light curve where superoutbursts are clearly visible (bottom).
Figure 4. Results from ANOVA which show increasing supercycle lengths. Data points without uncertainties are possible but not certain due to poor light curves’ coverage.

Figure 5. Results from ANOVA which show constant supercycle lengths. Due to the light curves’ quality, for some of the time ranges the analysis was impossible. We show only the available measurements.

For completeness, in Fig. 6, we additionally present the plot from our previous publication (Otulakowska-Hypka et al. 2013), which shows the increasing supercycle length of another active ER UMa-type star, IX Draconis. This plot indicates that the rate of the period change is $\dot{P} = 1.8 \times 10^{-3}$, see Fig. 6.

This result is based on four independent measurements from various papers from the literature (Klose 1995; Ishioka et al. 2001; Olech et al. 2004; Otulakowska-Hypka et al. 2013), which were obtained from short observational campaigns in each case. This star was in our original list of objects for the present study; however, the
M. Otulakowska-Hypka and A. Olech

The examination of its whole light curve was impossible since it was too poor to perform the ANOVA analysis.

For all of our targets, we found positive values of their period derivatives of supercycle lengths, \( \dot{P}_{sc} \). They are presented in Table 2.

Only in two cases, i.e. V344 Lyr and V1504 Cyg, the \( \dot{P}_{sc} \) values are so small that they seem to be constant. Within the uncertainties they could also be either positive or negative, thus the conclusive distinction is impossible here. For two other objects, DI UMa and V503 Cyg, it is also possible that within the uncertainties the values of \( \dot{P}_{sc} \) are positive, constant or negative. This is caused by the fact that measurements of their \( \dot{P}_{sc} \) show the highest dispersion. Nonetheless, for these two stars, growing trends of their supercycle lengths are highly probable, as Fig. 4 suggests.

A comparison of these results with other examples known from the literature is satisfactory. They are in agreement at least with the order of magnitude. Where there is some formal disagreement, it is generally because the earlier measurement spanned only a short baseline. This makes it different from our final result but it is in agreement with the corresponding value of our supercycle length for the given moment (Robinson, Honeycutt & Turner 1995; Szkody et al. 1999; Kato et al. 2000). On the other hand, the result presented by Zemko et al. (2012) for ER UMa is based on the analysis of a light curve with the time coverage of twenty years. Here, the result is consistent with ours to the order of magnitude, and the small difference probably comes from the differences in the data sources and methods of analysis. In turn, Antonyuk & Pavlenko (2005) showed for the five years spread of observations that the supercycle for V1504 Cyg seems to stay more or less constant, apart from short time-scale fluctuations.

Our examination of supercycle lengths’ behaviour on long time-scales demonstrates that all of the analysed active SU UMa stars have a positive value of their superoutbursts period derivative. In spite of the fact that they differ in terms of the value and the level of measurement’s dispersion, 8 out of 10 objects have an increasing trend in their \( \dot{P}_{sc} \) evolution. This behaviour seems to be typical for these stars. The fact that for most of these sources there is clear evidence of increasing supercycle lengths means that their mean mass-transfer rates have been constantly decreasing during the past decades. This scenario of evolution is in agreement with results for an extremely interesting ER UMa-type object, BK Lyncis, presented by Patterson et al. (2012). In this publication the authors showed a hypothesis of the evolutionary path of this star as its ER UMa stage is a transient phase of evolution, preceded by the classical nova and nova-like phases. If we assumed that this is true for all active SU UMa stars of our sample, this would mean that these objects are constantly fading since their classical nova eruptions. Considering the fact that they are rather diverse in terms of their orbital periods, i.e. evolutionary stages (see Fig. 1), even though they are all below the period gap, we can try to predict time-scales of their further steps of evolution. All of our objects are extremely active as for the SU UMa class. The most active of them are sometimes distinguished as a separate class of ER UMa-type, with \( P_{sc} \approx 50 \text{ d} \). They are believed to be typical SU UMa stars with only higher mass-transfer rates (DI UMa, ER UMa, IX Dra, RZ LMi and V1159 Ori from our sample). The rest of the sample are representatives of the SU UMa class of stars but still with extremely short supercycles (SS UMi, V1504 Cyg, V344 Lyr, V503 Cyg and YZ Cnc). A typical supercycle length for a star of SU UMa type is equal to a few hundred days and for the WZ Sge class it is of the order of decades (Hellier 2001). We adopted these standard values to find the expected time-scales in which our objects will reach next levels of evolution. For all of the stars, we estimate the time which is needed to become SU UMa-type object with \( P_{sc} = 300 \text{ d} \). For the two objects in our sample which evolves towards longer orbital periods after they reached the period minimum, i.e. DI UMa and IX Dra, we also give times needed to reach the next step, that is, becoming a WZ Sge star with \( P_{sc} = 10 \text{ yr} \). Results of this estimate are shown in Table 3.

| Object     | SU UMa stage \( P_{sc} = 300 \text{ d} \) | WZ Sge stage \( P_{sc} = 10 \text{ yr} \) |
|------------|------------------------------------------|------------------------------------------|
| DI UMa     | 1700                                     | 23 000                                   |
| ER UMa     | 500                                      | –                                         |
| IX Dra     | 400                                      | 6000                                     |
| RZ LMi     | 1500                                     | –                                         |
| SS UMi     | 200                                      | –                                         |
| V1159 Ori  | 600                                      | –                                         |
| V1504 Cyg  | 20 000                                   | –                                         |
| V344 Lyr   | 33 000                                   | –                                         |
| V503 Cyg   | 800                                      | –                                         |
| YZ Cnc     | 100                                      | –                                         |

5 CONCLUSIONS

We analysed a set of photometric data covering the last few decades of observations for the most active SU UMa stars in order to study changes of their supercycle lengths. Despite the common feature of the selected objects, which is the highest activity in this class of stars, they are diverse in terms of their orbital periods below the period gap. For all of the analysed objects, we found positive values of period derivatives of their supercycle lengths. There are some subtle fluctuations for short time-scales in the behaviour of \( P_{sc} \), but the general trend is the same in each case. Increasing supercycle lengths means that the mean mass-transfer rates have been decreasing for these objects over the last decades. This is in agreement with the

Figure 6. Plot from Otulakowska-Hypka et al. (2013), which shows the increasing supercycle length of IX Dra during the past twenty years. The data points are taken from the literature. Uncertainties are given when available. The line represents the best fit to the data. The corresponding rate of increase of the period is \( P = 1.8 \times 10^{-3} \).
scenario of the evolution of BK Lyn presented by Patterson et al. (2012), which seems to be a general case. This phenomenon is important in the context of evolution of such systems.

ACKNOWLEDGEMENTS

We acknowledge with thanks the variable star observations from the AAVSO International Database, operated in USA, the AFOEV data base, operated at CDS, France, the BAAVSS data base, operated in UK, and the Variable Star and Exoplanet Section of the Czech Astronomical Society, contributed by observers worldwide and used in this research. This paper includes data collected by the Kepler mission. Funding for the Kepler mission is provided by the NASA Science Mission directorate. Some of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts. This research has made use of the SIMBAD data base, operated at CDS, Strasbourg, France. The project was supported by Polish National Science Center grant awarded by decision number DEC-2011/03/N/ST9/03289. We are very grateful to an anonymous referee for his/her thoughtful comments which helped to improve the text of the paper.

REFERENCES

Antonyuk O. I., Pavlenko E. P., 2005, in Hameury J.-M., Lasota J.-P., eds, ASP Conf. Ser. Vol. 330, SU UMa-type Dwarf Nova V1504 Cygni During Several Supercycles. Astron. Soc. Pac., San Francisco, p. 379
Borucki W. J. et al., 2010, Sci, 327, 977
Bráš L., Zejda M., 2010, in Prša A., Zejda M., eds, ASP Conf. Ser. Vol. 435, Variable Star and Exoplanet Section of the Czech Astronomical Society. Astron. Soc. Pac., San Francisco, p. 457
Cannizzo J. K., 2012, ApJ, 757, 174
Eastman J., Siverd R., Gaudi B. S., 2010, PASP, 122, 935
Hellier C., 2001, Cataclysmic Variable Stars – How and Why They Vary. Springer-Verlag, Berlin
Ishioka R., Kato T., Uemura M., Iwamatsu H., Matsumoto K., Martin B. E., Billings G. W., Novak R., 2001, PASJ, 53, L51
Kato T., Kunjaya C., 1995, PASJ, 47, 163
Kato T., Hanson G., Poyner G., Muyllaert E., Reszelksi M., Dubovsky P. A., 2000, Inf. Bull. Var. Stars, 4932, 1
Klose S., 1995, ApJ, 446, 357
Olech A., Zloczewski K., Mularczyk K., Kedzierski P., Wisniewski M., Stachowski G., 2004, Acta Astron., 54, 57
Olech A., Mularczyk K., Kedzierski P., Zloczewski K., Wisniewski M., Szaruga K., 2006, A&A, 452, 933
Olech A., Wisniewski M., Zloczewski K., Cook L. M., Mularczyk K., Kedzierski P., 2008, Acta Astron., 58, 131
Olech A. et al., 2011, A&A, 532, A64
Osaki Y., 1995, PASJ, 47, L11
Osaki Y., 1996, PASP, 108, 39
Osaki Y., Kato T., 2012, preprint (arXiv:e-prints)
Oulakowska-Hypka M., Olech A., de Miguel E., Rutkowski A., Koff R., Bąkowska K., 2013, MNRAS, 429, 868
Paczyński B., 1997, in Ferlet R., Maillard J.-P., Raban B., eds, The Future of Massive Variability Searches. Editions Frontières, France, p. 357
Patterson J., 1998, PASP, 110, 1132
Patterson J., 2011, AAS Meeting Abstr. 218, Cataclysmic Variables in the Backyard. Am. Astron. Soc., p. 103.03
Patterson J. et al., 2012, preprints (arXiv:e-prints)
Pojmański G., 1997, Acta Astron., 47, 467
Robertson J. W., Honeycutt R. K., Turner G. W., 1995, PASP, 107, 443
Rutkowski A., Olech A., Wisniewski M., Pietrukowicz P., Pala J., Poleski R., 2009, A&A, 497, 437
Schwarzenberg-Czerny A., 1996, ApJ, 460, L107
Smak J., 2008, Acta Astron., 58, 55
Smak J., 2013, Acta Astron., 63, 109
Stolz B., Schoembs R., 1984, A&A, 132, 187
Szkody P. et al., 1999, ApJ, 521, 362
Szkody P. et al., 2012, J. Am. Assoc. Var. Star Obser., 40, 94
Waagen E. O., 2012, J. Am. Assoc. Var. Star Obser., 40, 222
Warner B., 2003, Cataclysmic Variable Stars. Cambridge Univ. Press, Cambridge
Zemko P., Kato T., Shugarov S., 2012, preprint (arXiv:e-prints)

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.