An improved ephemeris and physical elements of ER Vul*,**

P. Harmanec1,2, H. Božič3, K. Thanjavur4, R. M. Robb4, D. Ruždjak3, and D. Sudar3

1 Astronomical Institute of the Charles University, V Holešovičká 2, 180 00 Praha 8, Czech Republic
e-mail: hec@sunstel.asu.cas.cz
2 Astronomical Institute, Academy of Sciences of the Czech Republic, 251 65 Ondřejov, Czech Republic
e-mail: hec@sunstel.asu.cas.cz
3 Hvar Observatory, Faculty of Geodesy, Zagreb University, Kačićeva 26, 10000 Zagreb, Croatia
e-mail: hbozic, rdomagoj, dsudar@geof.hr
4 Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada, V8W 3P6
e-mail: karun@uvastro.phys.uvic.ca; robb@uvic.ca

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Abstract. New photoelectric UBV and BVRI observations, secured during August–November of 2002 at two observatories distant in local time are analyzed together with two earlier photometric data sets and all available radial velocities to derive the most accurate ephemeris of the binary and to set limits on its basic physical elements. These observations were obtained as a support for a high-dispersion spectroscopic study, results of which will be published separately. It was found that radial velocities and photometric observations spanning 53 years can be reconciled with the linear ephemeris \( T_{\text{prim.min}} = \text{HJD 2440182.25628(46)} + 0.0698095113(29) \times E \), where the rms errors of the last digits are given in brackets. Masses of the stars are 1.02 \( M_\odot \) and 0.97 \( M_\odot \) and the binary separation is 4.170 \( R_\odot \). There is still a large uncertainty in the stellar radii. We also report the discovery of rapid light variations on a time scale of hours seen in the \( U \) band light curve and offer a few thoughts on the future investigation of this binary.

Key words. stars: binaries: close – stars: binaries: eclipsing – stars: binaries: spectroscopic – stars: fundamental parameters – stars: individual: ER Vul

1. Introduction

ER Vul (HD 200391) is a well-known and astrophysically very important binary consisting of two early-G stars with masses similar to the mass of our Sun but rotating much more rapidly than the Sun due to a tendency to spin-orbit synchronization in the 0.698-day binary orbit. Both components of ER Vul are chromospherically very active and the light curve of the system exhibits remarkable secular variations in addition to binary eclipses.

In 2002, high-dispersion high-S/N spectroscopic observations of the binary were obtained in an effort to study line-profile variations related to active regions on the star’s surface. It was deemed important to know the most accurate orbital phases of these observations. For that reason, new photometric observations were secured at two observatories and their analysis, along with several already published data sets, and the determination of a new, very accurate linear ephemeris of the system, is the subject of this study. The results of spectroscopic observations will be published elsewhere.

Since the light curve of ER Vul exhibits secular variations, most notably uneven maxima between two consecutive eclipses of the binary, it is important to check the ephemeris derived from photometry also via analysis of radial velocities (RVs hereafter). To this end, we collected and analyzed all published RVs of ER Vul and also two important photometric data sets obtained earlier.

2. Observations and reductions

2.1. Photometry

New photometric observations were secured in 2002 at two observatories: Hvar in Croatia and Victoria in Canada. Additionally, we extracted Hipparcos \( H_p \) photometry (Perryman et al. 1997) and early BV observations published by Northcott & Bakos (1967). Basic information about these data sets is summarized in Table 1 and details of observations and data reduction are described below.

2.1.1. Hvar UBV photometry

Altogether, 167 new UBV observations of ER Vul = HD 200391 were secured on 11 nights at Hvar Observatory,
Croatia, using a 0.65 m reflector and a computer-controlled
photometer with an uncooled EMI 6256 tube. All these
observations were obtained differentially, relative to HD 200270
(HIP 103770). A check star HD 200468 (HIP 103874) was
observed as frequently as the variable. These two comparisons
have already been used in the majority of earlier photometric
studies of ER Vul. Our observations of ER Vul were secured
during the course of another observing program, aimed at
studies of ER Vul. Our observations of ER Vul were secured
for a detailed documentation of the reduction program, respectively.
Since a number of stars with accurate $UBV$ magnitudes from
the list of Harmanec et al. (1994) were observed on the same
nights as ER Vul and its comparisons, we were able to derive
very accurate all-sky $UBV$ values of the comparison and check
star which were used in subsequent analyses. These all-sky val-
ues are compared with several other determinations in Table 2.
Mean differential $UBV$ values of the check star HD 200468
are also listed in Table 2 to illustrate the accuracy of our
homogenization.

### 2.1.2. Victoria $BVR_{c}I_{c}$ photometry

The University of Victoria observations were made with
an automated 0.5m telescope, Star I CCD and reduced in
a fashion similar to that described in Robb & Greimel
(1999). Observations were made using filters closely match-
ing the Johnson $BV$ and Cousins $R_{c}I_{c}$ systems. The Julian
Dates of observations are 2452498–505, ..511–513, ..527,
and ..530–532. Table 3 lists the stars’ identification numbers,
magnitudes and positions from the Hubble Space Telescope
ER Vul = GSC 611, none of these stars showed any significant
variations in plots of the individual nights’ data or from night to
time. Because ER Vul is so much brighter than any of the other
stars in our field of view, our differential magnitudes are calcu-
ated in the sense of ER Vul minus the mean of the three next

### Table 1. Journal of photoelectric observations.

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Epoch (JD−2 400 000)</th>
<th>No. of obs.</th>
<th>No. of nights</th>
<th>Passband(s)</th>
<th>Comparison</th>
<th>Check</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>David Dunlap</td>
<td>35356.6–36119.7</td>
<td>275</td>
<td>10</td>
<td>$BV$</td>
<td>HD 200270</td>
<td>HD 200425</td>
<td>Northcott &amp; Bakos (1967)</td>
</tr>
<tr>
<td>Hipparcos</td>
<td>47857.8–48974.1</td>
<td>129</td>
<td>26</td>
<td>$BV$</td>
<td>all-sky</td>
<td>–</td>
<td>Perryman et al. (1997)</td>
</tr>
<tr>
<td>Victoria</td>
<td>52498.7–52533.0</td>
<td>*</td>
<td>15</td>
<td>$BVR_{c}I_{c}$</td>
<td>see the text</td>
<td>see the text</td>
<td>this paper</td>
</tr>
<tr>
<td>Hvar</td>
<td>52500.4–52550.4</td>
<td>167</td>
<td>11</td>
<td>$UBV$</td>
<td>HD 200270</td>
<td>HD 200468</td>
<td>this paper</td>
</tr>
</tbody>
</table>

* Different numbers of observations were obtained in different passbands as follows: 856 in $B$, 838 in $V$, 764 in $R$ and 815 in $I$. 

### Table 2. $UBV$ data for the comparison and check star used: the values denoted “diff.” in column “Remarks” are derived differentially relative to calibrated Hvar $UBV$ values for HD 200270.

<table>
<thead>
<tr>
<th>HD 200270 (comparison)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt;$772 ± 0.011</td>
<td>8°232 ± 0.011</td>
<td>8°173 ± 0.013</td>
<td>0°460</td>
<td>−0°059</td>
<td>Hvar</td>
<td>all-sky</td>
<td></td>
</tr>
<tr>
<td>$&gt;$769 ± 0.011</td>
<td>8°229 ± 0.011</td>
<td>–</td>
<td>0°460</td>
<td>–</td>
<td>Hipparcos</td>
<td>all-sky</td>
<td></td>
</tr>
<tr>
<td>$&gt;$771</td>
<td>8°16</td>
<td>–</td>
<td>0°45</td>
<td>–</td>
<td>David Dunlap</td>
<td>all-sky</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HD 200468 (check)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt;$869 ± 0.009</td>
<td>8°043 ± 0.021</td>
<td>8°166 ± 0.023</td>
<td>0°174</td>
<td>0°123</td>
<td>Hvar</td>
<td>all-sky</td>
<td></td>
</tr>
<tr>
<td>$&gt;$869 ± 0.008</td>
<td>8°042 ± 0.017</td>
<td>8°166 ± 0.019</td>
<td>0°174</td>
<td>0°123</td>
<td>Hvar</td>
<td>diff.</td>
<td></td>
</tr>
<tr>
<td>$&gt;$871 ± 0.010</td>
<td>8°045 ± 0.010</td>
<td>–</td>
<td>0°174</td>
<td>–</td>
<td>Hipparcos</td>
<td>all-sky</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HD 200425 (check)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt;$75</td>
<td>8°30</td>
<td>–</td>
<td>0°55</td>
<td>–</td>
<td>David Dunlap</td>
<td>all-sky</td>
<td></td>
</tr>
<tr>
<td>$&gt;$81</td>
<td>8°37</td>
<td>–</td>
<td>0°56</td>
<td>–</td>
<td>David Dunlap</td>
<td>diff.</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Stars observed with the CCD camera in the field of ER Vul.

<table>
<thead>
<tr>
<th>Star</th>
<th>RA</th>
<th>Dec</th>
<th>GSC GSC No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>611</td>
<td>21°02′26″</td>
<td>+27°48′25″</td>
<td>7.1</td>
</tr>
<tr>
<td>422</td>
<td>21°02′32″</td>
<td>+27°51′07″</td>
<td>11.2</td>
</tr>
<tr>
<td>356</td>
<td>21°02′02″</td>
<td>+27°49′44″</td>
<td>11.3</td>
</tr>
<tr>
<td>247</td>
<td>21°02′24″</td>
<td>+27°49′25″</td>
<td>12.0</td>
</tr>
</tbody>
</table>

brightest stars (GSC 2180-422, −356, −247) and are, therefore, in the form of magnitude differences with an unknown zero point.

To check for brightness variations of the comparison stars during a night, we calculated the standard deviation of the differential magnitudes of GSC 2180-422 minus the average of GSC 2180-356 and GSC 2180-247 for each night. The smallest standard deviations for any night are 0″023 for B, 0″008 for V, 0″007 for Rc and 0″005 for Ic. The standard deviation of 0″005 sets an approximate upper limit for variations on an hourly timescale for any comparison star. The standard deviation of the nightly means is a measure of the night-to-night variations. The mean of the 15 nightly means are 0″368 ± 0″009 for B, −0″069 ± 0″006 for V, −0″346 ± 0″006 for Rc, −0″583 ± 0″004 for Ic. The smallest of the standard deviations is 0″004 in the Ic band and this excellent photometry shows that night-to-night variations in any of these stars must be less than a few millimagnitudes.

2.1.3. Hipparcos H_p photometry

We extracted Hipparcos H_p photometry of ER Vul and its comparisons from the data archive published by Perryman et al. (1997). We used only observations with error flags 0 or 1 and assigned them weights 1.0 or 0.5 depending on the rms errors quoted in the Hipparcos archive. Weight 1.0 was given to an observation with error flag 0 and a rms error not larger than 0″010 while weight 0.5 was assigned to observations with error flag 1 and/or rms error of more than 0″010. ER Vul is rather faint for the sensitivity of the Hipparcos detector. There is no observation with an rms error smaller than 0″006, and the majority of observations qualifies for weight 0.5. Hipparcos H_p observations are, therefore, less accurate than the usual photometric observations of ER Vul. Yet, they represent a very useful data set to be combined with other observations because that they are free of 1-day aliases.

We transformed Hipparcos observations of ER Vul and its comparisons into Johnson V and B standard magnitudes, using their all-sky (B − V) and (U − B) colours derived at Hvar and applying Harmanec’s (1998) transformation formula. In analyses, we use only V magnitudes since the reconstructed B magnitudes do not represent an independent data set but the same set, only increased for the assumed, constant value of (B − V).

2.1.4. David Dunlap BV photometry

These early, but obviously quite accurate differential BV photometric observations were obtained with the 0.48 m reflector of the David Dunlap Observatory, relative to HD 200270, and published in detail by Northcott & Bakos (1967). The observations were corrected for differential extinction but were clearly left in the instrumental system. To bring them at least approximately into a comparable system of standard UBV magnitudes, we simply added the all-sky B and V magnitudes of HD 200270, based on numerous Hvar observations and listed in the first row of Table 2, to the magnitude differences ER Vul–HD 200270 tabulated by Northcott & Bakos (1967). Northcott & Bakos used HD 200425 as their check star, a different one from that used at Hvar. They only tabulate its mean all-sky BV values, based on their observations. For completeness, we also give their original all-sky values, and values corrected differentially to the adopted Hvar all-sky values of HD 200270, in Table 2. It is not clear from the Northcott & Bakos (1967) paper how they arrived at their all-sky values for both comparisons.

For the convenience of future investigators, we publish all the homogenized individual photoelectric observations in Table 4. To illustrate the quality of individual data sets, we plot the individual V-band light curves in Fig. 1. All four light curves are on the V scale of well calibrated Hvar data.

2.1.5. Radial velocities

We were able to compile RVs from five published sources. These data span a similar interval of time as the photometric data which we analyze here. In all cases, we omitted RVs for which the primary and secondary lines could not be resolved. Basic information about the data sets is summarized in Table 5. To take into account different dispersions of the spectrograms and the difference in S/N ratio between photographic and electronic spectra, individual data sets were assigned weights according to the following formula

\[ w = \frac{10 \cdot Q}{D}, \]

where D is the linear dispersion in Å mm\(^{-1}\) and Q = 4 for electronic, and Q = 1 for photographic spectra. These weights were applied in all RV solutions (see below).

A few comments on individual data sets are appropriate.

Source 1: Northcott & Bakos (1967). These RVs are based on photographic spectrograms secured in the Cassgrain focus of the 1.88 m reflector of David Dunlap Observatory.

Source 2: McLean (1982). RVs were obtained via the cross-correlation technique from digitized photographic spectra, secured in the coude focus of the 1.52 m reflector of Haute Provence Observatory. Times of observations, tabulated in modified heliocentric Julian Days, were converted to heliocentric Julian Days (HJDs hereafter), used in all other sources.

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1 Table 4 is only available in electronic form at the CDS via anonymous ftp cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/415/289
Fig. 1. Individual V-band light curves for the four data sets used here plotted vs. phase of ephemeris (5).

<table>
<thead>
<tr>
<th>Source</th>
<th>Epoch (JD−2400000)</th>
<th>No. of obs.</th>
<th>Dispersion (Å mm⁻¹)</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32.0986−35.0067</td>
<td>37</td>
<td>33</td>
<td>0.303</td>
</tr>
<tr>
<td>2</td>
<td>44.4736−44.4765</td>
<td>15</td>
<td>20</td>
<td>0.500</td>
</tr>
<tr>
<td>3</td>
<td>46.3050−47.0688</td>
<td>29</td>
<td>20</td>
<td>2.000</td>
</tr>
<tr>
<td>4</td>
<td>49.6437−49.6577</td>
<td>10</td>
<td>87</td>
<td>5.000</td>
</tr>
<tr>
<td>5</td>
<td>51.7674−51.8125</td>
<td>12</td>
<td>6</td>
<td>6.667</td>
</tr>
<tr>
<td>6</td>
<td>49.1416−49.5605</td>
<td>7</td>
<td>6</td>
<td>6.667</td>
</tr>
<tr>
<td>7</td>
<td>49.1665−50.2996</td>
<td>130</td>
<td>2</td>
<td>20.0</td>
</tr>
<tr>
<td>8</td>
<td>52.1363−52.1376</td>
<td>27</td>
<td>8</td>
<td>–</td>
</tr>
</tbody>
</table>


Source 3: Hill et al. (1990). RVs were obtained via the cross-correlation technique from electronic spectra secured in the coudé focus of the 1.22 m reflector of the Dominion Astrophysical Observatory with a Reticon 1872RF detector.

Source 4: Gunn et al. (1996). These RVs were also obtained via the cross-correlation technique from electronic spectra secured with the John Hall 1.1 m Lowell telescope and Solar-Stellar echelle Spectrograph, equipped with a TEK 512×512 CCD detector with a spectral resolution of 12000. The reconstruction of times of mid-exposures of these spectra was difficult. The authors published only epochs and phases of individual observations in their Table 3, without saying explicitly which ephemeris was actually used. In the text, they say that the ephemeris is usually taken from Hill et al. (1990) and that it agrees extremely well with their new observations. However, from the number of cycles tabulated for their data (13553−13573) it is immediately clear that they have not used the Hill et al. (1990) ephemeris in Table 3 but the ephemeris derived by İbanoğlu et al. (1987), although that paper is missing from their list of references. The ephemeris given by İbanoğlu et al. (1987) is

$$T_{\text{prim.min.}} = \text{HJD 2440182.2621} + 0.69809409 \times E.$$  (2)

However, their ephemeris is quoted incorrectly in Table 5 of Hill’s et al. (1990) paper as

$$T_{\text{prim.min.}} = \text{HJD 2440182.2945} + 0.6980907 \times E.$$  (3)

In Table 1 of Gunn’s et al. (1996) paper, only rounded-off ephemerides from the Strassmeier et al. (1993) catalogue are given for their program stars. In particular, for ER Vul they give

$$T_{\text{prim.min.}} = \text{HJD 2440182.259} + 0.6981 \times E.$$  (4)

We tentatively reconstructed HJDs of Gunn’s et al. RVs for all three ephemerides quoted above and found that one obtains smallest rms errors when combining Gunn’s et al. RVs with other available RV data sets for the reconstruction of HJDs based on the original ephemeris of İbanoğlu et al. (1987). This was, then, what we adopted for analyses presented here.
Source 5: Cakırlı et al. (2003). These are also RVs derived via the cross-correlation technique from electronic spectra obtained with a thinned, back-illuminated 1024 × 1024 CCD (pixel size 24 µm) and echelle spectrograph attached to the 0.91 m reflector of the Catania Astrophysical Observatory. There is an obvious misprint in their Table 2 with individual RVs: HJD 2 451 776 and ...

Source 6 and 7: Duenmmler et al. (2003). These are the best RVs of ER Vul available so far. They come from two instruments. File 6 are Rozhen 2.0 m reflector coudé spectra obtained with a Soviet-made ISTA camera with a CCD detector having 400 pixels in dispersion, each 24 µm wide. They cover about 60 Å centred on 6430 Å. The majority of the spectra come from the SOFIN echelle spectrograph mounted on the Nordic Optical Telescope with a 2.56 m reflector, located at La Palma. The EEV CCD used has a pixel size of 22.5 µm. All RVs were derived via a crosscorrelation technique.

Source 8: Kjurkchieva et al. (2003). These RVs come also from the Rozhen 2.0 m reflector coudé spectra. However, they were obtained with Photometrics AT2000 CCD camera and a SITe SI003AB chip having 1024 × 1024 24 µm wide pixels. They cover 200 Å centred on the Hα line. An inspection of these RVs, based on the Fe 6593 Å line, reveals that they suffer from a rather large scatter and a systematic zero-point difference between both nights of observations and also between the primary and secondary RVs. The authors themselves only mention that there is a problem with the zero point of their RV measurements. We, therefore, did not use these RVs in any period analyses but only to check that they do not contradict the new ephemeris derived here – see below.

3. New times of minima

Times of mid-eclipses were found using the method of Kwee-van Woerden (1956) for points within 0.04 days of the minimum for Victoria, and 0.031 days for Hvar data. They are listed in Table 6 for the Victoria observations, and in Table 7 for the Hvar data.

4. Determination of an improved ephemeris

To obtain an improved ephemeris of the binary, we used the program FOTEL (Hadrava 1990) designed to find either independent or simultaneous solutions of light and RV curves. Other convenient features of FOTEL are that it allows calculation of individual zero points for individual data sets and also a simultaneous solution for observations in several different bandpasses. FOTEL models the shape of the stars as triaxial ellipsoids and this gives good results even for binaries close to filling their respective Roche lobes. FOTEL is not designed, however, to model light curves of stars with spots. Thus, the relative photometric radii \( r_1 \) and \( r_2 \) resulting from modelling

\[ \begin{align*}
T_{\text{eff,1}} & = 6100 \quad 5800 & \text{(K)} & \text{Budding & Zeilik (1987)} \\
T_{\text{eff,2}} & = 5900 \quad 5750 & \text{(K)} & \text{Hill et al. (1990)} \\
T_{\text{eff,3}} & = 6000 \quad 5700 & \text{(K)} & \text{Oláh et al. (1994)} \\
\end{align*} \]

Table 6. Times of mid-eclipses, derived by the Kwee-van Woerden method from Victoria observations for each photometric passband and given in HJD-2 452 000. The errors of individual minima are all between 0.001 and 0.0015.

\[
\begin{array}{|c|c|c|c|}
\hline
 I_c & R_c & V & B \\
\hline
\text{primary} & & & \\
500.8457 & 500.8451 & 500.8461 \\
502.9392 & 502.9391 & 502.9398 \\
505.7328 & 505.7306 & 505.7295 \\
530.8635 & 530.8649 & 530.8666 \\
532.9578 & 532.9567 & - \\
\hline
\text{secondary} & & & \\
501.8950 & 501.8916 & 501.8921 \\
503.9881 & 503.9855 & - \\
513.7603 & 513.7609 & - \\
531.9109 & 531.9107 & 531.9124 \\
\hline
\end{array}
\]

Table 7. Time of one primary mid-eclipse, derived by Kwee-van Woerden method from one long series of Hvar UBV observations, and given in HJD-2 452 000.

\[
\begin{align*}
V & = 536.4478 \pm 0.0016 \\
B & = 536.4467 \pm 0.0011 \\
U & = 536.4485 \pm 0.0012 \\
\end{align*}
\]

Table 8. Various estimates of the effective temperatures of the components of ER Vul.

\[
\begin{align*}
T_{\text{eff,1}} & = 6100 \quad 5800 & \text{(K)} & \text{Budding & Zeilik (1987)} \\
T_{\text{eff,2}} & = 5900 \quad 5750 & \text{(K)} & \text{Hill et al. (1990)} \\
T_{\text{eff,3}} & = 6000 \quad 5700 & \text{(K)} & \text{Oláh et al. (1994)} \\
\end{align*}
\]

Table 9. Linear limb-darkening coefficients adopted from Claret (2000) for \( \log g = 4.5 \) and \( T_{\text{eff}} \) of 6000 K and 5750 K.

\[
\begin{align*}
\text{Star} & \quad U & \quad B & \quad V & \quad R & \quad I \\
\text{primary} & 0.82 & 0.77 & 0.66 & 0.59 & 0.51 \\
\text{secondary} & 0.85 & 0.79 & 0.68 & 0.61 & 0.53 \\
\end{align*}
\]
Table 10. A comparison of epochs of primary minimum, given as HJD-2 400 000, derived by FOTEL for historical (Northcott & Bakos 1967) and new data, separately for photometry and for RVs. The orbital period was kept fixed at a value of 0.06980951 in all solutions.

<table>
<thead>
<tr>
<th>photometry</th>
<th>RVs</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 199.95758 ± 0.00044</td>
<td>35 199.9576 ± 0.0017</td>
</tr>
<tr>
<td>52 537.14735 ± 0.00016</td>
<td>52 537.1474 ± 0.0027</td>
</tr>
</tbody>
</table>

Al-Naymiy 1978, 1981), more recent studies usually use values close to 0.0698095 (0.069409409: İbanoğlu 1987, 0.06980950: Hill et al. 1990; 0.0698951: Ekmecki et al. 2002). In principle, this fact could indicate the presence of a very mild secular increase of the orbital period. Since FOTEL allows determination of a period change as one of the elements, we did some exploratory calculations, both for RVs and photometry, and found that any period change is several orders of a magnitude smaller than its rms error. We, therefore, adopted the assumption of a constant period, satisfactory for the data at hand. A critical compilation and analysis of the wealth of existing observational data on ER Vul would allow a much more stringent test on possible mild variations of the orbital period. This task is beyond the scope of this study.

As the first test of what one can expect from modern period analyses of the existing RV and photometric data, we derived local epochs of the primary minimum separately from RVs and photometry for the early data by Northcott & Bakos (1967) and for the most recent RVs published by Cakırlı et al. (2003) and our new Victoria and Hvar photometry. The results, given in Table 10, are more than encouraging. In both instances, the epochs derived from photometry, and from RVs, agree within the rms errors. On the assumption of a constant period, one finds that the two local epochs are separated for 24 835 orbital periods and considering the associated errors, one easily finds that the epochs can be reconciled by values of the orbital period between 0.06980950 and 0.06980951. Assuming instead that the two epochs are separated for either 24 836 or 24 834 periods, one arrives at values of 0.06980669 and 0.06981231, respectively. Both these values are safely excluded by existing data so even this first experiment leaves us with a very good initial value of the period.

We then used FOTEL to derive separate solutions for all photometric data listed in Table 1, for all RVs listed in Table 5 and also combined solution in which UBVRI photometry and RVs were treated simultaneously. Note that if one would simply combine RVs and photometry, the result would be almost entirely dominated by RVs which numerically contribute much more to the total sum of squares of O–C errors (typical O–C of RVs are at least several km s⁻¹ while it is a few hundred for the magnitudes). To prevent this, we first run a test solution and then we empirically increase the relative weight of photometric data in such a way that photometry and RVs contribute about one half each to the total sum of squares of O–C deviations. The basic results of these solutions are listed in Table 11.

The separate solutions for photometry and RVs resulted in determination of identical periods within the limits of their errors. It is not so for the epoch of the primary minimum. Its value, derived separately from photometry and from RVs, differ by more than the quoted errors. Possibly, this fact may reflect the effects of an uneven and time-variable distribution of brightness on the stellar surfaces over longer periods of time³. The difference is small and the epoch of primary minimum from each of these solutions is quite close to the epoch already derived by İbanoğlu et al. (1987).

Our new linear ephemeris therefore reads as follows

\[
T_{\text{prim.min.}} = \text{HJD 2 440 182.25628(46) + 0.0698095113(3) \times E.} \quad (5)
\]

The composite light curves in all passbands and the RV curve, based on all data used here, are plotted in Figs. 2 and 3, respectively, together with the O–C deviations from the curves.

The epoch of primary mid-eclipse we derive from Kjurcheva et al. (2003) RVs, allowing for different systemic velocities for each component and for each night

³ The agreement of photometric and RV epochs shown for two data subsets in Table 10 may appear fortuitous from this point of view but note that both light curves used to arrive at these determinations are similar in shape and were obtained within limited time intervals.
Table 11. Simultaneous solutions of the UBVRI light curves, RVs and combined solution of UBVRI photometry and RVs. All epochs are in HJD-2 400 000.

<table>
<thead>
<tr>
<th>Element</th>
<th>UBVRI</th>
<th>RVs</th>
<th>UBVRI + RVs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P$ (d) 0.698095040 ± 0.000090021</td>
<td>0.698095055 ± 0.000090015</td>
<td>0.698095113 ± 0.000090029</td>
</tr>
<tr>
<td></td>
<td>$T_{\text{prim,ocl}}$ 40 182.26127 ± 0.00036</td>
<td>40 182.25611 ± 0.00019</td>
<td>40 182.25628 ± 0.00046</td>
</tr>
<tr>
<td>$e$</td>
<td>0.0 fixed</td>
<td>0.0 fixed</td>
<td>0.0 fixed</td>
</tr>
<tr>
<td>$K_1$ (km s$^{-1}$)</td>
<td>–</td>
<td>135.49 ± 0.50</td>
<td>135.33 ± 0.51</td>
</tr>
<tr>
<td>$K_1/K_2$</td>
<td>–</td>
<td>0.9517 ± 0.0048</td>
<td>0.9518 ± 0.0049</td>
</tr>
<tr>
<td>$i$ ($^\circ$)</td>
<td>67.42 ± 0.33</td>
<td>–</td>
<td>66.63 ± 0.33</td>
</tr>
<tr>
<td>$r_1$</td>
<td>0.3393 ± 0.0032</td>
<td>–</td>
<td>0.3388 ± 0.0038</td>
</tr>
<tr>
<td>$r_2$</td>
<td>0.2040 ± 0.0055</td>
<td>–</td>
<td>0.2175 ± 0.0058</td>
</tr>
<tr>
<td>$V_{\text{Dunlap}}$</td>
<td>7.3510 ± 0.0007</td>
<td>–</td>
<td>7.3517 ± 0.0008</td>
</tr>
<tr>
<td>$V_{\text{B}}$</td>
<td>7.3178 ± 0.0020</td>
<td>–</td>
<td>7.3188 ± 0.0020</td>
</tr>
<tr>
<td>$V_{\text{H}}$</td>
<td>7.3564 ± 0.0007</td>
<td>–</td>
<td>7.3574 ± 0.0008</td>
</tr>
<tr>
<td>$V_{\text{rms}}$</td>
<td>0.0086</td>
<td>–</td>
<td>0.0095</td>
</tr>
<tr>
<td>$\Delta V_{\text{Victoria}}$</td>
<td>–</td>
<td>–</td>
<td>–4.1621 ± 0.0004</td>
</tr>
<tr>
<td>$\Delta V_{\text{rms}}$</td>
<td>0.0086</td>
<td>–</td>
<td>0.0094</td>
</tr>
<tr>
<td>$B_{\text{Dunlap}}$</td>
<td>7.9616 ± 0.0008</td>
<td>–</td>
<td>7.9617 ± 0.0009</td>
</tr>
<tr>
<td>$B_{\text{H}}$</td>
<td>7.9829 ± 0.0008</td>
<td>–</td>
<td>7.9839 ± 0.0009</td>
</tr>
<tr>
<td>$B_{\text{rms}}$</td>
<td>0.0102</td>
<td>–</td>
<td>0.0110</td>
</tr>
<tr>
<td>$\Delta B_{\text{Victoria}}$</td>
<td>–</td>
<td>–</td>
<td>–4.6462 ± 0.0007</td>
</tr>
<tr>
<td>$\Delta B_{\text{rms}}$</td>
<td>0.0187</td>
<td>–</td>
<td>0.0194</td>
</tr>
<tr>
<td>$U_{\text{H}}$</td>
<td>8.0637 ± 0.0011</td>
<td>–</td>
<td>8.0648 ± 0.0011</td>
</tr>
<tr>
<td>$U_{\text{rms}}$</td>
<td>0.0131</td>
<td>–</td>
<td>0.0137</td>
</tr>
<tr>
<td>$\Delta U_{\text{Victoria}}$</td>
<td>–</td>
<td>–</td>
<td>–3.9306 ± 0.0004</td>
</tr>
<tr>
<td>$\Delta U_{\text{rms}}$</td>
<td>0.0084</td>
<td>–</td>
<td>0.0092</td>
</tr>
<tr>
<td>$R_{\text{H}}$</td>
<td>7.936 ± 0.0003</td>
<td>–</td>
<td>7.939 ± 0.0003</td>
</tr>
<tr>
<td>$R_{\text{rms}}$</td>
<td>0.0074</td>
<td>–</td>
<td>0.0087</td>
</tr>
<tr>
<td>$\Delta R_{\text{Victoria}}$</td>
<td>–</td>
<td>–</td>
<td>–3.7091 ± 0.0004</td>
</tr>
<tr>
<td>$\Delta R_{\text{rms}}$</td>
<td>0.0074</td>
<td>–</td>
<td>0.0087</td>
</tr>
<tr>
<td>$I_{\text{B}}$</td>
<td>0.829 ± 0.0003</td>
<td>–</td>
<td>0.816</td>
</tr>
<tr>
<td>$I_{\text{rms}}$</td>
<td>0.778</td>
<td>–</td>
<td>0.756</td>
</tr>
<tr>
<td>$\Delta I_{\text{Victoria}}$</td>
<td>–</td>
<td>–</td>
<td>–24.3 ± 1.5</td>
</tr>
<tr>
<td>$\Delta I_{\text{rms}}$</td>
<td>–</td>
<td>–</td>
<td>–24.3 ± 1.6</td>
</tr>
<tr>
<td>$\gamma_{\text{DDO}}$</td>
<td>–</td>
<td>–</td>
<td>–24.3 ± 1.6</td>
</tr>
<tr>
<td>$\gamma_{\text{OHP}}$</td>
<td>–</td>
<td>–</td>
<td>–24.3 ± 1.6</td>
</tr>
<tr>
<td>$\gamma_{\text{DAO}}$</td>
<td>–</td>
<td>–</td>
<td>–24.3 ± 1.6</td>
</tr>
<tr>
<td>$\gamma_{\text{Lowell}}$</td>
<td>–</td>
<td>–</td>
<td>–24.3 ± 1.6</td>
</tr>
<tr>
<td>$\gamma_{\text{Catania}}$</td>
<td>–</td>
<td>–</td>
<td>–24.3 ± 1.6</td>
</tr>
<tr>
<td>$\gamma_{\text{Rozhen}}$</td>
<td>–</td>
<td>–</td>
<td>–24.3 ± 1.6</td>
</tr>
<tr>
<td>$\gamma_{\text{La Palma}}$</td>
<td>–</td>
<td>–</td>
<td>–24.3 ± 1.6</td>
</tr>
<tr>
<td>$\gamma_{\text{mean UBVR rms}}$</td>
<td>0.0121</td>
<td>–</td>
<td>0.0129</td>
</tr>
<tr>
<td>$\gamma_{\text{mean RV rms}}$</td>
<td>–</td>
<td>5.010</td>
<td>5.087</td>
</tr>
<tr>
<td>$\gamma_{\text{No. of obs.}}$</td>
<td>4453</td>
<td>477</td>
<td>4453 + 477</td>
</tr>
</tbody>
</table>
5. Discovery of rapid variations

To the best of our knowledge, investigators of photometric variations of ER Vul were usually only concerned with orbital variations and long-term changes in the level of maximum light. Oláh et al. (1994) reported “short-term” changes but they meant variations in the light curve which occurred within one month of observations.

We noted that the $U$ and partly also $B$ curves exhibit scatter which is definitely larger than that of the check star. Figure 4 is a time plot of the $U$ magnitude of ER Vul and the check star for one night of observations at Hvar. One can see the increasing magnitude due to regress from a minimum and overlapping systematic rapid variations which substantially exceed the scatter of the fainter check star. We believe that this represents a discovery of truly rapid light variations of ER Vul, possibly related to rapid line-profile changes. This finding deserves dedicated future study.

6. Discussion

6.1. Colours of stars

The Hipparcos parallax of ER Vul corresponds to a distance of 50 pc. One can assume, therefore, that the interstellar reddening can be neglected. Then, the $(B - V)$ colours of the binary at maximum light follow from the calibrated Hvar data as follows $(B - V) = 0^m 627$ and $(U - B) = 0^m 081$. These values correspond to a star slightly earlier than G2.

As we have already mentioned, the FOTEL program does not allow modelling of star spots and it is, therefore, conceivable that the solutions presented here do not give correct relative radii. We verified, however, that similar radii are obtained even if one solves the light curves individually, both for the recent and historical data. Note also that FOTEL solutions gave the inclination of the orbit in agreement with other recent studies.

It is important to realize that the levels of maximum light are derived correctly, no matter whether the model describes the radii correctly or not. This means that the above colours of the whole binary can be trusted. If one reconstructs the colours of individual components on the basis of the combined RV and $UBVRI$ solution of Table 11, it leads to

\[(B - V)_1 = 0^m 610 \quad \text{and} \quad (U - B)_1 = -0^m 003\]

and

\[(B - V)_2 = 0^m 675 \quad \text{and} \quad (U - B)_2 = 0^m 391,\]

which roughly corresponds to G1 and G5 stars. However, these values are much less certain since the decomposition depends on the relative radii derived by FOTEL.

The accurate Hipparcos parallax which gives the distance of 49.85 pc for ER Vul does not contradict the radii of the stars derived via star-spot modelling (cf., e.g., Hill et al. 1990 or Oláh et al. 1994) and effective temperatures of about 6000 K and 5700 K.

6.2. Character of the light curve

Our limited set of light curves can suffer from selection effects and may not represent the behaviour of ER Vul accurately. Nowadays, an almost canonical picture of similar systems is the interpretation in terms of chromospheric activity and solar-like cycles. We note, however, that various attempts to find a
periodic, or at least clearly cyclical behaviour in the light maximum of ER Vul have not been fully convincing. Keskin (1990) reported \( BV \) observations obtained between 1981 and 1986 and constructed residual light curves. He concluded that the wave minimum had migrated towards decreasing phases with a cycle of 1.5 years while the mean brightness varied over a cycle of 2.5–3 years. However, he also found clear changes within one month and it is not clear whether his interpretation is the only possible (observations are not published). Oláh et al. (1994) reported variations within one month, too. A plot of \( V \) and \( B \) magnitude of ER Vul at both elongations vs. time in their Fig. 4 shows a possible cycle of 6 years over the interval 1980–1986 covered by Keskin’s data but a shorter cycle later on. There is a large scatter between individual determinations and the character of time variations at both elongations differ from each other.

We note that the O–C deviations from the final solution, shown in Fig. 2, exhibit a peculiar but phase-locked structure for data from five different passbands which span – though not densely – an interval of 53 years. The old David Dunlap Observatory light curve is quite similar to the recent light curve from Hvar – cf. Fig. 1. The depression following the secondary minimum is seen also in the light curves published by Oláh et al. (1994) or Keskin (1990). It is reminiscent of the effects of gas streams projected against the disk of the primary star in proper interval of phases, often observed for hot OBA emission-line binaries (cf., e.g., Kříž & Harmanec 1975). Conceivably – in addition to the non-uniform and variable brightness of the stellar disks – there could be some more or less permanent, phase-locked circumstellar structures, partly responsible for the observed Balmer emission. Note that Kjurkchieva et al. (2003) argue in favour of the presence of circumstellar matter in the system on the basis of their H\( \alpha \) observations.

6.3. Basic physical properties of the binary

Our solution for all existing RVs gives \( M_1 \sin^3 i = 0.7923 \, M_\odot \) and \( M_2 \sin^3 i = 0.7541 \, M_\odot \), which leads to binary masses of 1.024 and 0.9748 \( M_\odot \) and binary separation \( A = 4.170 \, R_\odot \), in accordance with values derived by Duemmler et al. (2003).

There is a larger uncertainty is the stellar radii. Hill et al. (1990) adopted relative radii of 0.25 ± 0.01 for both stars while Oláh et al. (1994) arrived at \( r_1 = 0.259 \) and \( r_2 = 0.253 \). Notably, Ekmecki et al. (2002), who modelled the light curves with spots using a new version of the Wilson-Devinney program, arrived at \( r_1 = 0.276 \) and \( r_2 = 0.290 \), i.e. a larger radius for the secondary. On the other hand, Kjurkchieva et al. (2003) analyzing their new \( BVR \) photometry arrived at \( r_1 = 0.299 \) and \( r_2 = 0.269 \). With our value for the binary separation, the above values define a range \( R_1 = 1.04–1.25 \, R_\odot \) for the primary, and \( R_2 = 1.04–1.21 \, R_\odot \) for the secondary. On the other hand, the most accurate projected rotational velocities of \( (97.4 \pm 1.3) \, \text{km s}^{-1} \) and \( (96.7 \pm 2.2) \, \text{km s}^{-1} \) for the primary and secondary, respectively, derived by Duemmler et al. (2003), inclination of 67°, and the assumption of spin-orbit synchronization would call for \( R_1 = 1.46 \, R_\odot \) and \( R_2 = 1.45 \, R_\odot \), i.e. relative radii close to 0.35 for both stars. Note, however, that Duemmler et al., who also discussed this problem, warn that their \( v \sin i \) value for the secondary might be biased because of the blending of the lines. Is it then only fortuitous that the relative radius derived with FOTEL agrees with the assumption of spin-orbit synchronization quite well (predicting \( v \sin i = 94 \, \text{km s}^{-1} \))? Can the mild deviations from the spin-orbit synchronization – if real – be responsible for some of the remarkable variations observed for this binary?

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