ACTA ASTRONOMICA
Vol. **63** (2013) pp. 1–11

Fifty Years of TT Arietis

J. Smak

N. Copernicus Astronomical Center, Polish Academy of Sciences,
Bartycka 18, 00-716 Warsaw, Poland
e-mail: jis@camk.edu.pl

Received

ABSTRACT

Results of photometric observations of the permanent negative superhumper TT Ari in 1961/62 and 1966 are presented. Together with data from the literature they are used to discuss the negative superhump amplitudes A_{nSH} and the amplitudes A_{beat} of the modulation with the beat period P_{beat}. Both amplitudes are shown to vary considerably from one season to another. Three correlations are found: (1) between A_{nSH} and A_{beat}, (2) between A_{nSH} and P_{nSH}, and (3) between A_{beat} and P_{beat}.

Key words: *binaries: cataclysmic variables, stars: individual: TT Ari*

1. Introduction

The variability of TT Ari = BD+14°341 was discovered by Strohmeier, Kippenhahn and Geyer (1957). In the fall of 1961 Herbig (1961) took several spectrograms of the star and found that its spectrum consists of a hot continuum and weak emission lines of hydrogen; this suggested that BD+14°341 could be a nova-like object. Following Dr. Herbig's suggestion the present author, then at the Lick Observatory, observed the star photometrically in December 1961 and January 1962 and found that on shorter time scales its variability consists of three components: (1) Periodic variations with $P = 0.1329$ d, or $\sim 3^h 12^m$, and full amplitude of about $2A \approx 0.2$ mag, often referred to as "3-hour" variations. (2) Transient, quasi-periodic fluctuations with periods between 14 and 20 minutes and full amplitudes up to $2A \approx 0.2$ mag. (3) Rapid flickering with amplitudes up to 0.1 mag and time scales of the order of 1 min. Those findings were later confirmed by results of two other series of photometric observations: in 1966 by the present author at the Observatoire de Haute Provence (OHP) and in 1967 by Dr. K. Stępień at the Lick Observatory. Only preliminary results of those three series of photometric observations were published by Smak and Stępień (1969, 1975).

It can be added that the "3-hour" variations of TT Ari were in fact the first superhumps (*negative* superhumps in this case) ever observed although they were identified as such only 30 years later (cf. Patterson et al. 1993).

In the following years TT Ari was observed photometrically and spectroscopically by many authors. The first extensive spectroscopic investigations of TT Ari by Cowley et al. (1975) revealed that its orbital period is $P_{orb} = 0.1375\,\mathrm{d}$, i.e. about 3 percent longer than the photometric period. This was confirmed later by Thorstensen, Smak and Robinson (1985) and by Wu et al. (2002) who determined $P_{orb} = 0.13755040 \pm 0.00000017\,\mathrm{d}$.

Semeniuk et al. (1987) found that the mean brightness of TT Ari observed in 1966 (see Section 3) varied also with the "4-day" beat period resulting from the combination of the orbital and negative superhump periods. So far, however, the existence of this "4-day" modulation was confimed only by Udalski (1987) and Kraicheva et al. (1997), but not by other observers.

In 1997 an unexpected transition occured from negative superhumps to common superhumps with $P_{SH} = 0.1492\,\mathrm{d}$, about 8 percent longer than the orbital period (Kraicheva et al. 1999, Skillman et al. 1998). The common superhumps disappeared and the negative superhumps begun to reappear again in 2005 (Andronov et al. 2005, Kim et al. 2009) and in 2007 they were observed with the MOST satellite (Vogt et al. 2013).

TT Ari is also a member of the VY Scl subtype of CV's showing the so-called low states, extending over months or years, during which it declines in brightness from $V \approx 10.6$ in its high state down to $V \sim 17$ (cf. Hudec, Huth, and Fuhrmann 1984, Shafter et al. 1985, Wenzel et al. 1992). The two most recent low states occured in 1980-1984 and in 2009/2010. It can be added that no superhumps are observed during those low states.

The purpose of the present paper is twofold: (1) to present in more detail the results of the 1961/62 Lick and 1966 OHP photometry (Sections 2 and 3), and (2) to re-analyze the available photometric data in order to clarify the problem of the "4-day" variations (Sections 4 and 5).

2. The 1961/62 Lick Light Curves

Observations were made with the Crossley Reflector and standard (at that time!) photometric equipment. The comparison star was BD+14° 336 with $\mathrm{V} = 8.944 \pm 0.009$, $\mathrm{B\text{-}V} = +0.220 \pm 0.003$, $\mathrm{U\text{-}B} = +0.108 \pm 0.004$ (based on 18 measurements during 8 nights). On one night TT Ari was observed in three colors allowing the determination of its mean magnitude and colors: $< V > \approx 10.6$, $< (B-V) > \approx -0.05$, $< (U-B) > \approx -0.95$. On the remaining nights it was observed in one color, either in yellow or in ultraviolet. Altogether 1570 data points were obtained. Results were expressed in the instrumental system in the form $\Delta m =$ TT Ari–BD+14° 336.

Fig.1 shows, as an example, the ultraviolet light curve observed on January 15 UT, 1962. This is the light curve which was analyzed by Williams (1966) who found no periodicities in its first part and three periodic components with periods

13.9, 17.6, and 42.2 min. during the second part. No oscillations with $P = 27$ min. suggested by Semeniuk et al. (1987) were present.

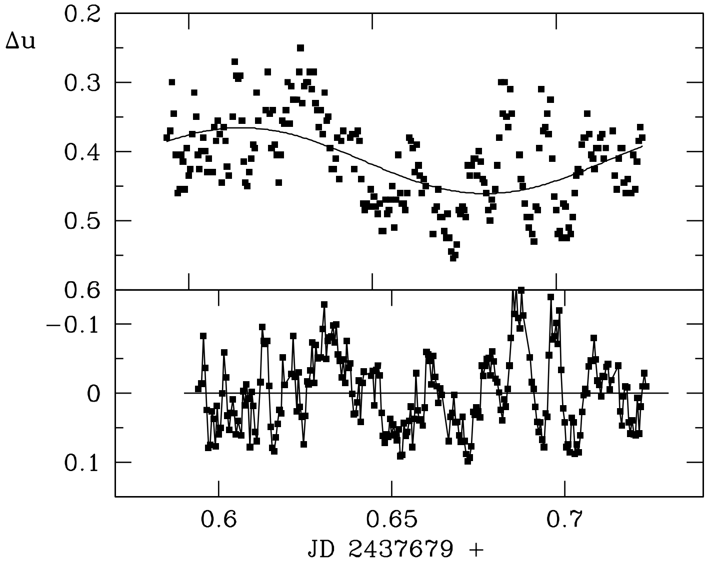

Fig. 1. *Top:* Ultraviolet light curve of TT Ari on January 15 UT, 1962. Solid line is the best fit cosine curve. *Bottom:* The residuals after subtracting the cosine curve.

The parameters describing the negative superhumps, i.e. the moments of maxima and minima and the corresponding magnitudes, were determined by fitting the cosine curves to the points observed on a given night. Results are listed in Table 1. Using those moments of maxima nad minima we find the following elements

$$\text{Maximum} = \text{JDhel.}2437646.6514(19) + 0.132896(12) \times E \ . \qquad (1)$$

The mean amplitudes of the negative superhumps, A_{nSH}, and of the "4-day" modulation with the beat period, A_{beat}, were determined directly by fitting the following formula to all data points

$$\Delta m = <\Delta m> - A_{nSH} \cos\phi_{nSH} - A_{beat} \cos(\phi_{beat} - \phi^{max}_{beat}) \ . \qquad (2)$$

This formula requires several comments. (1) The parameters $<\Delta m>=<\Delta y>$ or $<\Delta u>$, and $A_{nSH} = A^V_{nSH}$ or A^U_{nSH} were determined independently for the two colors. (2) The amplitude of the "4-day" modulation A_{beat} was assumed to be identical in V and U, this assumption being based on the commonly adopted interpretation of negative superhumps (see Section 6). (3) The beat phase ϕ_{beat} was calculated using the beat period P_{beat} related to the orbital and negative superhump periods:

$$1/P_{beat} = 1/P_{nSH} - 1/P_{orb} \ . \qquad (3)$$

Table 1

Maxima and Minima of TT Ari in 1961/62 and 1966

Maxima	C	Δm	Minima	C	Δm
2437000+			2437000+		
646.6547±.0018	V	1.537±.011	655.6129±.0043	V	1.808±.015
655.6863±.0020	V	1.640±.008	655.7527±.0016	V	1.812±.009
656.7563±.0029	V	1.714±.009	656.6851±.0016	V	1.846±.007
660.7362±.0020	U	0.397±.010	660.6723±.0015	V	1.858±.008
664.7239±.0016	U	0.364±.010	660.6720±.0015	B	1.594±.008
675.6269±.0015	U	0.350±.010	660.6744±.0013	U	0.593±.007
679.6156±.0033	U	0.363±.009	664.6569±.0018	U	0.557±.010
692.6255±.0023	U	0.451±.014	672.6350±.0027	U	0.552±.023
2439000+			679.6790±.0024	U	0.463±.008
360.6245±.0023	U	0.372±.009	2439000+		
375.6185±.0015	U	0.370±.010	375.5536±.0014	U	0.584±.009
376.5492±.0010	U	0.420±.010	376.6138±.0009	U	0.700±.008
377.6179±.0016	U	0.430±.012	377.5460±.0012	U	0.749±.011
378.5445±.0013	U	0.364±.008	378.6102±.0018	U	0.548±.009

The results of this "global" fit are: $<\Delta y>= 1.716\pm 0.003$ or $<V>= 10.66$, $A^{V}_{nSH} = 0.086\pm 0.004$, $<\Delta u>= 0.422\pm 0.003$, $A^{U}_{nSH} = 0.074\pm 0.003$, and $A_{beat} = 0.067\pm 0.003$. To avoid possible confusion it should be added that the "full amplitudes" of those variations are obviously 2 times larger than the amplitudes defined by Eq.(2).

Fig.2 shows the maximum and minimum magnitudes from Table 1 plotted as a function of the beat phase. Shown also are the best fit cosine curves obtained from the "global" fit (Eq.2).

3. The 1966 OHP Light Curves

Observations were made during five nights in August-September 1966 using the 60 cm reflector of the Observatoire de Haute Provence. TT Ari was observed only in ultraviolet (defined by the Lallemand's photomultiplier Maximilien and the Corning filter C9863). Altogether 1280 data points were obtained.

Fig.3 shows, as an example, the ultraviolet light curve observed on September

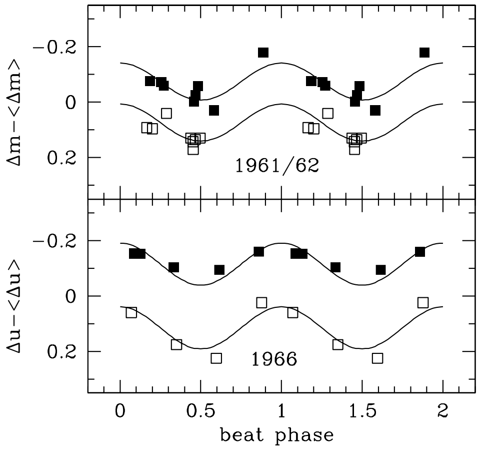

Fig. 2. Maximum (*filled squares*) and minimum (*open squares*) magnitudes as a function of the beat phase. *Top:* The 1961/62 Lick data. *Bottom:* The 1966 OHP data. Solid lines are the best fit cosine curves (Eq.2).

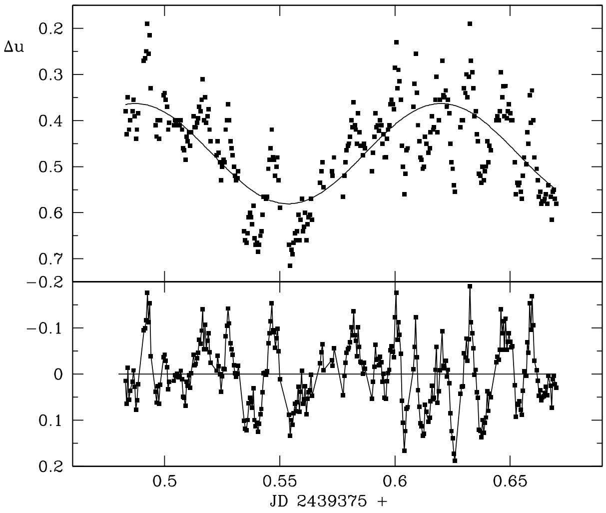

Fig. 3. *Top:* Ultraviolet light curve of TT Ari on September 6 UT, 1966. Solid line is the best fit cosine curve. *Bottom:* The residuals after subtracting the cosine curve.

6 UT, 1966. Visible in the residuals after JD 2439375.60 are quasi periodic oscillations with $P \approx 17$ min. No oscillations, however, with $P = 24$ min., suggested by Semeniuk et al. (1987), can be seen.

The data were analyzed in the same way as in Section 2 giving the moments of maxima and minima and the corresponding magnitudes listed in Table 1. The moments of maxima are represented with

$$\text{Maximum} \;=\; \text{JDhel.}2439360.6233(31) \;+\; 0.132730(26) \times E\;. \qquad (4)$$

Note that the period in 1966 was slightly shorter than in 1961/62 although this depends on the single maximum on JD 2439360.

The results of the "global" fit are: $<\Delta u>= 0.524 \pm 0.002$, $A^U_{nSH} = 0.115 \pm 0.003$, and $A_{beat} = 0.076 \pm 0.003$. The maximum and minimum magnitudes from Table 1 and the best fit cosine curves obtained from the "global" fit (Eq.2) are shown in Fig.2.

4. The "4-day" Modulation with Beat Period

4.1. The Data

A search through the literature was made for data suitable for the determination of amplitudes of the "4-day" modulation, resulting in the selection of the following sets of data.

1987/88. Kraicheva et al. (1997) observed TT Ari during three seasons. The nightly mean magnitudes $<\Delta u>$ plotted in their Fig.7 clearly show the "4-day" modulation. Regretfully, however, no information was given concerning the negative superhump amplitude! Fortunately, in 1987/88 TT Ari was also observed by Udalski (1988) and from his light curves we get $A_{nSH} = 0.065 \pm 0.010$.

1988. Tremko et al. (1996) published results of a large international campaign involving several observers and covering more than two months in 1988. They found $P_{nSH} = 0.132953 \pm 0.000013$d. Listed in their Tables 4 and 5 are moments of maxima and minima and the corresponding magnitudes, mostly in B. An inspection of light curves shows, however, that some of them were local maxima or minima unrelated to the superhumps and therefore had to be removed. The magnitudes Δm_{max} and Δm_{min} posed some problems. The primary comparison star used by Tremko et al. was BD+14°336 – the same which was used by the present author at Lick. However the UBV magnitude and colors obtained by them differ from those given in Section 2. Secondly, the values of Δm_{max} and Δm_{min} obtained by observers at Skalnate Pleso (SP) differ significantly from those obtained by observers at Sonneberg (SB). Thirdly, the values of Δm_{max} and Δm_{min} obtained observers in Kraków (KR) refer to another comparison star. Using data contained in Tables 4 and 5 and in Figs.6 and 7 of Tremko et al. we applied the following corrections: $\Delta m(\mathrm{SB}) = \Delta m(\mathrm{SP}) + 0.15$, and $\Delta m(\mathrm{SB}) = \Delta m(\mathrm{KR}) + 1.95$.

1994. Andronov et al. (1999) published results of another international campaign covering nearly three months in 1994. They found $P_{nSH} = 0.133160 \pm 0.000004$d and $A^B_{nSH} = 0.0513 \pm 0.0008$mag. Their Table 2 lists only the nightly mean magnitudes. To avoid problems with systematic differences between different observers we use only the results of a long series of observations made at the Odessa's Dushak–Eregdag Observatory.

1996. The long series of observations by Kraicheva et al. (1999) included the years 1995 and 1996 when the negative superhumps were observed and the years 1997 and 1998 when the common superhumps were observed. In 1996 they found

$P_{nSH} = 0.13424\,\mathrm{d}$ – the longest ever observed. Suitable for our analysis are the 1966 data: the bottom part of their Fig.4 showing the light curves (Δb) and Fig.6 showing the nightly mean values; using them we determine Δb_{max} and Δb_{min}.

2007. Vogt et al. (2013) presented results of continous monitoring of TT Ari by the MOST satellite during 10 days in 2007. They found $P_{nSH} = 0.133103 \pm 0.000036\,\mathrm{d}$ and $A^{B}_{nSH} = 0.045\,\mathrm{mag}$ but considered their data insufficient for a significant detection of the "4-day" periodicity. In spite of that we will use the mean magnitudes plotted in the upper part of their Fig.2.

4.2. The Results

The data described above were analyzed in the following way. In the case when maximum and minimum magnitudes were available they were fitted with

$$\Delta m_{min}/\Delta m_{max} \; = \; <\Delta m> \; \pm\, A_{nSH} \, - \, A_{beat}\, \cos(\phi_{beat} - \phi^{max}_{beat}) \,, \qquad (5)$$

where the ± sign refers to minimum/maximum. In the case when only nightly mean magnitudes were available they were fitted with

$$\Delta m \; = \; <\Delta m> \; - \, A_{beat}\, \cos(\phi_{beat} - \phi^{max}_{beat}) \,. \qquad (6)$$

Results are listed in Table 2 and shown in Fig.4 together with results from Sections 2 and 3. Listed in that Table are also the values of negative superhump periods P_{nSH} and the corresponding beat periods P_{beat} calculated from Eq.(3).

Table 2
Amplitudes and Periods

Year	C	A_{nSH}	A_{beat}	P_{nSH}	P_{beat}
1961/62	V	0.086±0.004	0.067±0.003	0.132896	3.931
1961/62	U	0.074±0.003	0.067±0.003	0.132896	3.931
1966	U	0.115±0.003	0.076±0.003	0.132730	3.787
1987/88	U	0.065±0.010	0.077±0.011	0.132946	3.972
1988	B	0.052±0.007	0.029±0.011	0.132953	3.978
1994	B	0.051±0.001	0.016±0.014	0.133160	4.172
1996	B	0.069±0.013	0.027±0.019	0.134240	5.578
2007	V	0.045±0.001	0.031±0.008	0.133103	4.114

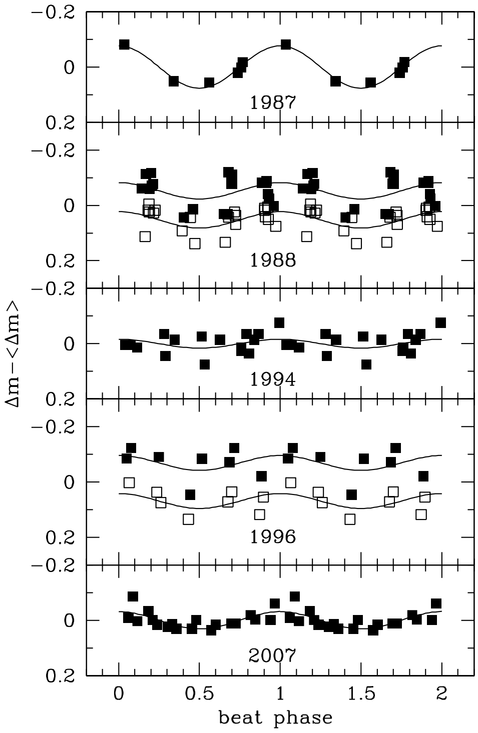

Fig. 4. Maximum (*filled squares*) and minimum (*open squares*) magnitudes or mean magnitudes as a function of the beat phase. Solid lines are the best fit cosine curves (Eqs.5 and 6).

5. The A_{nSH} – A_{beat} and the Amplitude – Period Correlations

The first, obvious conclusions based on results contained in Table 2 and shown in Fig.4 are: (1) the "4-day" modulation with beat period is always present, and (2) all parameters: A_{nSH}, A_{beat}, P_{nSH} and – consequently – P_{beat} vary significantly from one season to another.

The two amplitudes: A_{nSH} and A_{beat} are compared in Fig.5 and it turns out that they are correlated. One should note, however, that indivual values of A_{nSH} listed in Table 2 correspond to three different colors. From fragmentary UBV data (Tremko et al. 1996, Volpi et al. 1988) one finds that the amplitudes in B and V are practically the same, but those in U are by about 20 percent larger (on the other hand, however, the 1961/62 ultraviolet amplitude was *smaller* than the visual amplitude). Fortunately it turns out that decreasing the values of A^U_{nSH} by 20 percent affects the correlation seen in Fig.5 only slightly.

Shown in Fig.6 is a comparison between the amplitudes A_{nSH} and A_{beat} and the corresponding periods P_{nSH} and P_{beat}. As can be seen they are also correlated. Worth noting is the peculiar location of the 1996 data points. It may suggest that the period P_{nSH} and the corresponding period P_{beat} were incorrect. Supporting this suspicion is the fact that $P_{nSH} = 0.13424$ given by Kraicheva et al. (1999) differs

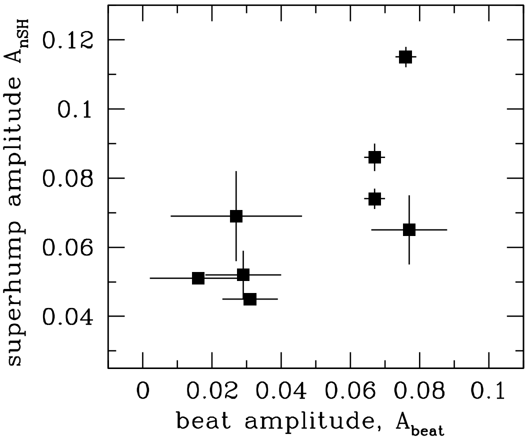

Fig. 5. Negative superhump amplitudes A_{nSH} *versus* beat amplitudes A_{beat}.

from the mean value $< P_{nSH} >= 0.132965$ based on all other determinations (see Table 2) by 9σ, while $P_{beat} = 5.578$ differs from $< P_{beat} >= 3.992$ by 13σ.

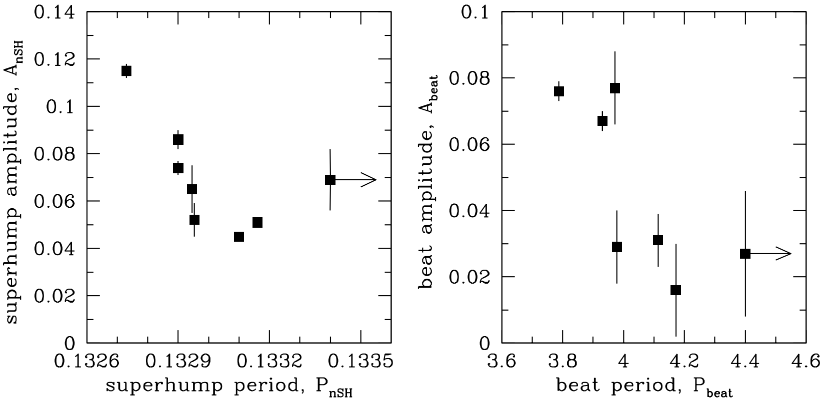

Fig. 6. *left*: Negative superhump amplitudes A_{nSH} *versus* periods P_{nSH}. *right*: Beat amplitudes A_{beat} *versus* periods P_{beat}. Arrows at symbols representing the 1966 data points indicate that – with $P_{nSH} = 0.13424$ and $P_{beat} = 5.578$ – they should actually be located far to the right, outside the plot limits.

It can be hoped that the existence of those correlations will be confirmed by results of two series of observations of TT Ari in 2012: with the MOST satellite and by the AAVSO observers (see Vogt et al. 2013). Using values of the negative superhump period $P_{nSH} = 0.132883$ given by Vogt et al., and the corresponding $P_{beat} = 3.916$, we predict (see Fig.6) that the two amplitudes, A_{nSH} and A_{beat}, should be fairly large.

6. Discussion

According to the commonly accepted interpretation of negative superhumps (Montgomery 2009ab, Wood, Thomas and Simpson 2009, and references therein) they are due to modulated dissipation of the kinetic energy of the stream as it collides with the surface of the tilted precessing disk. This "tilted-disk model" predicts that the negative superhump amplitude A_{nSH} should depend on disk tilt (Montgomery 2009a). Furthermore, as the inclination of the disk with respect to the observer changes with the precession period its observed luminosity is expected to be modulated with P_{prec}.

The beat amplitude observed in TT Ari (see Table 2 and Fig.5) varies between $A_{beat} = 0.02$ and 0.08 mag. Using Eq.(28) from Smak (2009) with $i = 29^\circ$ (Wu et al. 2002) we find that this corresponds to variations of the tilt angle between $\delta = 1^\circ$ and 5°.

The correlation between A_{beat} and A_{nSH} (Fig.5) provides further support for the "tilted-disk model". The significance of other correlations, however, between the amplitudes and periods (Fig.6), is not clear.

REFERENCES

Andronov, I.L., Arai, K., Chinarova, L.L., Dorokhov, N.I., Dorokhova, T.N., Dumitrescu, A., Nogami, D., Kolesnikov, S.V., Lepardo, A., Mason, P.A., Matsumoto, K., Oprescu, G., Pajdosz, G., Passuelo, R., Patkos, L., Senio, D.S., Sostero, G., Suleimanov, V.F., Tremko, J., Zhukov, G.V., Zoła, S. 1999, *AJ*, **117**, 574.

Andronov, I.L., Burwitz, V., Chinarova, L.L., Gazeas, K., Kim, Y., Niarchos, P.G., Ostrova, N.I., Patkós, L., Yoon, J.N. 2005, *Inf.Bull.Var.Stars*, 5664.

Cowley, A.P., Crampton, D., Hutchings, J.B., Marlborough, J.M. 1975, *ApJ*, **195**, 413.

Herbig, G.H. 1961, *Private information*.

Hudec, R., Huth, H., Fuhrmann, B. 1984, *Observatory*, **104**, No.1058, 1.

Kim, Y., Andronov, I.L., Cha, S.L., Chinarova, L.L., Yoon, J.N. 2009, *A&A*, **496**, 765.

Kraicheva, Z., Stanishev, V., Iliev, L., Antonov, A., Genkov, V. 1997, *A&ASuppl.Ser.*, **122**, 123.

Kraicheva, Z., Stanishev, V., Genkov, V., Iliev, L. 1999, *A&A*, **351**, 607.

Montgomery, M.M. 2009a, *MNRAS*, **394**, 1897.

Montgomery, M.M. 2009b, *ApJ*, **705**, 603.

Patterson, J., Thomas, G., Skillman, D.R., Diaz, M. 1993, *ApJSuppl.*, **86**, 235.

Semeniuk, I., Schwarzenberg-Czerny, A., Duerbeck, H., Hoffman, M., Smak, J., Stępień, K., Tremko, J. 1987, *Acta Astron.*, **37**, 197.

Shafter, A.W., Szkody, P., Liebert, J., Penning, W., Bond, H.E., Grauer, A.D. 1985, *ApJ*, **290**, 707.

Skillman, D.R., Harvey, D.A., Patterson, J., Kemp, J., Jensen, L., Fried, R.E., Garradd, G., Gunn, J., van Zyl, L., Kiyota, S., Retter, A., Vanmunster, T., Warhurst, P. 1998, *ApJ*, **503**, L67.

Smak, J. 2009, *Acta Astron.*, **59**, 419.

Smak, J., Stępień, K. 1969, *Non-Periodic Phenomena in Variable Stars*, ed. L.Detre (Budapest: Academy Press), p.355.

Smak, J., Stępień, K. 1975, *Acta Astron.*, **25**, 379.

Strohmeier, W., Kippenhahn, R., Geyer, E. 1957, *Kl.Veröff.Bamberg*, No.18.

Thorstensen, J.R., Smak, J., Hessman, F.V. 1985, *PASP*, **97**, 437.

Tremko, J., Andronov, I.L., Chinarova, L.L., Kumsiashvili, M.I., Luthardt, R., Pajdosz, G., Patkósz, L., Rößinger, S., Zoła, S. 1996, *A&A*, **312**, 121.

Udalski, A. 1988, *Acta Astron.*, **38**, 315.
Vogt., N., Chené, A.-N., Moffat, A.F.J., Matthews, J.M., Kuschnig, R., Guenther, D.B., Rowe, J.F., Ruciński, S., Sasselov, D., Weiss, W.W. 2013, arXiv: 1307.3083.
Volpi, A., Natali, G., D'Antona, F. 1988, *A&A*, **193**, 87.
Wenzel, W., Hudec, R., Schult, R., Tremko, J. 1992, *Contr.Astron.Obs.Skalnate Pleso*, **22**, 69.
Williams, J.O. 1966, *PASP*, **78**, 279.
Wood, M.A., Thomas, D.M., Simpson, J.C. 2009, *MNRAS*, **398**, 2110.
Wu, X., Li, Z., Ding, Y., Zhang, Z., Li, Z. 2002, *ApJ*, **569**, 418.