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

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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 $T_{\rm prim.min.}$ = HJD 2 440 182.25628(46) + $0\overset{\rm d}{.}698095113(29) \times E$, 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 (*RV*s hereafter). To this end, we collected and analyzed all published *RV*s 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 $H_{\rm p}$ 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,

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⋆ This research is based on photoelectric observations from Hvar and University of Victoria Observatories.

⋆⋆ Table 4 is only available in electronic form at the CDS 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/415/289

Table 1. Journal of photoelectric observations.

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

* 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.

V	*B*	*U*	*B* – *V*	*U* – *B*	Station	Remark
HD 200270 (comparison)						
$7\overset{\mathrm{m}}{.}772 \pm 0\overset{\mathrm{m}}{.}011$	$8\overset{\mathrm{m}}{.}232 \pm 0\overset{\mathrm{m}}{.}011$	$8\overset{\mathrm{m}}{.}173 \pm 0\overset{\mathrm{m}}{.}013$	$0\overset{\mathrm{m}}{.}460$	$-0\overset{\mathrm{m}}{.}059$	Hvar	all-sky
$7\overset{\mathrm{m}}{.}769 \pm 0\overset{\mathrm{m}}{.}011$	$8\overset{\mathrm{m}}{.}229 \pm 0\overset{\mathrm{m}}{.}011$	–	$0\overset{\mathrm{m}}{.}460$	–	Hipparcos	all-sky
$7\overset{\mathrm{m}}{.}71$	$8\overset{\mathrm{m}}{.}16$	–	$0\overset{\mathrm{m}}{.}45$	–	David Dunlap	all-sky
HD 200468 (check)						
$7\overset{\mathrm{m}}{.}869 \pm 0\overset{\mathrm{m}}{.}009$	$8\overset{\mathrm{m}}{.}043 \pm 0\overset{\mathrm{m}}{.}021$	$8\overset{\mathrm{m}}{.}166 \pm 0\overset{\mathrm{m}}{.}023$	$0\overset{\mathrm{m}}{.}174$	$0\overset{\mathrm{m}}{.}123$	Hvar	all-sky
$7\overset{\mathrm{m}}{.}869 \pm 0\overset{\mathrm{m}}{.}008$	$8\overset{\mathrm{m}}{.}042 \pm 0\overset{\mathrm{m}}{.}017$	$8\overset{\mathrm{m}}{.}166 \pm 0\overset{\mathrm{m}}{.}019$	$0\overset{\mathrm{m}}{.}174$	$0\overset{\mathrm{m}}{.}123$	Hvar	diff.
$7\overset{\mathrm{m}}{.}871 \pm 0\overset{\mathrm{m}}{.}010$	$8\overset{\mathrm{m}}{.}045 \pm 0\overset{\mathrm{m}}{.}010$	–	$0\overset{\mathrm{m}}{.}174$	–	Hipparcos	all-sky
HD 200425 (check)						
$7\overset{\mathrm{m}}{.}75$	$8\overset{\mathrm{m}}{.}30$	–	$0\overset{\mathrm{m}}{.}55$	–	David Dunlap	all-sky
$7\overset{\mathrm{m}}{.}81$	$8\overset{\mathrm{m}}{.}37$	–	$0\overset{\mathrm{m}}{.}56$	–	David Dunlap	diff.

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 observations of very bright stars. This forced us to use a rather low voltage which resulted in a somewhat lower S/N for ER Vul observations. An observation through each filter consisted of a mean of ten 1-s integrations followed by respective sky measurement. Each *UBV* observation of the variable and check was bracketed by observations of the comparison star HD 200270.

Observations were reduced with the help of a new release of the reduction program HEC22 which very conveniently also allows modelling of a time-variable extinction during the course of the night. Depending on the quality of each night of observations, judged via rms errors of individual observations from the fit to the extinction model for the night, we assigned weights 1.5, 1.0 or 0.5 to individual observations from excellent, normal and poor nights, respectively.

Program HEC22 uses non-linear formulæ for the transformation from the natural to the standard *UBV* system; see Harmanec et al. (1994) and Harmanec & Horn (1998) for the description of observing and reduction procedures and 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 values 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 $BVR_{\rm c}I_{\rm c}$ 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 matching the Johnson *BV* and Cousins $R_{\rm c}I_{\rm c}$ systems. The Julian Dates of observations are 2 452 498-505, ..511–513, ..527, and ..530–532. Table 3 lists the stars' identification numbers, magnitudes and positions from the Hubble Space Telescope Guide Star Catalogue (GSC) (Jenkner et al. 1990). Besides ER Vul = GSC 611, none of these stars showed any significant variations in plots of the individual nights' data or from night to night. Because ER Vul is so much brighter than any of the other stars in our field of view, our differential magnitudes are calculated in the sense of ER Vul minus the mean of the three next

Table 3. Stars observed with the CCD camera in the field of ER Vul.

Star GSC No.	RA J2000	Dec J2000	GSC Mag.
611	$21^{\mathrm{h}}02^{\mathrm{m}}26^{\mathrm{s}}$	$+27°48'25''$	7.1
422	$21^{\mathrm{h}}02^{\mathrm{m}}32^{\mathrm{s}}$	$+27°51'07''$	11.2
356	$21^{\mathrm{h}}02^{\mathrm{m}}02^{\mathrm{s}}$	$+27°49'44''$	11.3
247	$21^{\mathrm{h}}02^{\mathrm{m}}24^{\mathrm{s}}$	$+27°49'25''$	12.0

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 $0^{\mathrm{m}}.023$ for B, $0^{\mathrm{m}}.008$ for V, $0^{\mathrm{m}}.007$ for R_{c} and $0^{\mathrm{m}}.005$ for I_{c}. The standard deviation of $0^{\mathrm{m}}.005$ 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 $0^{\mathrm{m}}.368 \pm 0^{\mathrm{m}}.009$ for B, $-0^{\mathrm{m}}.069 \pm 0^{\mathrm{m}}.006$ for V, $-0^{\mathrm{m}}.346 \pm 0^{\mathrm{m}}.006$ for R_{c}, $-0^{\mathrm{m}}.583 \pm 0^{\mathrm{m}}.004$ for I_{c}. The smallest of the standard deviations is $0^{\mathrm{m}}.004$ in the I_{c} 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 $0^{\mathrm{m}}.010$ while weight 0.5 was assigned to observations with error flag 1 and/or rms error of more than $0^{\mathrm{m}}.010$. ER Vul is rather faint for the sensitivity of the Hipparcos detector. There is no observation with an rms error smaller than $0^{\mathrm{m}}.006$ 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 formulæ. 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* photoelectric 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[1]. 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 *RV*s 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 *RV*s 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

$$w = \frac{10 \cdot Q}{D}, \tag{1}$$

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 *RV*s are based on photographic spectrograms secured in the Cassegrain focus of the 1.88 m reflector of David Dunlap Observatory.

Source 2: McLean (1982). *RV*s were obtained via the cross-correlation technique from digitized photographic spectra, secured in the coudé 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.

[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`

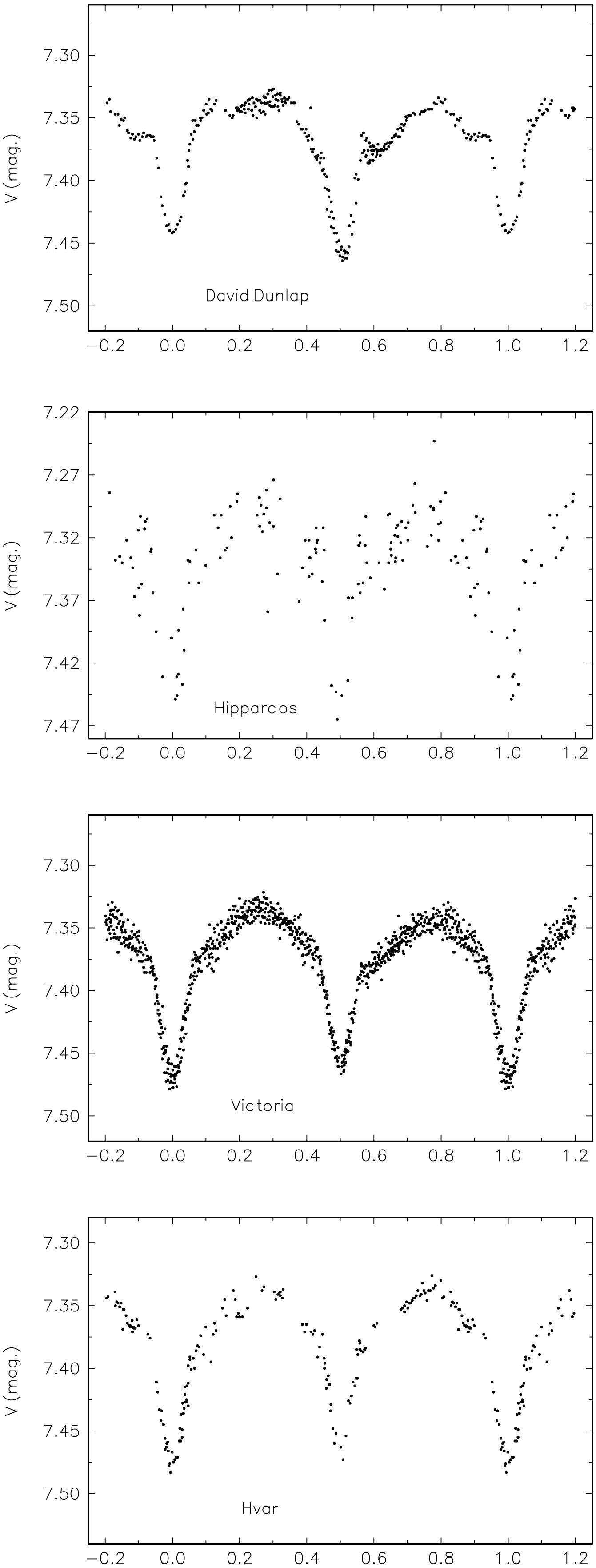

Fig. 1. Individual V-band light curves for the four data sets used here plotted vs. phase of ephemeris (5).

Table 5. Journal of available *RV*s; all observations where *RV*s of the primary and secondary could not be resolved were omitted.

Source	Epoch (JD−2 400 000)	No. of obs.	Dispersion (Å mm^{-1})	Weight
1	32 098.6–35 006.7	37	33	0.303
2	44 473.6–44 476.5	15	20	0.500
3	46 305.0–47 068.8	29	20	2.000
4	49 643.7–49 657.7	10	8?	5.000
5	51 767.4–51 812.5	12	6	6.667
6	49 141.6–49 560.5	7	6	6.667
7	49 166.5–50 299.6	130	2:	20.0
8	52 136.3–52 137.6	27	8	–

Sources: 1. Northcott & Bakos (1967); 2. McLean (1982); 3. Hill et al. (1990); 4. Gunn et al. (1996); 5. Cakırlı et al. (2003); 6. Duemmler et al. (2003): Rozhen ISTA CCD spectra; 7. Duemmler et al. (2003): La Palma spectra; 8. Kjurkchieva et al. (2003).

*Source 3: Hill et al. (1990). RV*s 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 *RV*s 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 12 000. 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 explicitely 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 (13 553−13 573) 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

$$T_{\rm prim.min.} = \mathrm{HJD}\ 2\,440\,182.2621 + 0\overset{\rm d}{.}69809409 \times E. \qquad (2)$$

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

$$T_{\rm prim.min.} = \mathrm{HJD}\ 2\,440\,182.2945 + 0\overset{\rm d}{.}6980907 \times E. \qquad (3)$$

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

$$T_{\rm prim.min.} = \mathrm{HJD}\ 2\,440\,182.259 + 0\overset{\rm d}{.}6981 \times E. \qquad (4)$$

We tentatively reconstructed HJDs of Gunn's et al. *RV*s for all three ephemerides quoted above and found that one obtains smallest rms errors when combining Gunn's et al. *RV*s 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 *RV*s 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 *RV*s: HJD 2 451 776 and ...775 need to be interchanged to correspond to correct *RV*s.

Sources 6 and 7: Duemmler et al. (2003). These are the best *RV*s 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 *RV*s were derived via a crosscorrelation technique.

Source 8: Kjurkchieva et al. (2003). These *RV*s come also from the Rozhen 2.0 m reflector coudé spectra. However, they were obtained with Photometrics AT200 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 *RV*s, 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 *RV*s. The authors themselves only mention that there is a problem with the zero point of their *RV* measurements. We, therefore, *did not use* these *RV*s 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[2]) 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 the light curves of ER Vul may not be realistic. Yet, we have chosen appropriate linear limb-darkening coefficients from a recent study by Claret (2000) and set all albedo coefficients equal to 0.5. In Table 8 we summarize several determinations of effective temperatures of both binary components based on detailed modelling. Guided by these estimates, we fixed the limb-darkening coefficients at values given in Table 9. Slight changes in the values of these coefficients have a negligible effect on the results. All solutions with FOTEL were converged to machine accuracy.

Numerous studies of ER Vul show that while a period close to $0\overset{\mathrm{d}}{.}69808$ was preferred earlier (Northcott & Bakos 1967;

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.

I_c	R_c	V	B
primary			
500.8457	–	500.8451	500.8461
502.9392	502.9396	502.9391	502.9398
505.7328	505.7315	505.7306	505.7295
530.8635	530.8628	530.8649	530.8666
532.9578	532.9557	532.9567	–
secondary			
501.8950	501.8927	501.8916	501.8921
503.9881	503.9873	503.9855	–
513.7603	513.7612	513.7609	–
531.9109	531.9110	531.9107	531.9124

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

V	B	U
536.4478 ± 0.0016	536.4467 ± 0.0011	536.4485 ± 0.0012

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

$T_{\mathrm{eff},1}$ (K)	$T_{\mathrm{eff},2}$ (K)	Source
6100	5800	Budding & Zeilik (1987)
5900	5750	Hill et al. (1990)
6000	5700	Oláh et al. (1994)

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

Star	U	B	V	R	I
primary	0.82	0.77	0.66	0.59	0.51
secondary	0.85	0.79	0.68	0.61	0.53

[2] The program is made freely available to interested users by the author. Its more detailed description, Fortran source code and user's guide can be obtained via `http://www.asu.cas.cz/~had/had.html` web page

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 *RV*s. The orbital period was kept fixed at a value of $0\overset{\rm d}{.}6980951$ in all solutions.

photometry	*RV*s
35 199.95758 ± 0.00044	35 199.9576 ± 0.0017
52 537.14735 ± 0.00016	52 537.1474 ± 0.0027

Al-Naymiy 1978, 1981), more recent studies usually use values close to $0\overset{\rm d}{.}698095$ ($0\overset{\rm d}{.}69409409$: İbanoğlu 1987, $0\overset{\rm d}{.}6980950$: Hill et al. 1990; $0\overset{\rm d}{.}698951$: Ekmekci 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 *RV*s 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 *RV*s and photometry for the early data by Northcott & Bakos (1967) and for the most recent *RV*s 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 *RV*s, 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 $0\overset{\rm d}{.}6980950$ and $0\overset{\rm d}{.}6980951$. Assuming instead that the two epochs are separated for either 24 836 or 24 834 periods, one arrives at values of $0\overset{\rm d}{.}6980669$ and $0\overset{\rm d}{.}6981231$, 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 *RV*s listed in Table 5 and also combined solution in which *UBVRI* photometry and *RV*s were treated simultaneously. Note that if one would simply combine *RV*s and photometry, the result would be almost entirely dominated by *RV*s which numerically contribute much more to the total sum of squares of O–C errors (typical O–C of *RV*s 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 *RV*s 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.

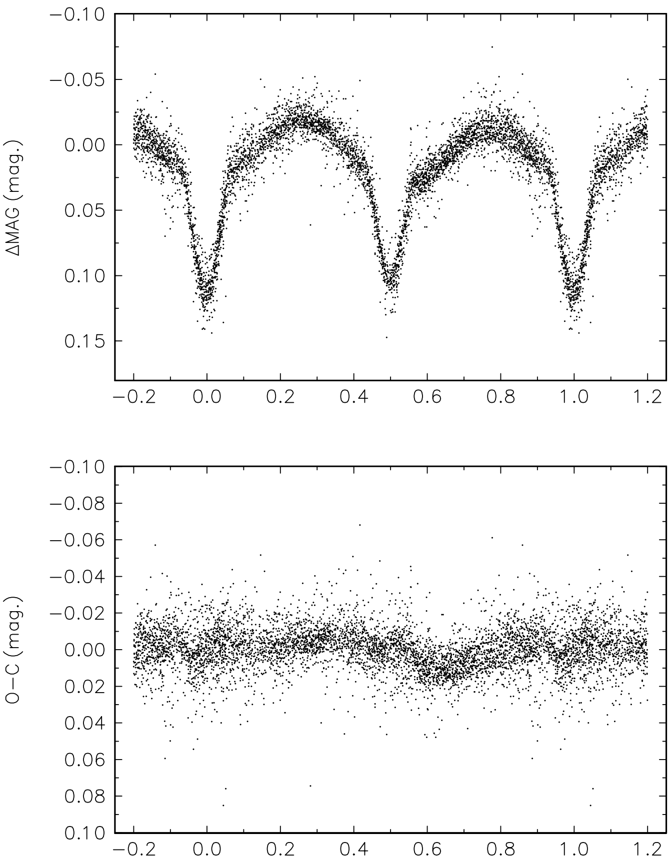

Fig. 2. The composite $UBVR_{\rm c}I_{\rm c}$ orbital light curve and O–C residuals from the final solution plotted vs. phase of ephemeris (5). The magnitude levels of maximum light derived in the solution and given in Table 11 were subtracted from data in each passband and data set to get all light curves on a comparable level.

The separate solutions for photometry and *RV*s 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 *RV*s, 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 time[3]. 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

$$T_{\rm prim.min.} = \text{HJD } 2\,440\,182.25628(46) + 0\overset{\rm d}{.}698095113(3) \times E. \quad (5)$$

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 Kjurchieva et al. (2003) *RV*s, 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, *RV*s and combined solution of *UBVRI* photometry and *RV*s. All epochs are in HJD-2 400 000.

Element	*UBVRI*	*RV*s	*UBVRI* + *RV*s
P (d)	$0^{\rm d}\!.698095040 \pm 0^{\rm d}\!.000000021$	$0^{\rm d}\!.69809505 \pm 0^{\rm d}\!.00000015$	$0^{\rm d}\!.698095113 \pm 0^{\rm d}\!.000000029$
$T_{\rm prim.ecl.}$	$40\,182.26127 \pm 0.00036$	$40\,182.2561 \pm 0.0019$	$40\,182.25628 \pm 0.00046$
e	0.0 fixed	0.0 fixed	0.0 fixed
K_1 (km s^{-1})	–	135.49 ± 0.50	135.33 ± 0.51
K_1/K_2	–	0.9517 ± 0.0048	0.9518 ± 0.0049
i (°)	67.42 ± 0.33	–	66.63 ± 0.33
r_1	0.3393 ± 0.0032	–	0.3388 ± 0.0038
r_2	0.2040 ± 0.0055	–	0.2175 ± 0.0058
$V_{\rm Dunlap}$	7.3510 ± 0.0007	–	7.3517 ± 0.0008
rms	0.0116	–	0.0128
$V_{\rm Hipparcos}$	7.3178 ± 0.0020	–	7.3188 ± 0.0020
rms	0.0215	–	0.0214
$V_{\rm Hvar}$	7.3564 ± 0.0007	–	7.3574 ± 0.0008
rms	0.0086	–	0.0095
$\triangle V_{\rm Victoria}$	-4.1626 ± 0.0004	–	-4.1621 ± 0.0004
rms	0.0086	–	0.0094
$B_{\rm Dunlap}$	7.9610 ± 0.0008	–	7.9617 ± 0.0009
rms	0.0125	–	0.0143
$B_{\rm Hvar}$	7.9829 ± 0.0008	–	7.9839 ± 0.0009
rms	0.0102	–	0.0110
$\triangle B_{\rm Victoria}$	-4.6468 ± 0.0007	–	-4.6462 ± 0.0007
rms	0.0187	–	0.0194
$U_{\rm Hvar}$	8.0637 ± 0.0011	–	8.0648 ± 0.0011
rms	0.0131	–	0.0137
$\triangle R_{\rm Victoria}$	-3.9306 ± 0.0004	–	-3.9302 ± 0.0004
rms	0.0084	–	0.0092
$\triangle I_{\rm Victoria}$	-3.7096 ± 0.0003	–	-3.7091 ± 0.0004
rms	0.0078	–	0.0087
$L_{1,\rm U}$	0.829	–	0.816
$L_{1,\rm B}$	0.778	–	0.756
$L_{1,\rm V}$	0.767	–	0.744
$L_{1,\rm R}$	0.770	–	0.741
$L_{1,\rm I}$	0.761	–	0.733
$\gamma_{\rm DDO}$	–	-24.3 ± 1.5	-24.3 ± 1.6
$\gamma_{\rm OHP}$	–	-21.6 ± 2.2	-21.6 ± 2.2
$\gamma_{\rm DAO}$	–	-24.30 ± 0.62	-24.30 ± 0.63
$\gamma_{\rm Lowell}$	–	-31.0 ± 2.8	-31.0 ± 2.9
$\gamma_{\rm Catania}$	–	-24.7 ± 2.8	-24.7 ± 2.7
$\gamma_{\rm Rozhen}$		-25.4 ± 1.2	-25.4 ± 1.4
$\gamma_{\rm La\ Palma}$		-25.73 ± 0.26	-25.72 ± 0.27
mean *UBVRI* rms	0.0121	–	0.0129
mean *RV* rms	–	5.010	5.087
No. of obs.	4453	477	4453 + 477

The “mean rms“ and “rms” following each zero level of respective magnitude are the rms errors of one observation of unit weight for the solution; all errors quoted with individual elements are rms errors of these elements calculated from the covariance matrix.

of observation (see our comments on this data set in Sect. 2.1.5) is HJD $2\,452\,136.436 \pm 0.004$ while ephemeris (5) predicts HJD $2\,451\,136.437$. From photometry over 6 years, Keskin (1990) derived HJD $2\,446\,235.4395 \pm 0.0004$ while ephemeris (5) predicts HJD $2\,446\,235.4390$. Note that using the epoch from Table 11, which is based solely on photometric data, would lead to a perfect agreement with Keskin’s epoch. This may strengthen the suspicion that the small difference between epochs based on *RV* and photometric solutions is a real one, yet the difference remains marginal. In any case it seems that the new ephemeris is performing very well and can safely be used to reconcile all existing data.

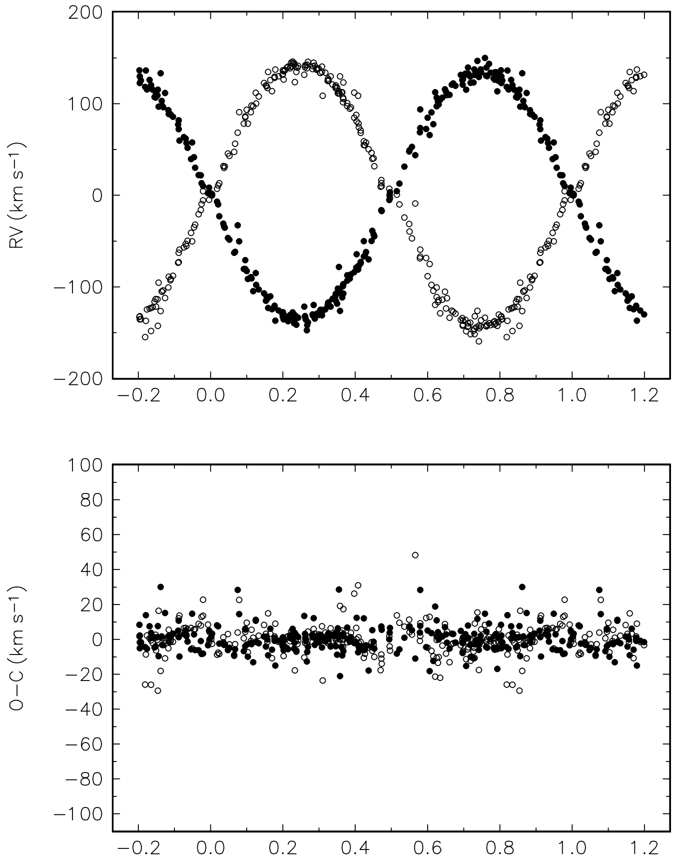

Fig. 3. All *RV*s (individual systemic velocities subtracted from the respective data sets) and O–C residuals from the final solution plotted vs. phase of ephemeris (5). *RV*s of the primary are shown by filled symbols.

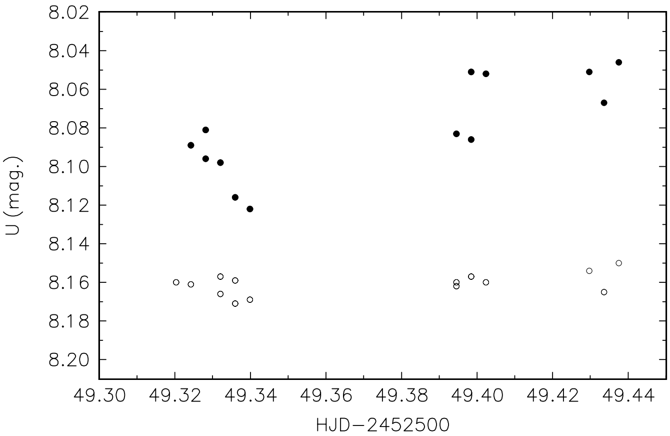

Fig. 4. The *U* light curve of ER Vul (filled circles) and the check star HD 200468 (open circles) for one observing night at Hvar. One can clearly see rapid variations of ER Vul, in addition to the regress from a light minimum.

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 $(B-V) = 0\overset{\mathrm{m}}{.}627$ and $(U-B) = 0\overset{\mathrm{m}}{.}081$. 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

$$(B-V)_1 = 0\overset{\mathrm{m}}{.}610 \quad \text{and} \quad (U-B)_1 = -0\overset{\mathrm{m}}{.}003$$

and

$$(B-V)_2 = 0\overset{\mathrm{m}}{.}675 \quad \text{and} \quad (U-B)_2 = 0\overset{\mathrm{m}}{.}391,$$

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 maxima 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 Hα observations.

6.3. Basic physical properties of the binary

Our solution for all existing *RV*s 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, Ekmekci 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 ± 1.3) km s^{-1} and (96.7 ± 2.2) 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 fortituous that the relative radius derived with FOTEL agrees with the assumption of spin-orbit synchronization quite well (predicting $v \sin i = 94$ 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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References

Al-Naimiy, H. M. K. 1978, Inf. Bull. Var. Stars, No. 1481
Al-Naimiy, H. M. K. 1981, A&AS, 43, 85
Budding, E., & Zeilik, M. 1987, ApJ, 319, 827
Cakırlı, Ö., İbanoǧlu, C., Frasca, A., & Catalano, S. 2003, A&A, 400, 257
Claret, A. 2000, A&A, 363, 1081
Duemmler, R., Doucet, C., Formanek, F., Ilyin, I., & Tuominen, I. 2003, A&A, 402, 745
Ekmekci, F., Özeren, F. F., & Ak, H. 2002, Astron. Nachr., 323, 1
Gunn, A. G., Hall, J. C., Lockwood, G. W., & Doyle, J. G. 1996, A&A, 305, 146
Hadrava, P. 1990, Contr. Astron. Obs. Skalnaté Pleso, 20, 23
Harmanec, P. 1988, Bull. Astron. Inst. Czechosl., 39, 329
Harmanec, P. 1998, A&A, 335, 173
Harmanec, P., & Horn, J. 1998, J. Astron. Data, 4, CD-ROM file 5
Harmanec, P., Horn, J., & Juza, K. 1994, A&AS, 104, 121
Hill, G., Fischer, W. A., & Holmgren, D. 1990, A&A, 238, 145
İbanoǧlu, C., Evren, S., & Tunca, Z. 1987, Ap&SS, 136, 225
Jenkner, H., Lasker, B., Sturch, C., et al. 1990, AJ, 99, 2082
Keskin, V. 1990, Ap&SS, 169, 165
Kjurkchieva, D. P., Marchev, D. V., & Zola, S. 2003, A&A, 404, 611
Kříž, S., & Harmanec, P. 1975, Bull. Astron. Inst. Czechosl., 26, 65
Kwee, K. K., & van Woerden, H. 1956, Bull. Astr. Inst. Netherland, 12, 327
McLean, B. J. 1982, MNRAS, 201, 421
Northcott, R. J., & Bakos, G. A. 1967, AJ, 72, 89
Oláh, K., Budding, E., Kim, H.-I., & Etzel, P. B. 1994, A&A, 291, 110
Perryman, M. A. C., Høg, E., Kovalevsky, J., Lindegren, L., & Turon, C. 1997, ESA SP-1200: The Hipparcos and Tycho Catalogues
Robb, R. M., & Greimel, R. 1999, ASP Conf. Ser., 189, 198
Strassmeier, K. G., Hall, D. S., Fekel, F. C., & Scheck, M. 1993, A&AS, 100, 173