The Eclipsing Triple System U Ophiuchi Revisited

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Abstract

The absolute dimensions of the mid B-type eclipsing triple system U Oph were determined through a fully consistent analysis, taking into account both the exceptionally short period ($\sim$21.2 yr) apsidal motion and both the third light and the light-time orbit around a tertiary star ($P_3\sim$38.4 yr). A new ephemeris was determined with the exact method proposed by Lacy and 353 – 229 primary, 124 secondary – times of minimum (selected out of 482 – 312 primary and 170 secondary – times from the literature, many referring to the same minimum). A modified version of the Wilson-Devinney (WD) code, adapted to treat systems with apsidal motion and/or light-time orbit effect with arbitrary atmosphere models for the stellar fluxes, was used to simultaneously analyze the 4 light ($uvby$Hβ system at the Strömgren Automatic Telescope at ESO, La Silla, Chile) and the radial velocity curves (Coudé spectrograph at the ESO 1.5 m telescope), with both the least-squares and the SIMPLEX minimization methods.

The derived absolute dimensions of U Oph and those of other 3 systems, whose components have similar masses, namely V760 Sco, MU Cas and DI Her, are used to control and compare the evolutionary models of the Padova Group and the ones by Claret, with the astrophysical quantities $\log \boldsymbol{g}$, $\log \boldsymbol{T}_{\mathbf{eff}}$, $\log \boldsymbol{M}$ and the derived luminosities.

1. Introduction

Empirical stellar masses, radii, and luminosities are fundamental test data for stellar models, provided they are determined to high precision ($\leq$2%) and without significant systematic error (Andersen 1991). While a substantial body of such data exists for stars below $\sim$4M$_\odot$, the number of good determinations for higher-mass stars remains small. We have therefore undertaken to redetermine the absolute dimensions of the detached, mid-B eclipsing binary U Ophiuchi from new spectroscopic and photometric observations.

The most recent comprehensive study of U Oph is by Holmgren et al. (1991), who summarised its previous observational history and redetermined the masses from new Reticon spectra, using cross-correlation techniques. They also reanalysed the then existing light curves. Later papers have added new photometry and polarimetry (Eritsian et al. 1998) and times of minimum (Wolf et al. 2002), but not materially improved our knowledge of the properties of the stars in U Oph.

2. Observational data

34 coudé spectrograms of U Oph were obtained on fine-grain, high-contrast IIIa-J plates during 1980-1986 with the ESO 1.5 m telescope and coudé spectrograph at La Silla, Chile, at dispersions of 20 and 12.4 Å/mm. Mean exposure times were $\sim$10 min, with observing and measuring procedures as described by Andersen & Nordström (1983), who also discuss the zero-point and accuracy of rv observations with this instrument.

The star eclipsed at primary eclipse has stronger and broader lines than those of the secondary star (see also Popper 1981, Fig. 5). The spectral type is $\sim$B4, with lines broadened by rotation. The interstellar Ca II H and K lines are weak, but measurable. Fig. 1 shows the measured radial velocities and our computed orbits for U Oph.

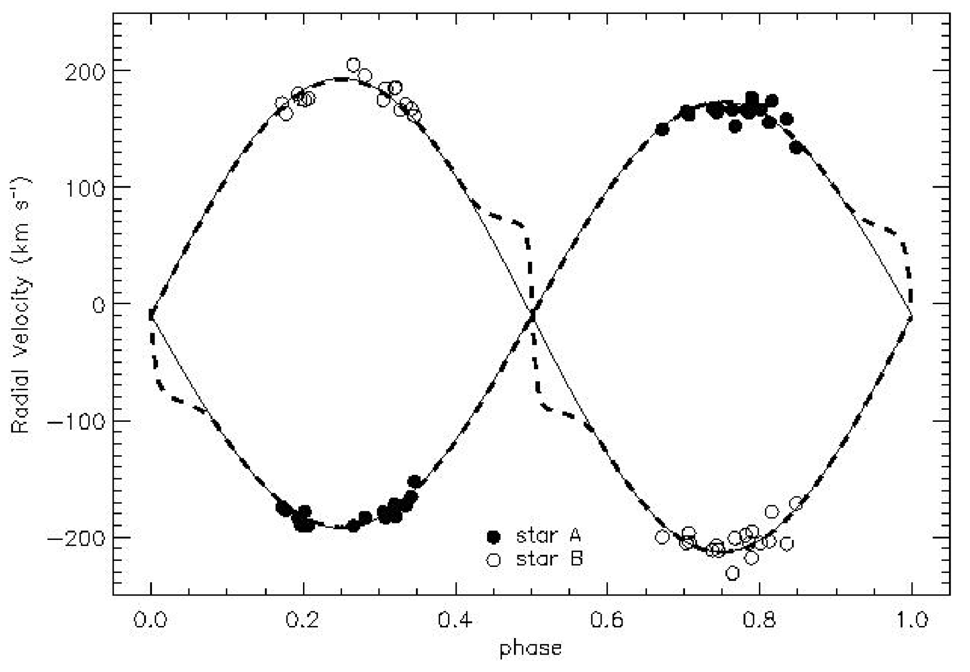

Figure 1. Observed radial velocities and computed orbits for U Oph, for the circular (solid lines) as well as the eccentric (dashed) solution. The only differences are due to eclipse effects, included in the WD model but not affecting the observed phases.

Using the 6-channel spectrograph-photometer and photon counting system of the 0.5-m SAT telescope at ESO, La Silla, Chile (Nielsen el al. 1987), we observed U Oph in the Strömgren $uvby$Hβ system during 4 nights in 1992 (JA), 3 in 1993, and 18 nights in 1994 (LPRV). A circular diaphragm of $17''$ diameter was used to exclude the visual companion. Three comparison stars, HR 6367, HR 6353 and SAO 122251 ($\boldsymbol{d}<3^\circ$ of U Oph) were observed alternately with U Oph.

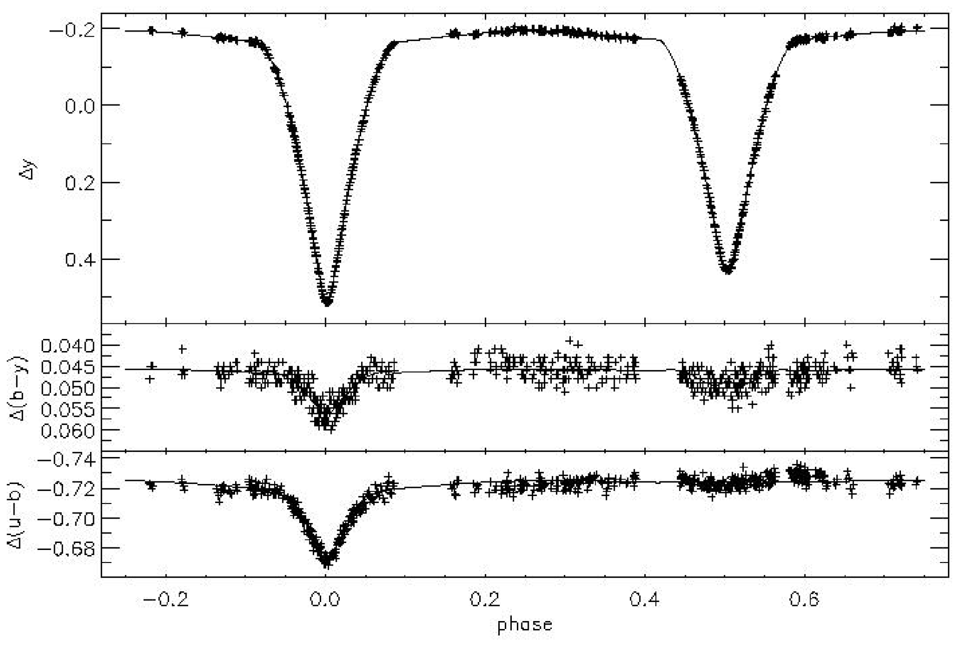

Figure 2. $\boldsymbol{y}$, $\boldsymbol{b}-\boldsymbol{y}$, and $\boldsymbol{u}-\boldsymbol{b}$ magnitude and colour differences (instrumental system) between U Oph and HR 6367, 645 points in each colour, 114 from 1992, 203 from 1993 and 328 from 1994. The lines show the computed light curve for the mean periastron angle of 13°.6.

Fig. 2 shows our observed and theoretical light curves. We solved (with our improved version of the WD model) simultaneously the radial velocity curves of both components and the 4 light curves, taking fully account to both the apsidal motion and the light-time orbit, through the ephemeris derived in Sect. 3. Moreover, the model parameters (eg., $\log \boldsymbol{g}$, limb-darkening coefficients) and the orbital parameters (eccentricity, periastron longitude, etc.) were derived iteratively and always fully consistent in all the solution steps.

3. New ephemeris

The ephemeris for eclipsing systems with apsidal motion is usually approximated by a series expansion of the solution to the transcendental equations involved (Giménez & Bastero 1995, Giménez & Garcia-Pelayo 1986). An exact method was proposed by Lacy (1992), based on a Levenberg-Marquardt optimisation technique. For U Oph, we added the light-time effect to Lacy's method, using the equations given by Irwin (1952, 1959), which refer to the geometric centre of the orbit, not to the centre of mass of the system. After a careful study of literature data, we selected 353 (229 primary, 124 secondary) times of minimum and obtained the ephemeris shown in Fig. 3 and in Table 1, where the mass funcion of the triple system, $f(\mathcal{M})$, is

$$\boldsymbol{f}(\mathcal{M}) = \frac{(\mathcal{M}_3 \sin \boldsymbol{i}_3)^3}{(\mathcal{M}_1+\mathcal{M}_2+\mathcal{M}_3)^2} = \frac{(\boldsymbol{a}_{12,3} \sin \boldsymbol{i}_3)^3}{\boldsymbol{P}_3^2}. \quad (1)$$

Table 1 Final parameters for the apsidal motion and light-time orbit of U Oph. The light-time amplitude, $\boldsymbol{A}$, is $\boldsymbol{a}_{12,3}\sin \boldsymbol{i}_3/\boldsymbol{c}$, $\boldsymbol{a}_{12,3}$ is the semi-major orbital axis of the eclipsing pair around the centre of mass of the total system, $\boldsymbol{i}_3$ the inclination of this orbit, and $\boldsymbol{c}$ the speed of light. $\boldsymbol{U}$, $\boldsymbol{P}_{\mathbf{sid,ecl}}$, and $\boldsymbol{P}_{\mathbf{anom,ecl}}$ are the apsidal motion, sidereal, and anomalistic periods of the eclipsing system, respectively, and $\boldsymbol{f}(\mathcal{M})$ the mass function of the light-time orbit. Standard deviations (weighted residuals) from the fit for primary, secondary, and all eclipses are given. The weigths were proportional to (obs. error)$^{-2}$. The standard deviation for unweighted residuals is 0$^{\mathrm{d}}$.0048 (6.9 min) for all eclipses.

Apsidal Motion		Light-Time orbit	
parameter	final value	parameter	final value
$P_{\mathrm{anom,ecl}}$	1$^{\mathrm{d}}$.6777150 ±25	P_3 (year)	38.350 ±79
e	0.003049 ±75	e_3	0.279 ±13
ω_0, at T_0	−26°.926 ±38	ω_3	122°.2 ±3°.0
ω_1 (°/cycle)	0.0791902 ±91	A (day)	0.010384 ±57
T_0 (HJD)	2 440 484.68577 ±89	$T_{\mathrm{periastron}}$ (HJD)	2 435 169. ±112.
U (year)	20.88 ±14	$f(\mathcal{M})$	0.003951 ±27
$P_{\mathrm{sid,ecl}}$	1$^{\mathrm{d}}$.677345899 ±10	σ_{pri} (229 points)	0$^{\mathrm{d}}$.00072
σ_{all} (353 points)	0$^{\mathrm{d}}$.00062	σ_{sec} (124 points)	0$^{\mathrm{d}}$.00050

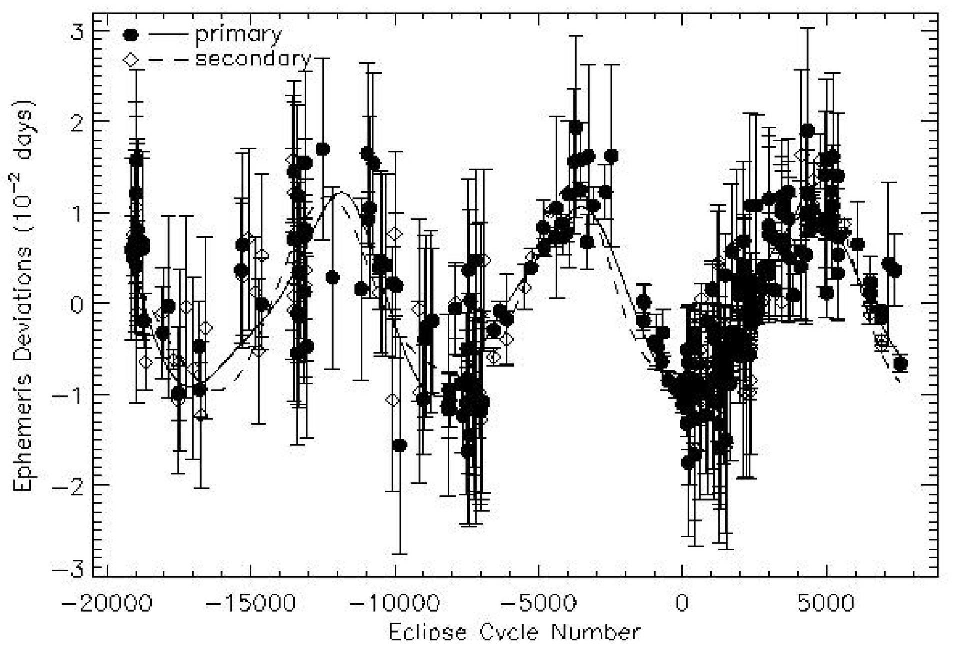

Figure 3. O−C curve from a linear ephemeris for U Oph. Computations for primary (solid line) and secondary minima (dashed) with the method by Lacy (1992), modified to include the light-time effect using the parameters of Table 1. Vertical bars show the errors of each point, used to weight the data during the optimisation.

4. Absolute dimensions

Table 2 shows the absolute dimensions and the physical parameters we derive for U Oph. Errors $<$1.7% and 1.5% for the masses and $<$0.57% and 1.1% for the radii of primary and secondary eclipsing components, respectively, together with the effective temperature determination, yielded to a distance determination with an error $<$2.3% (much better but in agreement with Hipparcos value, probably disturbed by U Oph being a hierarquical triple system). The chemical diversity of these young nearby systems (all $<$ 100 Myr old) presents a challenge to models of galactic chemical evolution.

5. Results

In Fig. 4 we show the eclipsing components of U Oph and of 3 other systems with components of similar masses, together with the theoretical models of Claret (2004), in $\log \boldsymbol{g}$ versus both log($\boldsymbol{M}$/M$_\odot$) and $\log \boldsymbol{T}_{\mathbf{eff}}$ diagrams. We plot the isochrones which best represent the secondaries of all 4 systems for $\boldsymbol{Z}$=0.01 and 0.02.

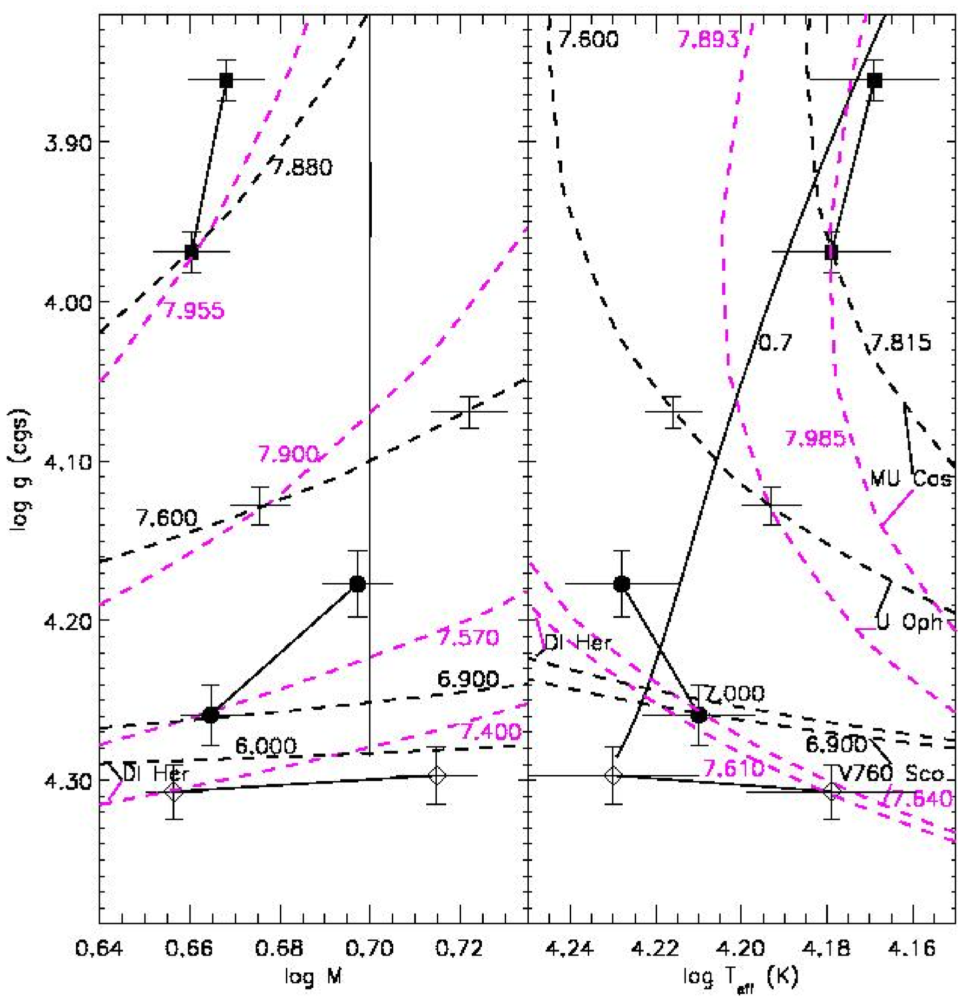

Figure 4. Theoretical diagrams of $\log \boldsymbol{g}$ versus $\log \boldsymbol{M}$ (left) and versus $\log \boldsymbol{T}_{\mathbf{eff}}$ (right) from Claret 2004 models (thick lines) for $\boldsymbol{Y}$=0.28, $\boldsymbol{Z}$=0.02. The eclipsing components of U Oph (Table 2) are represented by error bars, while those of DI Her (Popper 1982), V760 Sco (Andersen et al. 1983), MU Cas (Lacy et at. 2004) are identified by the ●, ◇ and ■ symbols, respectively, being connected with thin solid lines. The evolutionary track for $\log \boldsymbol{M}$=0.7, $\boldsymbol{Z}$=0.02 is shown in both panels as solid lines, while the isochrones which best match the secondaries of the 4 systems are shown as dashed lines, black for $\boldsymbol{Z}$=0.02 and magenta for $\boldsymbol{Z}$=0.01 (same colors for the corresponding log(age,yr)).

Assuming coevality, the theoretical isochrones should fit both components of a binary system. While U Oph is very well represented by the $\boldsymbol{Z}$=0.02 models at an log(age,yr)=7.60 (Fig. 4), MU Cas and V760 Sco seem to require models with $\boldsymbol{Z}<$0.01 to have isochrones with the right slope to reproduce their components. DI Her is clearly the youngest and models with $\boldsymbol{Z}\sim$0.02 seem to best reproduce the components.

U Oph is significantly evolved but still on the lower half of the MS phase, with Claret (2004) models giving a log(age,yr)=7.60±0.02, slightly younger as compared with his former models (Claret 1995, 1997) and with Padova P-93 (7.63±0.02, Girardi et al. 1996 and references therein) and P-99 (7.68±0.02, Girardi et al. 2000) models ($\boldsymbol{X}$=0.70, $\boldsymbol{Z}$=0.02).

The $\log \bar{\boldsymbol{k}}_{\mathbf{2,obs}}$ for U Oph, corrected for relativistic contribution, is in very good agreement with the models. MU Cas has a theoretical apsidal motion period of (17.5±2.6) 10^3 yr, too long to be detected with the available span of times of minima. DI Her presents the problem of having a theoretical relativistic term much larger than the observed apsidal motion (Claret 1998).

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Table 2 Physical parameters for U Oph.

	A (Primary)	B (Secondary)
Absolute dimension:		
Mass (M$_\odot$)	5.273 ± 0.091	4.738 ± 0.072
$\log M$	0.7220 ± 0.0084	0.6756 ± 0.0066
Radius (R$_\odot$)	3.483 ± 0.020	3.109 ± 0.034
$\log R$	0.5419 ± 0.0025	0.4927 ± 0.0047
$\log g$ (c.g.s.)	4.0682 ± 0.0098	4.128 ± 0.012
V$_{\mathrm{synchr}}$ (km s^{-1})	108.7 ± 0.6	96.6 ± 1.0
$\omega/\omega_{\mathrm{orb}}$	1.16 ± 0.14	0.99 ± 0.16
Photometric data:		
$\log T_{\mathrm{e}}$(K)	4.2159 ± 0.0066	4.1928 ± 0.0070
$\log L/L_\odot$	2.900 ± 0.027	2.709 ± 0.029
M_{bol}	−2.499 ± 0.067	−2.022 ± 0.073
M_{V}	−0.913 ± 0.067	−0.566 ± 0.073
$L_{\mathrm{B}}/L_{\mathrm{A}}$	0.727±0.092	
Distance (pc)	216±5	

Acknowledgments. We gratefully acknowledge financial support from the Brazilian agencies CAPES, CNPq, FAPEMIG and FUNDEP.