VW LMi: tightest quadruple system known. Light-time effect and possible secular changes of orbits

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1 INTRODUCTION

The photometric variability of VW LMi (HIP 54003, HD 95660, sp. type F3–5V, \( V_{\text{max}} = 8.0 \)) was found by the Hipparcos mission (ESA 1997), where it was correctly classified as a W UMa-type eclipsing binary with an orbital period of 0.477 547 d. The first ground-based photometric observations of the system obtained in 1999 and 2000 (taken in the \( B \) and \( V \)Johnson filters) were published by Dumitrescu (2000). The analysis of these light curves (LCs) (Dumitrescu 2000) leads to the photometric mass ratio \( q_{\text{ph}} = 0.395 \) and inclination \( i = 72.4 \) for the system. Later, Gomez-Forrellad et al. (2003) presented new \( BV \) photometry and its preliminary analysis. Assuming convective envelopes for both components and the temperature of the primary as \( T_{1} = 6700 \) K, the authors estimated the mass ratio as \( q = 0.4 \) and inclination around 70°. Fourier analysis of its Hipparcos LC presented by Selam (2004) yielded quite different parameters: \( q = 0.25 \), \( i = 72.5 \) and fill-out factor \( f = 0.4 \). The discovery of the second (non-eclipsing) binary in VW LMi by Pribulla et al. (2006) makes all previous photometric solutions almost useless due to the strong-light contribution of the second pair of about \((L_{3} + L_{4})/(L_{1} + L_{2}) = 0.42\) (at the maximum brightness of the contact pair) which was not taken into account.

Pribulla et al. (2006) presented long-term spectroscopy (209 spectra taken between 1998 and 2005) of the system obtained at David Dunlap Observatory (DDO) which enabled to disentangle all three orbits in this tight-multiple system: the contact binary with the \( P_{12} = 0.4775 \) d period is orbiting another binary with \( P_{34} = 7.93 \) d in a relatively tight, 355-d, mutual orbit. Using preliminary inclination angle of the contact binary orbit found by photometric analysis, \( i_{12} = 80.1 \), the authors determined masses of all components and

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Key words: binaries: eclipsing – binaries: spectroscopic.
found that the orbits of the binaries are not coplanar. Light-time effect (LITE) with peak-to-peak range of $2 \Delta = 0.0074$ d was predicted to be seen in the minima of the contact pair as a result of the mutual revolution of the binaries. The LITE was found in published minima by Sánchez-Bajo, García-Melendo & Gómez-Forrellad (2007). The corresponding orbital parameters, $A = 0.0037(4)$ d, $P_{1234} = 353(2)$ d, $e = 0.5(2)$ and $\omega = 2.8(4)$ rad, are rather preliminary due to few available minima. The eccentricity corresponding to their orbital solution is much higher than predicted spectoscopically by Pribulla et al. (2006).

The spectral type of VW LMi was estimated as F5V by Pribulla et al. (2006), while observed Tycho-2 ($B - V$) = 0.21 and Two-Micron All-Sky Survey (2MASS) $J - K = 0.34$ colours correspond to F2V spectral type. Both determined spectral type and colours refer to the whole quadruple system.

VW LMi is the tightest quadruple system known (Tokovinin 2008). Also, it has the shortest period of the outer orbit within multiple systems harbouring contact binaries. The ratio of the outer orbital period and orbital period of the non-eclipsing pair is only about $P_{1234}/P_{14} = 44.5$, hence we can expect secular orbital changes on the time-scales as short as decades. The chances of resolving of components (binaries) by either speckle or long-baseline interferometry are rather meagre: the maximum angular separation of the components was estimated to be only about 10 mas (Pribulla et al. 2006). Astrometric observations of VW LMi do not indicate its multiplicity.

Goals of the present paper are as follows: (i) to present and analyse new photometric and spectroscopic observations, (ii) to perform simultaneous solution of LITE using both minima times of the contact binary and radial velocities (RVs) of the individual components, (iii) to assess possibility of the tidal disturbances of the inner orbits and resulting precession and (iv) to determine absolute parameters of all four components.

## 2 NEW OBSERVATIONS

### 2.1 Photoelectric and CCD photometry

To secure as many minima times as possible, photometry was performed at several observatories in Slovakia and Germany. Since the system was too bright for most of the instruments equipped with CCD cameras, photolenses were extensively used, and on larger telescopes the observations were mostly performed in the Johnson $B$ filter which enabled reasonable exposure times. The information on individual observatories and instruments used is given in Table 1; parameters of variable and comparison stars are comprehensively listed in Table 2.

Photoelectric photometry of VW LMi was obtained using 60-cm Cassegrain telescope in the G2 pavilion of the Astronomical Institute of the Slovak Academy of Sciences. VW LMi was observed in the Johnson $BV$ filters and with neutral filter (optical glass BK7, denoted in tables as $N$). $BV$ observations were transformed to the international photometric system. The magnitude differences with respect to the comparison star HD 95606 were corrected for the differential extinction using nightly or seasonal extinction coefficients. Since the angular distance of the comparison and variable star is only 5.65 arcmin, the differential extinction correction was rather negligible, and never exceeded 0.002 mag. Occasionally, observed check star, HD 95527, showed good stability of the comparison star, HD 95606.

Most of the CCD photometry was secured using 50 cm Newtonian telescope in the G1 pavilion of the Astronomical Institute of the Slovak Academy of Sciences. Practically all observations were taken through the Johnson $B$ filter, only on 2007 March 25 $B$ observations were transformed to the $UBVRI_c$ package.

| Obs. | Telescope | Detector | Filters |
|------|-----------|----------|---------|
| G1   | 508/2500  | SBIG ST10-MXE | $UBVRRI_c$ |
| G2   | 600/7500  | EM1 9789QB  | $UBVN$   |
| GSH  | 250/2250  | CTK1024   | $B$      |
| KO180| 60/180    | MEADE DSI Pro| $N$     |
| KO400| 80/400    | MEADE DSI Pro| $VN$    |
| KO   | 300/2400  | SBIG ST9-XE | $B$      |
| RO200| 100/200   | MEADE DSI Pro| $N$     |

Table 1. Overview of telescopes and instruments/detectors used to obtain photometry of VW LMi. Abbreviations of the observatories (Obs.): G1, G2 pavilions of the Stará Lesná Observatory, GSH – Grossschwäbhausen observing station of the Jena University, KO – Astronomical Observatory at Kolonica saddle (belongs to the Vihorlat Observatory), RO – Roztoky Observatory. Instruments using a photolens at KO and RO are named using its focal length.

Table 2. Parameters of the variable and comparison stars used. The proper motions and $(B - V) = 0.85$ ($B - V)_c$ colours were taken from the Tycho-2 Catalogue (Høg et al. 2000), parallaxes from the Hipparcos Catalogue (ESA 1997), infrared colours, $(J - K)$, from the 2MASS (Skrutskie et al. 2006). RV and rotational velocity ($v \sin i$) and spectral types were determined from the DDO spectroscopy; for VW LMi, the listed RV corresponds to the systemic velocity of the whole quadruple.

|                | VW LMi | cmp1       | cmp3       |
|----------------|--------|------------|------------|
| $\mu_\alpha \cos \delta$ (mas yr$^{-1}$) | 12.7(11) | 10.7(11)   | -9.8(12)   |
| $\mu_\delta$ (mas yr$^{-1}$)           | -5.0(12) | -3.4(11)   | -67.9(12)  |
| RV (km s$^{-1}$)                        | -0.15   | 7.80       | 11.10      |
| $v \sin i$ (km s$^{-1}$)               | <13     | -32        | <13        |
| $\pi$ (mas)                             | 8.04(0.90) | 7.07(1.25) | -         |
| $(B - V)$                                | 0.340(21) | 0.39(28)   | 0.57(34)   |
| $(J - K)$                                | 0.208(30) | 0.266(31)  | 0.30(35)   |
| sp. type                                 | F3–5V   | F5V        | G0V        |

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### 2.2 Medium dispersion spectroscopy

New spectroscopic observations were obtained using the slit spectrograph in the Cassegrain focus of 1.88-m telescope of DDO. The
observations were performed between 2007 March and very beginning of 2008 July, when DDO ceased to operate. The spectra were taken in a window of about 240 Å around the Mg I triplet (5167, 5173 and 5184 Å) with an effective resolving power of R = 12 000–14 000. The diffraction grating with 2160 lines mm\(^{-1}\) was used with the sampling of 0.117 Å pixel\(^{-1}\). One-dimensional spectra were extracted by the usual procedures within the IRAF environment\(^2\) after the bias subtraction and the flat-field division. Cosmic-ray trails were removed using a program of Pych (2004).

All exposures were 900-s long and lead to signal-to-noise ratio of about 100–150. The observations were analysed using the technique of broadening functions, described in Rucinski (1992, 2002). For VW LMi, we used HD 222368 as the template (F7V, \(\sin i = 3\) km s\(^{-1}\)). This star provided the best match to the observed spectra – integral of broadening function (BF) was always 0.95–1.00.\(^3\) Similar to Pribulla et al. (2006), we first fitted simple multicomponent Gaussian model to the extracted BFs (see Fig. 1), then detached pair with slowly rotating components was subtracted. The wide features corresponding to the contact pair were subsequently modelled by the rotational profiles which effectively correspond to the approximation of the components of the contact binary by rotating limb-darkened spheres. Since shapes of the profiles strongly depend on the limb darkening, we fixed \(u = 0.53\) according to the tables of van Hamme (1993) appropriate for main-sequence F3V star at 5184 Å. RVs determined from the new spectra are given in Table 3. Several BFs extracted from observations taken close to conjunction of the contact binary did not allow to determine their RVs. In case of non-eclipsing binary, RVs of its components could be reliably determined from all new spectra.

### 3 MINIMA DETERMINATION

Most widespread approach to obtain instants of minima of eclipsing binaries is to use Kwee & van Woerden’s method (Kwee & van Woerden 1956). From our experience, the errors estimated using their formula (14) are often unrealistically small. The real uncertainties are very probably dominated by systematic errors. The principal problem in case of CCD photometry is scattered light which cannot be fully corrected by flat-fielding. This results in spurious shifts/trends in differential photometry in case that the field is not perfectly guided making times of minima systematically shifted.\(^4\) Our photometry could possibly be improved by using an algorithm based on principal component analysis proposed by Tamuz, Mazeh & Zucker (2005). Unfortunately, the frames were obtained at several observatories with different setups and even different orientation of...
the field. Systematic errors in minima positions were partially removed by fitting technique proposed below.

Since LC of the system appears to be very stable (we do not see any asymmetries or changes) fitting templates were prepared to obtain instant of conjunction (minimum) for any sufficiently long photometric sequence. Such a way, we made use not only of the minima but also of other LC segments. The template LCs were represented by symmetric trigonometric series of the 10th order. Even if the eclipsing pair is a contact binary, amplitude of its LC depends on the wavelength. Using CCD photometry of 2007 March 23, we see the following amplitudes $\Delta B = 0.46, \Delta V = 0.43, \Delta R_c = 0.41$ and $\Delta I_c = 0.38$. The differences in amplitude primarily result from wavelength-dependent limb darkening and light contribution of the third component (see Section 5). Due to the differences in filter transparencies and wavelength response of detectors, we had to form a template LC for each filter separately and the fitting LC was scaled to match the observations. We also noted small ($\approx 0.02$ mag) shifts of the LCs observed even with the same instrument. Sometimes even slight slopes of the LC were recorded. These shifts/slopes are probably caused by scattered light combined with different pointing of the telescope.

To obtain good fits of the observed LCs by templates $T(x)$, we formed the following fitting function:

$$F(x) = A + Bx + CT(x - D).$$

(1)

This allowed for shifting, scaling and 'slanting' of the template LC. Fixing of the parameters was judged according to the appearance of individual LCs. All new times of minima are listed in Table 4. The formal errors given are still much smaller than systematic errors. Times of 'minima' determined from sections of LC not containing minima were omitted from further analysis because of significantly higher errors.

The resulting (O–C) diagram including published minima times is shown in Fig. 2. The minima times of VW LMi can be found in Gomez-Forrellad et al. (2003), Dumitrescu (2003), Derman &

Figure 2. (O–C) diagram of VW LMi showing best covered interval since 2005. The (O–C) data were given with respect to the following ephemeris for the primary minimum: 245 2500.1510 + 0.477552E. The primary and secondary minima were plotted using the same symbols. The optimum fit corresponding to Table 5 is plotted.

Table 4. New times of minima of VW LMi determined by the template fitting to observed LCs. Observations in individual filters were treated separately. If both minima were observed in given night (indicated in column 'Type'), the instant given in the table refers to the first one. The standard errors of the last digit are given in parentheses.

| HJD 2400000+ | Filters | Observatories | Type | HJD 2400000+ | Fil. Observatories | Type | HJD 2400000+ | Filters | Observatories | Type |
|--------------|---------|---------------|------|--------------|-------------------|------|--------------|---------|---------------|------|
| 53461.45927(21) | B | G2 | I | 54063.65646(14) | B | G1 | I | 54245.35634(11) | B | G1 | II |
| 53461.45883(16) | V | G2 | II | 54066.52319(13) | B | G1 | I | 54415.61257(30) | V | KO | I |
| 53461.45969(20) | N | G2 | II | 54085.62425(21) | V | KO400 | II | 54469.57672(29) | B | G1 | I |
| 53465.51832(22) | B | G2 | II | 54088.49087(24) | B | G1 | I | 54469.57628(29) | V | G1 | I |
| 53465.51792(15) | V | G2 | II | 54095.65269(10) | B | G1 | I | 54469.57549(20) | N | KO180 | I |
| 53465.51843(22) | N | G2 | II | 54114.51541(08) | B | G1 | II | 54499.66040(07) | B | GSH | I |
| 53767.57388(15) | N | G2 | II | 54116.66409(07) | B | G1 | I | 54505.38874(26) | N | KO400 | I |
| 53791.44941(26) | B | G2 | I | 54117.61952(14) | N | KO400 | I | 54509.44938(43) | N | KO400 | II |
| 53791.44924(21) | V | G2 | I | 54148.65937(14) | B | G1 | I | 54512.52503(10) | B | GSH | I |
| 53791.45004(33) | N | G2 | II | 54148.65953(35) | V | KO400 | II | 54521.62540(08) | V | GSH | I |
| 53794.31433(08) | B | G1 | I | 54149.61531(13) | B | G1 | I | 54532.36983(15) | N | KO400 | I |
| 53797.41955(16) | B | G2 | I | 54162.50371(27) | V | KO400 | I | 54556.48581(26) | V | KO400 | I |
| 53802.43347(31) | B | G2 | II | 54167.28101(36) | V | KO400 | I | 54557.43985(19) | N | RO | I |
| 53802.43276(22) | V | G2 | I | 54172.53421(10) | B | G1 | I | 54571.28992(25) | N | RO | II |
| 53802.43260(24) | N | G2 | I | 54173.48896(12) | B | G1 | I | 54581.31655(14) | N | RO | II |
| 53814.37177(07) | B | G1 | I | 54173.48891(17) | V | KO400 | I | 54582.51234(24) | N | RO | II |
| 53815.32588(05) | B | G1 | I | 54175.39958(16) | V | KO400 | I | 54584.41972(65) | N | KO400 | II |
| 53815.32524(08) | N | G2 | I | 54185.42614(26) | B | G1 | I | 54584.42043(18) | N | RO | I |
| 53833.47072(07) | B | G1 | I | 54185.42681(32) | V | G1 | I | 54585.37523(15) | N | RO | II |
| 53845.40690(09) | B | G1 | I | 54185.42691(41) | R | G1 | I | 54586.32887(24) | B | GSH | I |
| 53850.42278(11) | B | G1 | I | 54185.42709(39) | I | G1 | I | 54588.47856(17) | B | GSH | I |
| 53867.37715(08) | B | G1 | I | 54191.39733(21) | V | KO400 | II | 54593.43939(18) | N | RO | II |
| 53894.55622(16) | B | G1 | I | 54199.48500(30) | V | KO400 | II | 54594.44843(18) | N | RO | I |
| 54026.64630(10) | B | G1 | II | 54191.39733(21) | V | KO400 | II | 54595.40379(19) | V | KO400 | I |
| 54027.60191(19) | B | G1 | I | 54195.45500(15) | V | KO400 | I | 54599.46132(19) | B | GSH | I |
| 54057.68914(14) | B | G2 | I | 54212.40823(10) | B | G1 | II | 54615.46100(25) | N | RO | II |
| 54059.59910(10) | B | G1 | II | 54213.36179(07) | B | G1 | II | 54616.41716(20) | N | RO | II |
Kalci (2003), Porowski (2005), Dworak (2005, 2006), Hubscher (2007), Nelson (2007) and there are four unpublished CCD times of minima observed by K. Nakajima$^5$ – HDJ 245 3461.9371(2), 245 3462.1586(2), 245 3886.0001(3) and 245 4603.9984(2). The residuals, from rather arbitrary ephemeris given in the figure, clearly show wave-like behaviour with 1-yr periodicity.

4 GLOBAL FIT OF THE DATA

Multiple data set fitting is rather a widespread technique nowadays. It is typical to combine RVs and visual orbits or RVs and interferometric visibilities of binary stars (e.g. Pourbaix 1999; Tango et al. 2006). Eclipsing binary modelling programs (see van Hamme & Wilson 2007) enable us to combine RV data LCs to determine third body parameters. The case of VW LMi is, however, special and unprecedented, requiring ad hoc approach.

Since our photometry was performed at several observatories, often without filter, we decided not to fit a global model to LCs together with RVs and to use only minima times to better characterize the outer orbit. Rigorous modelling of those data sets (four RV curves and times of minima) is quite complex since times of all RV observations should be properly corrected for the LITE caused by the mutual revolution of the binaries. This effect is minor in the non-eclipsing pair, where amplitude of LITE is about 0.004 d, which amounts to only about ±0.0005 in phase. In case of eclipsing pair, the amplitude of LITE is about 0.0037 d, and $P_{12} = 0.4775$ d make for ±0.0077 phase shifts which cannot fully be neglected. In fact, correcting observed times of RV measurements for the LITE significantly decreased global $\chi^2$. LITE is also manifested directly in observed times of minima. The informational contents of the minima is, unfortunately, very similar to having observed only RVs of the eclipsing pair. Integrals of RV curves are radial distances from the observer corresponding directly to the LITE through the finite speed of light. Both data sets are, however, nicely complementary: during the spectroscopic conjunction, when the RVs of the components are not measurable, we can observe minima giving the radial distance of the eclipsing binary in the outer orbit. Moreover, the precise minima times are easy to observe using a small telescope or photolense equipped with a cheap CCD camera. As we will see later, the relative orbit of mass centre of the contact binary is much better defined by the LITE than RVs. This is crucial to establish mass ratio of binaries, inclinations and masses of components.

In further description, we will use similar notation of parameters as in Pribulla et al. (2006): common parameters (orbital period, eccentricity, time of periastron passage and longitude of periastron) for orbits will be denoted by index ‘12’ (contact binary), ‘34’ (detached non-eclipsing binary) and ‘1234’ (mutual orbit). Semi-amplitudes of RV changes for the individual stars will be denoted by separate index ‘1’, ‘2’, ‘3’ or ‘4’ while semi-amplitudes of systemic velocity changes of both binaries as whole in the mutual orbit will be denoted as ‘12’ and ‘34’. Finally, systemic velocity of the mass centre of the whole quadruple as $V_0$. For RVs of components of contact binary, we can write

$$RV_i = V_0 + K_{12}[e_{12} \cos \omega_{12} + \cos(\nu_{1234} + \omega_{1234})]$$

$$+ (−1)^{i+1} K_{ij}[e_{ij} \cos \omega_{ij} + \cos(\nu_{ij} + \omega_{ij})],$$

where index $i = 1, 2$ denotes the component. For the detached binary, we similarly have

$$RV_i = V_0 - K_{1234}[e_{1234} \cos \omega_{1234} + \cos(\nu_{1234} + \omega_{1234})]$$

$$+ (−1)^{i+1} K_{ij}[e_{ij} \cos \omega_{ij} + \cos(\nu_{ij} + \omega_{ij})],$$

with $i = 3, 4$. True anomalies of inner orbits ($\nu_{12}, \nu_{34}$) have to be corrected for the LITE caused by the mutual revolution of binaries. If we accept the plane-parallel to the sky and intersecting mass centre of the quadruple system as the reference plane, then LITE seen in either of the binaries is

$$\Delta T_{ij} = \frac{K_{ij} P_{1234} (1 - e_{1234} \cos \nu_{1234})^2}{2\pi c} \sin(\nu_{1234} + \omega_{1234})$$

$$1 + e_{1234} \cos \nu_{1234},$$

where index $j$ is either ‘12’ or ‘34’. In case of the eclipsing pair, where the orbital eccentricity is zero, the predicted times of minima occurring at epoch $E$ would be

$$T \min = T_{12} + P_{12} E + Q E^2 + \Delta T_{12},$$

if true anomalies in the eclipsing binary orbit are counted from the upper conjunction of the more massive component (then $\omega_{12} = \pi/2$ with $e_{12} = 0$).

While amplitude of the RV changes of the systemic velocity of the detached pair around the common centre of gravity is rather reliable due to very well defined sharp peaks in BFs ($v \sin i < 12$ km s$^{-1}$ which is the limit given by the spectral resolution), the RVs of contact binary components are rather imprecise due to a ‘cross-talk’ with the second binary and wide profiles. This makes the size of the relative orbit of the contact binary (related to $K_{12}$) rather unreliable. The shape of the orbit is, fortunately, coupled through well-defined orbit of the detached pair. The size of the contact binary orbit is much better defined by LITE seen in the observed minima.

The best fits to the data (four RV curves and the LITE orbit) were performed using differential corrections method using analytic derivatives of the functions. The dependence of true anomaly on mean anomaly ($M$) and eccentricity was represented in derivatives by the truncated series up to the second degree in orbital eccentricity:

$$v \approx M + 2e \sin M + \frac{5}{4} e^2 \sin 2M.$$  

Since all orbits are being close to circular, this approximation was sufficient to make the optimization process quickly convergent. The sum of normalized $\chi^2$ was used as the merit function

$$S = \sum_{j=1}^{4} \sum_{n=1}^{n_j} (O_{nj} - C_{nj})^2 / \sigma_j^2 = \sum_{j=1}^{4} \chi_j^2,$$

where $j$ is the index of the data set, $n_j$ is number of observation for the given data set, $i$ is index of individual observation and $\sigma_j$ is average standard deviation of individual data point for the $j$th data set. Average uncertainty of a data point for individual data sets was estimated fitting separately times of minima and RVs. For minima times, we got $\sigma_{\text{min}} = 0.0008$ d (which is significantly more than typical error in Table 4), for RVs $\sigma_{\text{RV1}} = 11.3$ km s$^{-1}$, $\sigma_{\text{RV2}} = 13.1$ km s$^{-1}$, $\sigma_{\text{RV3}} = 2.6$ km s$^{-1}$ and $\sigma_{\text{RV4}} = 2.2$ km s$^{-1}$. The estimated average uncertainties were found to be realistic since normalized $\chi^2$ for individual data sets were close to unity. Observations within individual data sets were assigned the same errors (as given above) due to the fact that both times of minima and RVs are mostly affected by systematic errors which cannot reliably be determined. One minimum (245 0877 4658), published by Gomez-Forrellad et al. (2003), giving very large (O–C) (probably due to a typing error), was omitted from further analysis.

$^5$ See http://www.kusastro.kyoto-u.ac.jp/vsnet/.
Table 5. Simultaneous fit to RVs of both binaries and times of minima of the eclipsing pair. The designation of parameters is as follows: the index ‘12’ refers to the orbit of the contact pair, while the index ‘34’ refers to the orbit of the second, detached binary. Parameters of the mutual orbit of these binaries are indexed as ‘1234’. The orbit of the contact pair is assumed to be circular ($e_{12} = 0, \omega_{12} = \pi/2$). Masses of the systems are abbreviated as $M_{1234} = M_1 + M_2 + M_3 + M_4, M_{12} = M_1 + M_2$ and $M_{34} = M_3 + M_4$. Standard errors of parameters are given in parentheses.

| Parameter                  | Contact (eclipsing) pair – circular orbit | Detached (non-eclipsing) pair | Mutual wide orbit |
|----------------------------|------------------------------------------|------------------------------|------------------|
| $P_{12}$ (d)               | 0.477 551 06(3)                          | 7.9306(3)                    | 355.02(17)       |
| $Q$ (d)                    | 1.63(9) $10^{-10}$                       | 0.035(3)                     | 0.097(11)        |
| $T_{12}$ (HJD)             | 245 2500.1497(2)                         | 245 2274.54(11)              | 245 2274.54(11)  |
| $K_1$ (km s$^{-1}$)        | 105.81(1.0)                              | 63.99(23)                    | 21.61(49)        |
| $K_2$ (km s$^{-1}$)        | 250.2(1.2)                               | 65.53(27)                    | 23.22(33)        |
| $M_{12} \sin^2 i_{12} [M_\odot]$ | 2.25(23)                              | 1.785(11)                    | 3.32(10)         |
| $\chi^2$(RV1)              | 1.086                                    | 0.862                        | 0.851            |
| $\chi^2$(RV2)              | 1.058                                    |                              |                  |
| $\chi^2$(MIN)              | 1.086                                    |                              |                  |
| Mutual wide orbit          |                                          |                              |                  |
| $P_{1234}$ (d)             | 355.02(17)                               |                              |                  |
| $e_{1234}$                 | 0.097(11)                                |                              |                  |
| $\omega_{1234}$ (rad)      | 2.20(12)                                 |                              |                  |
| $T_{1234}$ (HJD)           | 245 3046.63(3)                           |                              |                  |
| $K_1$ (km s$^{-1}$)        | 21.61(49)                                |                              |                  |
| $K_2$ (km s$^{-1}$)        | 23.22(33)                                |                              |                  |
| $M_{1234} \sin^2 i_{1234} [M_\odot]$ | 3.32(10)                              |                              |                  |
| $V_0$ (km s$^{-1}$)        | 0.15(25)                                 |                              |                  |

Fitting theoretical curves to five data sets required 18 parameters. It is interesting to note that LITE of the eclipsing pair required only one additional parameter, $Q$, due to the fact that the orbital period of the contact binary was found to be continuously increasing. Since orbital eccentricity of the detached binary was found to be only $e_{34} = 0.03$, we also considered a circular orbit. This, however, leads to a substantially worse fit to the data. Resulting parameters are given in Table 5. Corresponding fits are shown in Figs 2 and 3.

Unfortunately, the orbital period of the mutual orbit is close to 1 yr. The system can be observed for minima from the beginning of November till the beginning of June. The observing interval to get spectrum just before dawn and just after twilight is about a month longer. Therefore, to cover the whole outer orbit, the system would have to be monitored for at least 12–15 yr (for ground-based observations). Until then, parameters depending on the overall shape of the RV curve (all except orbital period) cannot be reliably determined. This affects the reliable determination of mass ratio of the binaries $M_{34}/M_{12} = K_{12}/K_{34}$ and projected total mass $(M_1 + M_2 + M_3 + M_4) \sin^2 i_{1234}$.

### 5 LIGHT-CURVE SOLUTION

The eclipsing pair revolves in rather tight orbit around another binary which results in phase shifts of about ±0.008, which cannot be neglected as seen in long-term modelling of RVs (see Section 4). Therefore, we used photometry from a short interval compared to mutual, 355-d orbit. To determine photometric elements of the eclipsing pair, we used $BV$ photoelectric LCs obtained on 2005 March 31 and April 4 at the Stará Lesná observatory giving full coverage of the phases in relatively short time compared to the mutual orbital period (about 1.2 per cent). The orbital

Figure 3. RVs of all four components and their best fits assuming hierarchic quadruple model. Phases of the measurements in inner orbits were corrected for LITE in the outer orbit. Longitude of the periastron of the detached pair is assumed to be constant. Top and centre panels show RVs of the contact and detached pairs, respectively, after correction for the revolution in the outer 355-d orbit. The bottom panel displays velocities of individual components corrected for motion in inner orbits – reflecting mass-centre revolution (observations of the secondary component of the contact binary were not plotted for clarity). Because the outer orbit period is close to 1 yr, the seasonal observing interval only slowly moved in the orbital phases between 1998 and 2008 and all phases have not been covered yet (bottom). The best fits corresponding to the global solution (Table 5) are plotted.
The major deficiency of the fits is an insufficient interpretation of the primary minimum, which is sharper than predicted suggesting either higher mass ratio, surface inhomogeneities or deficiency of the Roche model for this system. It cannot be excluded that the observed LC is affected by some night-to-night changes resulting in systematically wrong parameters and fits.

6 Long-term Evolution of Orbits

The ratio of the orbital periods of the outer orbit and the orbit of the non-eclipsing pair is \( P_{1234}/P_{34} = 44.76 \). Corresponding period ratio in the case of the contact binary is as large as \( P_{1234}/P_{12} = 743 \). Therefore, visible precession of the orbit can be detected (on human time-scales) only in the case of the detached pair.

According to Soderhjelm (1975), the nodal precession period caused by the perturbations in the close triple is

\[
P_{\text{node}} = \frac{4}{3} \left( \frac{M_{1234}}{M_{34}} \right) \frac{P_{1234}^2}{P_{34}} (1 - e_{1234}^2)^{3/2} \frac{L_{1234}}{(L_{34} + L_{1234}) \cos j},
\]

where \( L_{12} \) is the angular momentum in the detached binary orbit and \( L_{1234} \) is (vector) the sum of angular momenta in the detached binary orbit and the outer orbit. In our case, we can neglect the term in the last parentheses since \( (L_{34} + L_{1234})/L_{1234} \sim 1.08 \) and orbits are close to being coplanar; hence, \( \cos j \sim 1.00 \). Then, we get \( P_{\text{node}} \approx 120 \text{ yr} \). Since the detached pair on \( P_{34} = 7.93 \text{-d orbit} \) is non-eclipsing binary (at least at present), we can detect possible precession of the orbit only from the RVs. Precession of the orbital plane should result in changes of the amplitude of RVs and apsidal motion.

The possibility of long-term changes of the 7.93-d orbit was assessed by dividing RV observations into individual observing seasons. Since neither the LITE in the eclipsing pair nor RVs of its components are affected, simultaneous fits in separate time intervals used all measurements for the eclipsing pair with the parameters of the contact binary orbit and outer orbit fixed to those of the global solution.

Five solutions given in Table 6 can be described/interpreted as follows: (i) eccentricity is stable – solutions are reliable and small eccentricity is not spurious; (ii) semi-amplitudes of RVs remain stable within the errors – mutual orbit and orbit of the detached pair are very probably close to coplanar; (iii) there is definite apsidal motion. The coplanarity of the orbits means that the orbit of the non-eclipsing binary very probably does not change its inclination angle, and we cannot expect the appearance of the eclipses in this binary in future (see Mayer 2005). The period of the apsidal motion can roughly be estimated from longitude of periastron in 1998 and in 2007/2008 season as about 80 yr. Further observations are, however, needed to precisely determine the rate of the apsidal advance and its quantitative interpretation in terms of the tidal distortion, relativistic and gravitational perturbation effects.

Table 6. Long-term evolution of the non-eclipsing binary orbit. Parameters of contact binary orbit and wide mutual orbit were adopted from the global solution in Table 5. Standard error of the last digit is given in parentheses.

| Parameter          | 1997  | 1999–2000 | 2002  | 2004–05 | 2007–08 |
|--------------------|-------|-----------|-------|---------|---------|
| HJD (240 0000+)    | 50852–50960 | 51261–51673 | 52277–52391 | 53060–53836 | 53823–54650 |
| No of points       | 40    | 19        | 73    | 71       | 36       |
| e_{34}             | 0.032(6) | 0.030(6) | 0.032(5) | 0.03(4) | 0.039(4) |
| \( \omega_{34} \)  | 1.43(19) | 1.81(12) | 2.04(15) | 2.17(14) | 2.18(9)  |
| \( K_{1} \) (km s\(^{-1}\)) | 63.69(37) | 62.72(27) | 65.00(39) | 63.72(28) | 63.59(34) |
| \( K_{2} \) (km s\(^{-1}\)) | 65.67(42) | 66.47(32) | 65.51(43) | 65.22(33) | 65.79(39) |
7 POSSIBLE ASTROMETRIC AND DIRECT DETECTION

VW LMi (HIP 54003) was astrometrically observed during the Hipparcos mission. No positional disturbance or acceleration terms in the proper motion were found and there is no double/multiple systems annex flag (H59 field) in spite of the fact that VW LMi is the member of multiple system with orbital period much shorter than the time span of the Hipparcos astrometry. The apparent simplicity of VW LMi is reflected in small formal error of its annual parallax, 0.90 mas.

There are probably two reasons for negative detection in the Hipparcos astrometry: (i) the orbital period is close to 1 yr and orbital wobble mimics parallactic motion and changes apparent annual parallax; (ii) Hipparcos astrometry refers to the photocentre of VW LMi which substantially decreases the astrometric wobble. Ecliptical latitude of VW LMi is about $\beta = 22:325$. The inclination angle of the outer orbit is $i_{1234} = 64.1 \pm 4.2$ (see Section 8). Then, $\sin \beta \approx \cos i_{1234}$, which means that parallactic ellipse and relative orbit of the photocentre would be ellipse of similar shape (with practically the same period of apparent motion). The chances of disentangling the effects and solving the problem depend on the longitude of the ascending node.

Outer-orbit parameters (Table 5) provide projected major axis as $a_{1234} \sin i_{1234} = 1.456 \pm 0.019$ au. Neglecting small eccentricity of the orbit, the maximum angular separation of the components is $\tau a_{1234}$. Assuming $i_{1234} = 64.1 \pm 4.2$ (Section 8), the maximum angular separation is just about 13 mas.

The full amplitude of the photocentre motion can be found assuming $(L_1 + L_4)/(L_1 + L_2) = 0.42$ and $a_{13}/a_{12} = 1.09$ and $\alpha = 13$ mas as

$$a_{\text{phot}} = \alpha \frac{L_{34} a_{34}}{L_{14} + L_{12}}. \quad (9)$$

For VW LMi, we get $a_{\text{phot}} = 5.0$ mas. This is comparable to the typical residuals seen in the Hipparcos astrometric solutions. Some improvement of the astrometric solution can be obtained using proper motion as known parameter from ground-based observations. The solving of the orbit might be complicated by variability-induced motion caused by light changes of the eclipsing pair. Therefore, VW LMi is rather a difficult target for astrometric modelling. With expected maximum separation of the components of about 13 mas and with a total brightness of only $V_{\text{max}} = 8.08$ ($K = 7.20$), it would not be an easy target for interferometric observations.

8 ABSOLUTE PARAMETERS OF THE COMPONENTS

Parameters of the components can be determined by a simple procedure used in Pribulla et al. (2006). Using new determination of the inclination angle $i = 79.0$ and the projected total mass of the contact pair $(M_1 + M_2) \sin^2 i_{12} = 2.231 \pm 0.023 M_\odot$, we obtain $(M_1 + M_2) = 2.359 \pm 0.024 M_\odot$. The outer, 355-d orbit defines the mass ratio for the two pairs, $(M_1 + M_2)/(M_3 + M_4) = 1.074 \pm 0.025$. Therefore, the true (not the projected) mass of the second spectroscopic binary is $(M_3 + M_4) = 2.196 \pm 0.073 M_\odot$. Using the projected mass $(M_3 + M_4) \sin i_{34} = 1.785 \pm 0.011 M_\odot$, we estimate the inclination of the orbit of the second pair to be about 68.9$^\circ \pm 1.5$. The outer, 355-d orbit is even less inclined to the sky:

$$(M_1 + M_2 + M_3 + M_4) = 4.56 \pm 0.07 M_\odot$$

with the projected total mass of only 3.32 $\pm$ 0.10 $M_\odot$, we obtain $i_{1234} = 64.1 \pm 4.2$. In the view of large uncertainties, the planes of the detached pair and mutual wide orbit could still be coplanar.

Individual masses of components are then $M_1 = 1.66 M_\odot$, $M_2 = 0.70 M_\odot$, $M_3 = 1.11 M_\odot$ and $M_4 = 1.09 M_\odot$. Masses of the components are rather inconsistent with the fact that all four components show practically the same spectral type. Assuming $L \sim M^{3.45}$ and that all four components produce energy as main-sequence stars result in $L_{14}/L_{12} = 0.49$. In the region of Mg i triplet, we arrived at rather compatible value. The only remaining problem is the fact that the third light as found from photometry is virtually the same in the B and V passbands indicating the same $T_{\text{eff}}$ for both binaries which is incompatible with their masses. The second binary should have components of about GOV spectral type according to their masses.

Due to the fact that we have spectra just in short wavelength region, the individual component spectra cannot be reliably disentangled. The issue could be resolved either by echelle spectroscopy and/or by multicolour photometry.

9 CONCLUSIONS

Tightest known quadruple system VW LMi is really unique. It definitely deserves additional observations and analysis. The study of this system could bring light on (i) the evolution and origin of binary stars in multiple systems of stars, (ii) tidal interaction of third body and its influence on the Roche geometry and (iii) long-term evolution of orbits in tight multiple systems. The system is useful for further analysis since all four components are visible in the spectrum. The determination of the individual component’s parameters, such as $T_{\text{eff}}$, log g, metallicity, could benefit from spectra disentangling (see Hadrava 1995). The absolute parameters of all components which had to originate at practically the same time could be used to determine the evolutionary status and the history of the system.

The study of VW LMi is, however, complicated by (i) the outer orbital period being close to 1 yr which complicates its phase coverage by Earth-bound observer, (ii) very small angular separation of the components making direct resolving of the mutual wide orbit and reliable determination of $i_{1234}$ difficult (which would definitely improve the determination of individual masses), (iii) fast rotation of the components of the contact binary making RV measurements unsure and rectification to real continuum impossible (due to the line blanketing), (iv) eclipses and Roche geometry in the contact pair making usual assumption of the spectra disentangling techniques not valid (line profiles of individual components cannot change with the orbital revolution).

It is also interesting to note that VW LMi and HD 95606 show very similar proper motion, parallax and RVs (see Table 2) – the stars definitely form a loosely bound pair and all components very probably evolved from the same protostellar cloud (see Oswalt et al. 2007).

The orbit of the detached pair in VW LMi with 7.93-d period is almost circular. This is the case of another two quadruples detected by the DDO observations, TZ Boo and V2610 Oph (DDO series No. XIV; Pribulla et al., in preparation). That means that either it evolved with such orbit or it was circularized by the gravitational interaction with the contact binary. Detected apsidal motion in VW LMi requires further observing to reliably determine apsidal period. Investigation of the observed eccentricities of the second binaries and their predicted synchronization time-scales in quadruple systems.
Contact binaries could shed light on the age and evolutionary status of contact binaries (Rucinski, private communication).

Better characterization of VW LMi calls for long-term monitoring to cover the whole 355-d orbital cycle. Especially, times of minima should be obtained free of any systematic effects. The understanding of the system would greatly benefit from visual orbit obtained by means of long-baseline interferometry. Multicolour photometry and/or echelle spectroscopy could lead to reliable determination of component’s temperatures and luminosities.

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