A&A 418, 249–254 (2004)
DOI: 10.1051/0004-6361:20034543

Astronomy & Astrophysics

On the δ Scuti star in the eclipsing binary WX Eridani⋆,⋆⋆

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Received 21 October 2003 / Accepted 11 January 2004

Abstract. WX Eri is an eclipsing binary system for which one component was reported to show δ Scuti type pulsations with periods close to integer fractions of the orbital period. This makes it an interesting candidate for investigating the interaction between binarity and pulsation and a potential new member of the recently defined group of mass-accreting pulsating components (gainers) in semi-detached Algol binaries called "oscillating EA" stars. We present new photometric time-series observations of this star. The Wilson-Devinney code was applied to find the best fitting model for the eclipsing binary's light curve. The aim of the observations was to investigate the short-period δ Scuti type pulsations of WX Eri. However, no evidence for the presence of such oscillations was found in our data.

Key words. stars: binaries: eclipsing – stars: individual: WX Eri – stars: oscillations – δ Sct

1. Introduction

There is a bonus attached to the study of pulsating stars in binary systems because one can use the dynamical information from the binarity to better understand the pulsation characteristics of the variable component. In a review of known pulsating δ Scuti stars belonging to double or multiple stars, Lampens & Boffin (2001) discussed several potentially interesting objects. One of these is WX Eridani (HD 21102), an eclipsing binary detected by Henrietta Leavitt on Harvard plates (Pickering 1908) with an orbital period of 0.8233 days as first reported by Jensch (1934). Photoelectric *B* and *V* light curves were collected and published by Sarma & Abhyankar (1979, SA79) and later by Srivastava & Kandpal (1986). Based on the normal data points of SA79, Giuricin & Mardirossian (1981, GM81) and Russo & Milano (1983, RM83) computed binary models. They came to different conclusions: while GM81 derived a close, near-contact but still detached configuration, RM83 concluded that the binary is a semi-detached system of Algol type with a F0V primary and a G5III-IV Roche lobe filling evolved secondary.

No X-ray emission from WX Eri was found by the ROSAT All-Sky Survey (Shaw et al. 1996). The physical parameters of WX Eri are not yet well-understood as illustrated by the range in spectral type derived for the components, e.g., from A5 V to F3 V for the primary. No spectroscopic study of the system has been done so far, although one is in preparation (Boffin et al., private communication).

WX Eri is also listed as a δ Scuti variable star (Rodríguez et al. 2000) and thus a potential new member of the recently defined group of mass-accreting pulsating components (gainers) in Algol binaries called "oscillating EA" stars (Mkrtichian et al. 2003). Indeed, SA79 found short-period δ Scuti type oscillations with periodicities close to integer fractions of the orbital period ($5f_{\rm orb}$, $6f_{\rm orb}$) in the residuals of the rectified light curve. This suggests tidally excited pulsations because pulsation periods equal to exact integer fractions of the orbital period can be interpreted as the result of a resonance mechanism between the tidal forces in the system and the pulsation. The amplitudes of these variations were of the order of 4 mmag only. Srivastava & Kandpal (1986) were unable to confirm this upon close examination of two nights of their own data at quadrature (the primary is the suspected pulsating component). However, this may be due to the quality of their data as they call for further observations to shed light on this issue.

Both as a binary and as a pulsating star, WX Eri still appears to elude clear answers. This is the reason why a careful study based on new observations – photometric and spectroscopic – was deemed necessary. We will here report on the analysis of new photometric time series data. We describe our observational material in Sect. 2. The application of the Wilson-Devinney method is presented in Sect. 3. An analysis

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⋆ Based on observations obtained at the South African Astronomical Observatory, ESO, Las Campanas, Beersel Hills, Hoher List and Esteve Duran Observatories.

⋆⋆ Table 2 is available in electronic form via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/418/249

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Table 1. Observing log of the WX Eri observations. The fourth column gives the photometric shift (in magnitudes, V) needed to bring the data to the same scale (see text).

Telescope	Instrument	Filter	Phot.shift	Observer(s)	Hrs of meas.
SAAO 1.0-m	SAAO CCD	B, V	0.000	TA	15.5
Beersel Hills 0.4-m	SBIG-ST7E CCD	V	−0.043	PVC, PL	7.0
Las Campanas 1.3-m	8kMOSAIC	V	−0.029	HWD	4.6
Hoher List 1.0-m	HOLICAM	V	0.029	PL, PVC	2.4
ESO 1.54-m	DFOSC	V	0.050	CS	1.9
Esteve Duran 0.6-m	CCD	V	0.025	EG-M	1.0
Total					32.4

of the residuals and our conclusions are given in Sects. 4 and 5, respectively.

2. Observations and reduction

The photometric CCD observations were obtained at 6 different sites during 2001 and early 2002. Data were obtained at SAAO (South Africa), where a number of short (1–2 hrs) time series were obtained in the V and B filters. Additional V-light curves were obtained at Beersel Hills Observatory (Belgium), at Las Campanas Observatory and at ESO (both Chile), at Sternwarte Hoher List (Germany) and at Esteve Duran Observatory (Spain). The total data set comprises 789 (V) and 319 (B) usable data points spanning a time interval from JD 2452095 to JD 2 452 348, adding up to 32.4 hrs of data distributed over 21 nights. The observing log is given in Table 1, and all individual data-points are listed in Table 2, which is available in electronic form at the CDS.

One part of the data (SAAO – ESO – Las Campanas) was reduced using the MOMF-package (Kjeldsen & Frandsen 1992), the other part with the packages MIRA-AP[1] and LAIA[2], respectively. Both these packages are based upon pure aperture photometry which is adequate for these reductions as the field is non-crowded.

Differential B- and V-magnitudes were computed with respect to the $0\overset{\mathrm{m}}{.}5$ fainter K0 type star BD −1°485. Due to the paucity of relatively bright stars in this field, we checked the constancy of the comparison star with respect to the $3\overset{\mathrm{m}}{.}5$ fainter GSC 04709:01168. The standard deviation of the differences in the sense (check – comparison star) was 10 mmag at best (SAAO), which limits our capacity to detect a possible variability of the comparison star. Since the check star is 16× less luminous than the comparison star, the observational precision of the photometric differential data can be estimated to be 4× higher, i.e. of order 3 mmag. The standard deviation within individual nights actually ranges between 3 and 9 mmag, thus illustrating the varying conditions under which the data were taken. Adopting a conservative approach we estimate that we are able to detect possible variations in the differences (WX Eri – comp star) with semi-amplitudes of at least 4 mmag.

Because different instruments at different sites have been used, the combined data suffered from zero-point shifts. When possible, we corrected this using the mean of the (much) fainter check star but in some cases, where the noise-level in the check star was too high (up to $0\overset{\mathrm{m}}{.}1$ rms), we had to use the depth of the secondary minima to shift the data to the same scale (still on a telescope-to-telescope basis). All data were brought to the scale of the SAAO data using the zero-point shifts listed in Table 1. However, nightly shifts are still present in the data as illustrated in Fig. 1. Within the homogeneous SAAO data, which is shown in the middle panel, the two nights around phase 0.2 differ in zero-point. Looking at the (check – comparison star) data in the upper panel, we can see that the cause of this small shift lies with the redder comparison star ($B-V = 1.2$ vs. $B-V = 0.35$ and $B-V = 0.62$ for WX Eri and the check star, respectively).

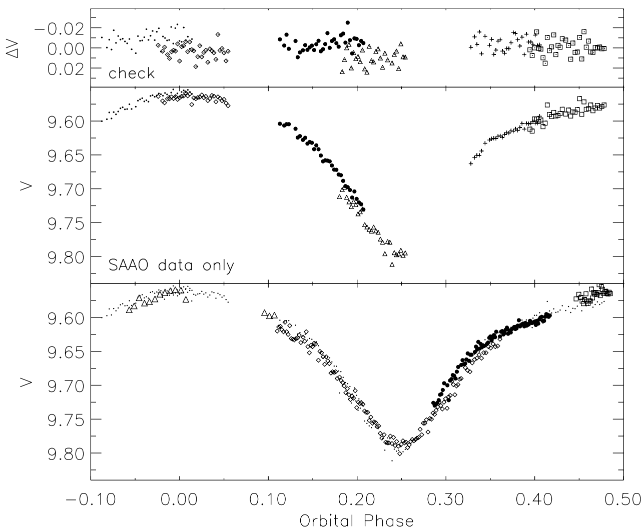

Fig. 1. Photometric zero-point shifts present in the data. The upper panel shows the difference between the check and comparison star (mean shifted to zero) for the SAAO data phased with the orbital period of WX Eri. The middle panel shows the SAAO data, near secondary minimum. In both the upper and middle panels are data from different nights marked with different symbols. The vertical shift needed to overlap the triangles and filled circles at phase 0.2 is about 10 mmag. The lower panel shows all data, except one night omitted for clarity, at secondary minimum. Here, data from different telescopes are plotted with different symbols.

[1] The MIRA-AP software is produced by Axiom Research Inc., http://www.axres.com/

[2] Laboratory for Astronomical Image Analysis, http://www.astrogea.org/soft/laia/laia.htm

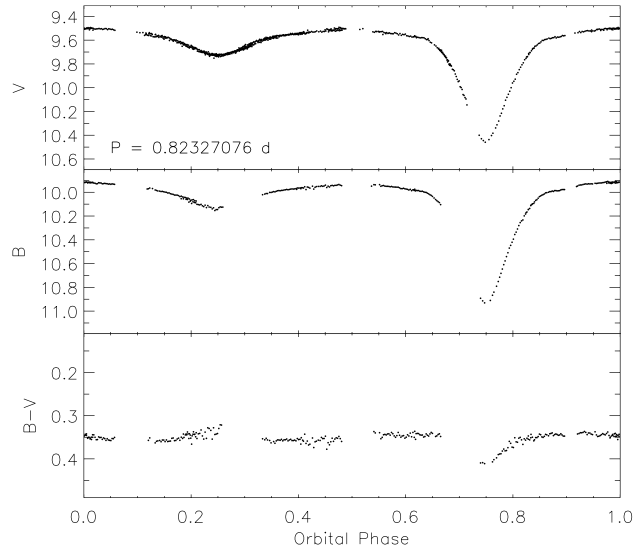

Fig. 2. Phased ΔV, ΔB and $\Delta(B-V)$ light curves shifted in magnitude to the standard values given by Srivastava & Kandpal (1986).

A similar effect can be seen for the check star around phase 0, but the effect on WX Eri is smaller. However, in the lower panel, which includes data from the other telescopes, the effect is masked by the additional data. We investigated all useful check star data from the different sites for similar cases, but did not find any. We therefore did not correct the data around phase 0.2 but will keep this zero-point shift in mind for the analysis of the residuals in Sect. 4. Other differences are seen as well in the lower panel of Fig. 1, e.g. at phase 0.3–0.4, but we have no means of correcting such differences which appear not only to be a simple zero-point shift but also a slight difference in shape.

The complete ΔV, ΔB and $\Delta(B-V)$ light and colour curves folded with the period of 0.82327076 days (Srivastava & Kandpal 1986) are shown in Fig. 2 and three times of minimum light as well as their (O−C) values with respect to the ephemeris given in Srivastava & Kandpal are listed in Table 3. These authors found the orbital period to be very stable and indeed, our (O−C) values are within the range of those listed by Srivastava & Kandpal (see their Fig. 2) even though the time-span between the two data sets corresponds to about 7500 orbits.

3. The light curve of the binary system

We used the Wilson-Devinney (WD) (Wilson 1998) code to model the binary light curve to derive physical information on the components and to investigate the (very) short-term variability in WX Eri. The WD code consists of two parts; the LC program which can generate synthetic light- and radial velocity curves from a set of input binary parameters, and a differential corrections program DC which uses least squares for parameter adjustment to improve on an existing solution. We applied the LC programme with the initial set of parameters as found by RM83 in a first attempt. They adopted a primary spectral type of F0V although this determination is very imprecise (A5 to F3 were mentioned). In that case the Roche lobe filling secondary could be of spectral type G5III-IV.

Table 3. New times of minimum light and (O−C) values (in days) for WX Eri. The cycle count scheme (E) follows Srivastava & Kandpal (1986).

HJD	E	(O−C)	Type of minimum
2 452 257.398	30 033	−0.015	Secondary
2 452 267.269	30 045	−0.007	Secondary
2 452 269.331	30 048	0.011	Primary

Because a strong correlation between the inclination and the other parameters is expected (RM83) we employed the method of parameter subsets (Wilson & Biermann 1976). Thus we adopted the following set of initial parameters: $q = 0.33$ for the mass ratio M_c/M_h, $T_h = 7500$ and $T_c = 5095$ K as the temperatures of the hot and cool components respectively, and $i = 86°$ for the inclination. Other assumptions taken from the literature were: a radiative envelope for the primary star (radiative bolometric albedo ($A = 1$), gravity darkening ($g = 1$)) and a convective envelope for the secondary (convective bolometric albedo ($A = 0.5$), gravity darkening ($g = 0.32$)) and a linear limb darkening law.

This solution gave a reasonably good fit to the new data but it could be improved by applying the DC programme running in Mode 5 (semi-detached configuration). A better fit was found with $q = 0.36$. The overall standard deviation of the V-residuals of the original solution was 9.4 mmag, while that of the new solution was 8.4 mmag (i.e., a reduction by 20% of the variance). These numbers include the small nightly zero-point shifts still present in the data, as discussed in Sect. 2. Both theoretical solutions along with the observed data and the residuals are displayed in Fig. 3.

We also performed a grid of solutions for different values of the mass ratio ranging between 0.25 and 1.25, to look for other possible solutions, and it turned out that several combinations of mass ratio and inclination would fit the data equally well. For example, we found a quite different configuration that would fit the data even better than the $q = 0.36$ solution discussed above, leaving a standard deviation of the residuals of 8.0 mmag. This solution adopts $q = 0.75$, component temperatures of 7700 K (spectral type A7-8V; Lang 1992) and 5070 K (spectral type of G6III-IV; Lang 1992) and $i = 77°$. Both the $q = 0.36$ and the $q = 0.75$ solutions are among the best solutions investigated, however a range of models with other q values are all possible solutions as well.

We note here that both GM81 and RM83 restricted their searches to q-values between 0.1 and 0.7 as they expected a photometric mass ratio around 0.5–0.6. A difference between the two discussed solutions is the probable state of evolution of the secondary component: while the system could comprise two main-sequence components in the former solution ($q = 0.36$), e.g., with spectral types of A7-8V and K0-1V (in agreement with Srivastava & Kandpal's 1986 discussion about the components' colours), the latter solution ($q = 0.75$) implies that the secondary is a slightly evolved cooler subgiant. Considering that the ratio of the eclipse depths is proportional

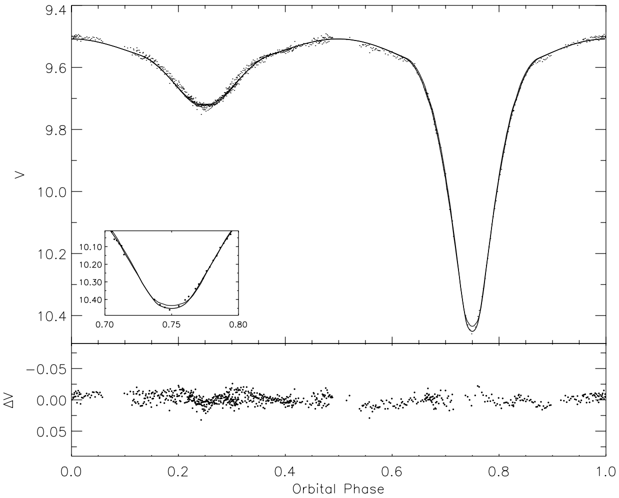

Fig. 3. The upper panel shows the phased V light curve and the new solution ($q = 0.36$) obtained with the WD code. The lower panel shows the residuals at an expanded magnitude scale. The shallower solution during primary eclipse is the one adopted from the literature (RM83), the insert shows the (small) differences between the solutions in more detail.

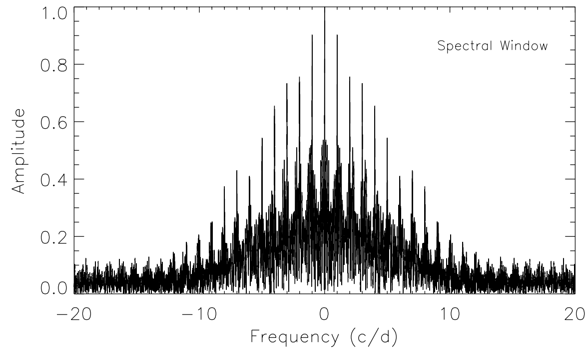

Fig. 4. The spectral window function for the residual time-series data in V.

to the ratio of the surface brightnesses, $\frac{J_c}{J_h} = \frac{0.25}{0.95}$ and that $\frac{L_c}{L_h} = (\frac{r_c}{r_h})^2 \times \frac{J_c}{J_h} \times \frac{1-x_c/3}{1-x_h/3}$ (Kallrath & Milone 1999, p. 67) we find that $\Delta M_{bol} = +2.2$, i.e. a plausible difference between a hot and a cool main-sequence component or a hot main-sequence component and a cooler subgiant.

With any of these two models, the residuals in V after the subtraction of the binary light curve show peak-to-peak differences of 20 mmag at most. We note that none of these solutions fits the less abundant ΔB data perfectly as the standard deviation of the B-residuals is about 10 mmag while the corresponding SAAO ΔV residuals have a standard deviation of 8 mmag. However, we have insufficient data to resolve this problem as we miss ΔB measurements during the critical phase of the minima. The only B data we have at secondary minimum is of poor quality due to very bad seeing.

The two discussed solutions illustrate that, even with good-quality photometric light curves, it is not possible to determine unambiguously a physical model for such a binary system as solutions with different photometric mass ratios cannot be discriminated (as was also the case previously). A spectroscopic determination of the mass ratio is needed before the model can be fully constrained (see Kallrath & Milone 1999, p. 13).

Both existing studies (SA79 and Srivastava & Kandpal 1986) reported stand-stills in the binary light-curve. This effect is most noticeable in Fig. 1 of SA79. Our data confirm this effect: the data on either side of the primary eclipse fall systematically below the theoretical solution (cf. Fig. 3 at phases from 0.55 to 0.65 and from 0.85 to 0.90). We have at present no explanation for this effect but it could be connected to spots on the surface of the cooler companion. However, the true binary model should be determined from spectroscopy before an investigation of such finer details would be useful.

4. Analysis of the residuals out-of-primary-eclipse

A visual inspection of the residual data for each individual night revealed no signs of short-term variability. The only exceptions were during two phases of secondary minimum where the residuals of the $q = 0.36$ binary solution displayed short-term fluctuations on a time-scale of about 2 hrs. By adding various offsets to the data it was checked that these fluctuations were not caused by nightly zero-point shifts such as those discussed in Sect. 2. However, we believe these fluctuations are spurious because they were in both cases symmetric around the center of the secondary minimum and they were not visible when applying the $q = 0.75$ solution – the detection of any possible short-term oscillations must be independent of the solution chosen for the binary light curve in order to be deemed real.

Is there then any evidence for short-term variability in the residual light curves when using Fourier techniques? To address this question, only the data obtained outside-of-primary-eclipse were used (the primary – and thus the dominant light source – is the suspected variable star). In this way, 721 V data points remained and the corresponding residuals were analysed using the program `Period98` (Sperl 1998). The (complicated) spectral window function of the data is displayed in Fig. 4.

4.1. The candidate frequencies at $5f_{orb}$ and $6f_{orb}$

First, we searched for evidence of variability at the frequencies 6.078 and 7.288 c d^{-1}, corresponding to $5f_{\rm orb}$ and $6f_{\rm orb}$ (SA79). The amplitude spectra after subtraction of the $q = 0.36$ and $q = 0.75$ binary solutions, respectively, are shown in Fig. 5. We note that the amplitude spectra were calculated up to 50 c d^{-1} but no high-frequency terms were found. We find no evidence for a signal with a periodicity of $5f_{\rm orb}$. Although there is a minor peak near $6f_{\rm orb}$ in the $q = 0.36$ residuals, it does not show up in the $q = 0.75$ residuals and there is therefore no evidence for such a frequency either in our data.

In a simulation we added the two known periodicities with semi-amplitudes of 4.5 mmag to the original observational data prior to the subtraction of the synthetic binary light curves (this was tried for both binary solutions). Although not dominant due to the overall noise level in the data (see Fig. 6), the resulting peaks were clearly present in the amplitude spectra of the

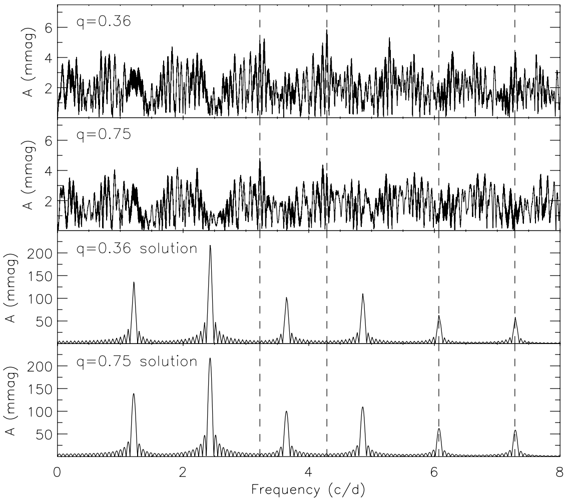

Fig. 5. The two upper panels: amplitude spectra of the residuals after removal of each of the two possible binary solutions for WX Eri. The frequency values discussed in the text are marked (3.22 and 4.28 $\mathrm{c\,d^{-1}}$ as well as $5f_{\mathrm{orb}}$ and $6f_{\mathrm{orb}}$). Note in the upper panel that the 3.22 $\mathrm{c\,d^{-1}}$ peak and the 3.28 $\mathrm{c\,d^{-1}}$ alias to the 4.28 $\mathrm{c\,d^{-1}}$ peak are well separated. The two bottom panels shows the amplitude spectra of the synthetic $q = 0.36$ and $q = 0.75$ binary light curve solution.

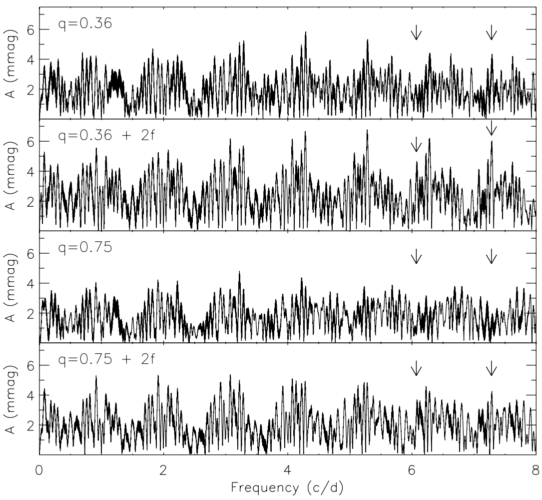

Fig. 6. The effect on the amplitude spectra of adding the $5f_{\mathrm{orb}}$ and $6f_{\mathrm{orb}}$ periodicities to the data prior to subtraction of the $q = 0.36$ solution (two upper panels) and the $q = 0.75$ solution (two lower panels). The arrows mark the positions of the added frequencies.

residuals. This indicates that if such oscillating signals are excited in WX Eri, we should see stronger signs of their presence in our data. We conclude that the frequencies found by SA79 are not detected in our data.

4.2. Other possible frequencies

The amplitude spectrum of the $q = 0.36$ residuals (Fig. 5) displays a signal at 4.28 $\mathrm{c\,d^{-1}}$ (including 1 $\mathrm{c\,d^{-1}}$ aliases), which is close to the 3 $\mathrm{c\,d^{-1}}$ alias of $6f_{\mathrm{orb}}$ and equals $7/2f_{\mathrm{orb}}$. Prewhitening for this frequency leaves a flat residual amplitude spectrum (cf. the upper panel in Fig. 7) and the peak persists if we select different subsets of the data. The same

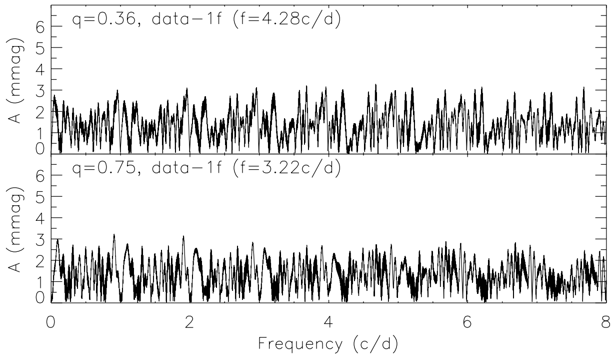

Fig. 7. Amplitude spectrum of the residuals after removal of each of the two possible binary solutions for WX Eri *and* after subtracting 1 frequency term (see text for discussion).

frequency is also present in the amplitude spectrum of the *B*-data (but embedded in strong $1/f$-noise, not shown). Prewhitening for it reduces the standard deviation of these data notably, i.e. from 9.2 to 7.3 mmag (a reduction by 37% of the variance). The amplitude spectrum of the $q = 0.75$-residuals shows only a weak peak at the 4.28 $\mathrm{c\,d^{-1}}$ position and instead a stronger one at $f = 3.22\ \mathrm{c\,d^{-1}}$. The latter peak is also present in the $q = 0.36$ residuals with similar amplitude. It is not a 1 $\mathrm{c\,d^{-1}}$ alias to the 4.28 $\mathrm{c\,d^{-1}}$ signal as can be seen in the upper panel of Fig. 5 – the peaks at 3.22 and (4.28 − 1) $\mathrm{c\,d^{-1}}$ are clealy separated.

In the $q = 0.36$-residuals, the 4.28 $\mathrm{c\,d^{-1}}$ signal has a *S/N* ratio of 4.4 and is therefore statistically significant as peaks reaching a *S/N* of 4 usually are deemed to be so (Breger et al. 1993; Kuschnig et al. 1997). However, because this 4.28 $\mathrm{c\,d^{-1}}$ signal is not present in the $q = 0.75$-residuals, it is *not* independent of the chosen binary model and must originate from the binary motion. Indeed, a Fourier analysis of the two synthetic light-curve models shows that both models have power at 7.28 $\mathrm{c\,d^{-1}}$ (see the two lower panels in Fig. 5). The differences between the two upper panels in Fig. 5 therefore most likely illustrate that the $q = 0.75$ solution gives a slightly better fit to the binary motion than the $q = 0.36$ solution, as is also supported by the lower residual noise (cf. Sect. 3). In this way the 4.28 $\mathrm{c\,d^{-1}}$ peak is an alias of the 7.28 $\mathrm{c\,d^{-1}}$ ($6f_{\mathrm{orb}}$) orbital signal. That the 4.28 $\mathrm{c\,d^{-1}}$ alias dominates the 7.28 $\mathrm{c\,d^{-1}}$ signal is then due to our time sampling (Fig. 4), perhaps in combination with nightly variations not intrinsic to WX Eri as well as instrumental noise which is often present at low frequencies when combining data from several telescopes (Breger 1994). This is also corroborated by the fact that a combination of the frequencies 7.28 and 3.22 $\mathrm{c\,d^{-1}}$ fits the $q = 0.36$-residuals just as well as 4.28 combined with 3.22 $\mathrm{c\,d^{-1}}$. It is possible that similar effects originating from the binary solution explain the $5f_{\mathrm{orb}}$ and $6f_{\mathrm{orb}}$ frequencies in SA79 as they included terms up to $4f_{\mathrm{orb}}$ only in the rectification of the binary's light curve.

The frequency at 3.22 $\mathrm{c\,d^{-1}}$ appears more interesting as its presence is unaffected by the choice of binary model, although prewhitening the $q = 0.36$ residuals with the frequency at 4.28 $\mathrm{c\,d^{-1}}$ diminishes its amplitude. Prewhitening the $q = 0.75$ residuals for the 3.22 $\mathrm{c\,d^{-1}}$ frequency results in a flat residual amplitude spectrum (cf. the lower panel in Fig. 7).

However, in this case the frequency is only weakly significant as it has a (fitted) semi-amplitude of 5.3 mmag and a *S/N* ratio of 3.8 only. We note that there are no peaks at 3.22 c d^{-1} in the amplitude spectrum of the (check – comparison) star data.

Finally, as shown in Sect. 2 we could for one night associate the dip at phase 0.20 in the WX Eri light curve with a brightening of the comparison star. For completeness, we re-analysed the residuals taking this zero-point shift into account but the results discussed above did not change. The conclusion remains that WX Eri, based on our data, does not host a pulsating star.

5. Conclusions

We investigated new photometric time series data of the eclipsing binary WX Eri to derive some physical information on the components and to investigate the δ Scuti type pulsations. From the data, three new times of minimum light were determined. The new (O−C) values were within the range of the existing (O−C) values given by Srivastava & Kandpal (1986), indicating a stable binary period.

No unique solution for the binary model could be found as the value of the mass ratio is not constrained by the photometry alone. Instead, a range of possible solutions was obtained, two of which were discussed in detail: one consisting of two main-sequence components with $q = 0.36$ and one consisting of a hot main-sequence and a cooler evolved component with $q = 0.75$. It is clear that a combined photometric-spectroscopic study is needed to solve the binary system completely.

Still, we were able to analyse the residual light curves after subtraction of the two binary models from the original data to investigate the (very) short-term variability previously found in this star. The conclusions of this analysis are:

- The findings of Sarma & Abhyankar (1979), namely that short-period δ Scuti type oscillations with periodicities very close to integer fractions of the orbital period ($5f_{\rm orb}$ and $6f_{\rm orb}$, pointing to possible tidally excited pulsations) are superimposed on the light variability of this eclipsing system, are not confirmed by our data.
- We find only weak indication of a signal with a frequency of 3.22 c d^{-1} (i.e., a period of 7.5 h – outside of the range of periodicities for normal δ Scuti stars) with a semi-amplitude of about 5 mmag and a *S/N* of 3.8.

We conclude that our data do not support the model of WX Eri containing a variable component of the δ Scuti type.

Acknowledgements. TA acknowledges financial support for this work from the Belgian Federal Office for Scientific, Technical and Cultural Affairs, under contract number MO/33/007 and from the Danish Natural Science Research Council (since May 2002). This research was also supported by the Belgian Fund for Scientific Research Flanders (FWO), by FWO-project G.0178.02, by the Flemish Ministry for Foreign Policy, European Affairs, Science and Technology, under contract BIL 99/2, by the National Research Foundation of South Africa and by the Belgian Federal Office for Scientific, Technical and Cultural Affairs under project IUAP P5/36. PL and PVC are grateful to Prof. W. Seggewiss for the telescope time and the hospitality at the Observatorium Hoher List, Universitätssternwarte, Bonn, Germany. The authors are also grateful to Prof. R. Wilson (University of Florida) for providing the Wilson-Devinney code and thank P. Wils and G. Kopacki for giving advice on the use of the code.

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