

value at a given iteration to the succeeding one. The initial estimate is  $E_0 = 141^\circ.370493$ , which iterates to  $E_1 = 154^\circ.443789$ , for a change of  $13^\circ.073296 = 47063.9$  arcseconds and a change in the logarithm of 4.673; this is plotted at the location of iteration 1. Arcsecond-level convergence is achieved on going from the 10th to the 11th iteration, and micro-arcsecond convergence on going from the 11th to the 12th; at this point the procedure is running up against the limitation of the computer's accuracy of about 1 part in  $10^{15}$ . At convergence,  $E = 178^\circ.082209\dots$ . The author would be happy to share the spreadsheet with any interested reader.

In conclusion, solving Kepler's equation need not be daunting or mysterious. Sometimes, a simple approach to an old problem can yield perfectly respectable results.

### References

- (1) [https://en.wikipedia.org/wiki/Kepler%27s\\_equation](https://en.wikipedia.org/wiki/Kepler%27s_equation)
- (2) See, for example, A. W. Odell and R. H. Gooding, 'Procedures for Solving Kepler's Equation' in *Cel. Mech.*, **38**(4), 307, 1986.
- (3) E. D. Charles & J. B. Tatum, 'The Convergence of Raphson Iteration with Kepler's Equation' in *Cel. Mech.*, **69**(4), 357, 1998.

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## REDISCUSSION OF ECLIPSING BINARIES. PAPER 27: THE TOTALLY-ECLIPSING SYSTEM UZ DRACONIS

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UZ Dra is a detached and totally-eclipsing binary containing two late-F stars in a circular orbit of period 3.261 d. It has been observed by the *Transiting Exoplanet Survey Satellite* in 41 sectors, yielding a total of 664 809 high-quality flux measurements. We model these data and published radial velocities to determine the physical properties of the system to high precision. The masses of the stars are  $1.291 \pm 0.012 M_\odot$  and  $1.193 \pm 0.009 M_\odot$ , and their radii are  $1.278 \pm 0.004 R_\odot$  and  $1.122 \pm 0.003 R_\odot$ . The high precision of the radius measurements is made possible by the (previously unrecorded) total eclipses and the extraordinary amount of data available. The light-curves show spot modulation at the orbital period, and both stars rotate synchronously. Our determination of the distance to the system,  $185.7 \pm 2.4$  pc, agrees very well with the parallax distance of  $185.39 \pm 0.39$  pc from *Gaia* DR3. The properties of the system are consistent with theoretical predictions for an age of  $600 \pm 200$  Myr and a slightly super-solar metallicity.

Introduction

Detached eclipsing binaries (dEBs) are our primary source of direct measurements of the basic physical properties of normal stars<sup>1–3</sup> because their masses and radii can be determined from light and radial-velocity (RV) curves using only geometry and celestial mechanics. Within this class of object, those that have total eclipses are the most valuable because the times of contact during eclipse enable the radii of the stars to be measured to the highest precision<sup>4,5</sup>.

In this work we present an analysis of the late-F-type dEB UZ Dra, which shows total eclipses and a circular orbit. This analysis is part of our project to redetermine systematically the properties of known dEBs using new space-based light-curves<sup>6</sup> and published spectroscopic results<sup>7</sup>.

UZ Draconis

The variability of UZ Dra (Table I) was announced by Pickering<sup>14</sup>, following its discovery by Henrietta Leavitt in photographic patrol plates from Harvard. It was awarded the designation ‘HV 2972’, its range of variation was given as 0.7 mag, and its variability type was described using the phrase “appear[s] to be of the Algol type”.

Dugan & Wright<sup>15</sup> found an orbital period of 1.63 d, half the true period because the secondary eclipses were mistaken as primaries. Lacy *et al.*<sup>16</sup> (hereafter L89) state that a doubled period of 3.26 d was adopted by Tsesevitch<sup>17</sup>. This was confirmed and refined by Koch & Koch<sup>18</sup> using brightness measurements from 35-mm film. Gülmen *et al.*<sup>19</sup> collected all times of minimum up to the year 1986.

Imbert<sup>20</sup> presented the first spectroscopic orbits of UZ Dra, obtaining precise velocity amplitudes ( $K_A$  and  $K_B$ ) from 40 RVs per star measured with the *Coravel* cross-correlation spectrometer<sup>21</sup>. Lacy<sup>22</sup> found it to be a double-lined binary system.

TABLE I

*Basic information on UZ Draconis. The BV magnitudes are each the mean of 115 individual measurements<sup>8</sup> distributed approximately randomly in orbital phase. The JHK<sub>s</sub> magnitudes are from 2MASS<sup>9</sup> and were obtained at an orbital phase of 0.296.*

Property	Value	Reference
Right ascension (J2000)	19 <sup>h</sup> 25 <sup>m</sup> 55 <sup>s</sup> .054	10
Declination (J2000)	+68°56′07″.16	10
<i>Tycho</i> designation	TYC 4444-1595-1	8
<i>Gaia</i> DR3 designation	2261658485914111744	11
<i>Gaia</i> DR3 parallax (mas)	5.3941 ± 0.0115	11
<i>TESS</i> Input Catalog designation	TIC 48356677	12
<i>B</i> magnitude	10.08 ± 0.03	8
<i>V</i> magnitude	9.60 ± 0.02	8
<i>J</i> magnitude	8.616 ± 0.020	9
<i>H</i> magnitude	8.426 ± 0.020	9
<i>K<sub>s</sub></i> magnitude	8.372 ± 0.019	9
Spectral type	F6 + F8	13

L89 presented the first — and so far only — detailed study of UZ Dra. This was based on 35 nights of photoelectric *BV* photometry from Ege University (ref. 19) and 16 high-resolution spectra from two telescopes. Six spectra were obtained with the coude spectrograph and Reticon detector on the 2.7-m telescope at McDonald Observatory, and the remaining ten with the coude spectrograph and a CCD detector on the 2.1-m telescope at Kitt Peak National Observatory. From analysis of this material they measured the masses and radii of the component stars to precisions of 1.5–2.3%. They also obtained projected rotational velocities of  $20 \pm 1$  km s<sup>-1</sup> and  $19 \pm 1$  km s<sup>-1</sup>, both consistent with synchronous rotation in the assumed circular orbit, spectral types of F7 and G0, and a spectroscopic light ratio of  $0.73 \pm 0.03$  from the 6400 Å-Fe I and 6439.1-Å Ca I lines.

Since that work, Popper<sup>13</sup> has indicated spectral types of F6 and F8 for the two stars, and Graczyk *et al.*<sup>23</sup> have presented updated masses, radii, and temperatures of the stars. A large number of times of eclipse are also available; UZ Dra is a popular target for amateur astronomers.

### Photometric observations

UZ Dra has been observed by the NASA *Transiting Exoplanet Survey Satellite*<sup>24</sup> (*TESS*) in an extraordinary 41 sectors to date, due to its placement within the satellite's northern continuous viewing zone. In all cases data are available at 120-s cadence from the SPOC (Science Processing Center<sup>25</sup>). Lower-cadence observations are also available for all sectors but were not used here. The data were downloaded from the NASA Mikulski Archive for Space Telescopes (MAST\*) using the LIGHTKURVE package<sup>26</sup>.

We used the simple aperture photometry (SAP) light-curves from the SPOC data-reduction pipeline<sup>25</sup> for our analysis, and rejected low-quality data using the LIGHTKURVE quality flag “hard”. A total of 664 809 data points survived this cut, coming from *TESS* sectors 14 to 86. These data were converted into differential magnitudes and the median magnitude was subtracted from each sector for convenience.

Fig. 1 shows the light-curve from sector 84, chosen because of its high duty cycle; the remaining sectors are similar so are not plotted. One feature of the light-curve immediately apparent on closer inspection is that the eclipses are total. This seems not to have been noticed previously, which led L89 to use a spectroscopic light ratio to constrain the ratio of the radii of the stars measured from the eclipse shapes.

We queried the *Gaia* DR3 database<sup>†</sup> for all sources within 2 arcmin of UZ Dra. Of the sources returned — 53 excluding the dEB itself — all are at least 5 mag fainter in the *Gaia*  $G_{\text{RP}}$  band so should contribute little additional flux to the *TESS* light-curves.

### Light-curve analysis

The components of UZ Dra are well-separated so we modelled the *TESS* light-curves using version 44 of the JKTEBOP<sup>‡</sup> code<sup>27,28</sup>. We defined star A to be the star eclipsed at the primary (deeper) minimum, and star B to be its

\*<https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html>

†<https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/355/gaiadr3>

‡<http://www.astro.keele.ac.uk/jkt/codes/jktebop.html>

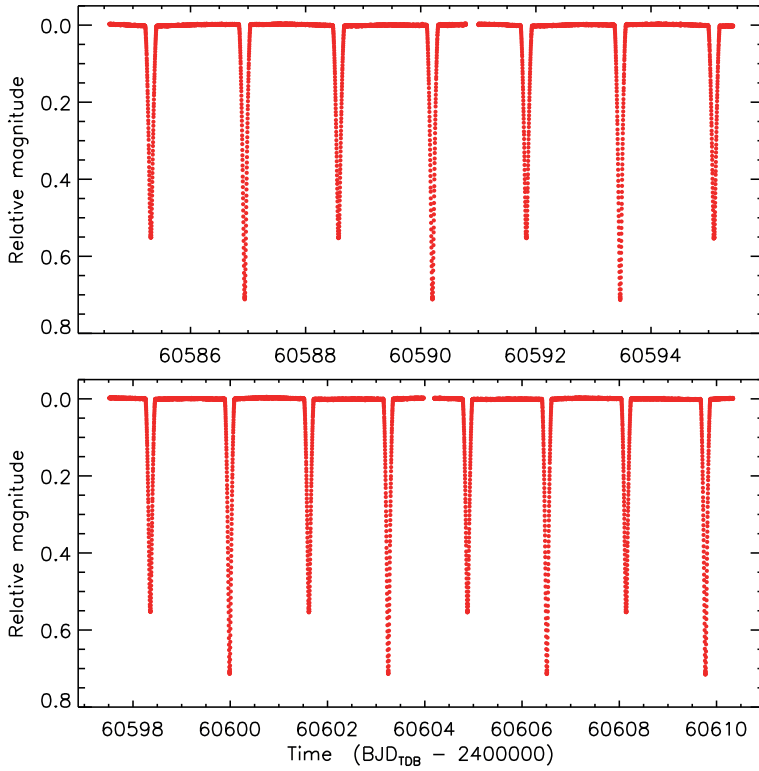


FIG. 1

*TESS* sector-84 photometry of UZ Dra. The flux measurements have been converted to magnitude units after which the median was subtracted. The other sectors used in this work are very similar so are not plotted.

companion. Star A is hotter, larger, and more massive than star B.

The exceptional amount of data necessitated the analysis of each sector separately, which in turn required the automation of some tasks usually performed manually.

For each *TESS* sector we chose a primary eclipse close to the midpoint of the light-curve, rejected data with large scatter or close to partially-observed eclipses, and defined normalization polynomials to remove slow variations in the measured brightness of the system. A total of 608 575 data points were retained for analysis.

We then fitted the data from each *TESS* sector using JKTEBOP with the following fitted parameters: the fractional radii of the stars ( $r_A$  and  $r_B$ ) taken as the sum ( $r_A + r_B$ ) and ratio ( $k = r_B/r_A$ ), the central-surface-brightness ratio ( $\mathcal{J}$ ), third light ( $L_3$ ), orbital inclination ( $i$ ), orbital period ( $P$ ), and a reference time of primary minimum ( $T_0$ ). A circular orbit provides a good fit to all data so we assumed an eccentricity of zero; experiments with a fitted eccentricity

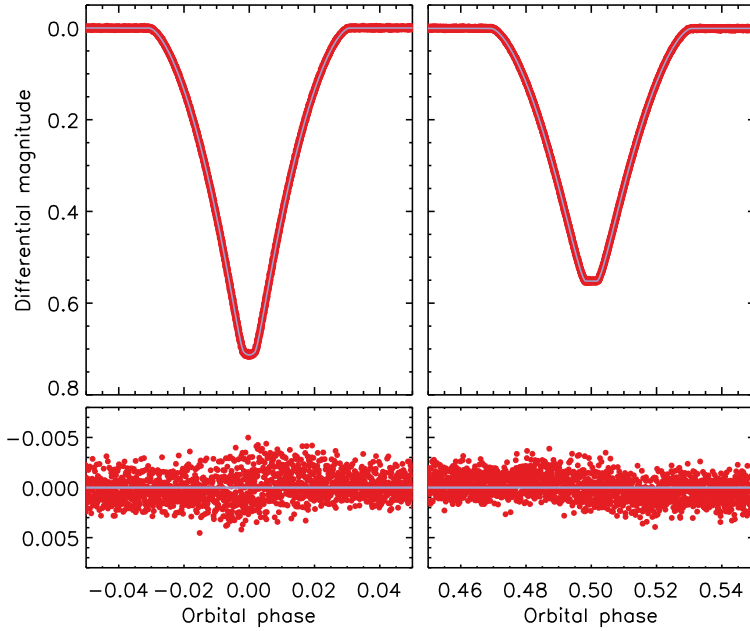


FIG. 2

JKTEBOP best fit to the light-curves of UZ Dra from *TESS* sector 84 for the primary eclipse (left panels) and secondary eclipse (right panels). The data are shown as filled red circles and the best fit as a light-blue solid line. The residuals are shown on an enlarged scale in the lower panels.

caused changes in the measured fractional radii at approximately the 0.004% level. Limb darkening (LD) was accounted for using the power-2 law<sup>29–31</sup>, the linear coefficients ( $c$ ) were fitted, and the non-linear coefficients ( $\alpha$ ) were fixed at theoretical values<sup>32,33</sup>. The measurement errors were scaled to force a reduced  $\chi^2$  of  $\chi^2_\nu = 1.0$ . An example fit is shown in Fig. 2.

Table II lists the results of this analysis. For each parameter we took the final value and error bar to be the unweighted mean and standard deviation of the values from the individual sectors. We did not convert the standard deviation into a standard error because it is already at the limit to which we trust our photometric model for some parameters — in particular the fractional radii in JKTEBOP have been shown to be reliable to 0.1% precision<sup>5</sup> but not beyond.

We also calculated uncertainties using Monte Carlo simulations\* to provide error bars on all parameters. The Monte Carlo error bars are smaller than the standard deviation of the values by factors of 1–3 in the case of UZ Dra, likely due to the influence of spot modulation on the light-curve fits (see below).

Fig. 3 shows the variation of the most important photometric parameters with time, with one data point for each *TESS* sector. The small variation in the parameters is striking, confirming the reliability of the solutions for UZ Dra.

\*Running 500 Monte Carlo simulations for each light-curve required a total of 40 hours of computing time on a standard consumer-grade laptop.

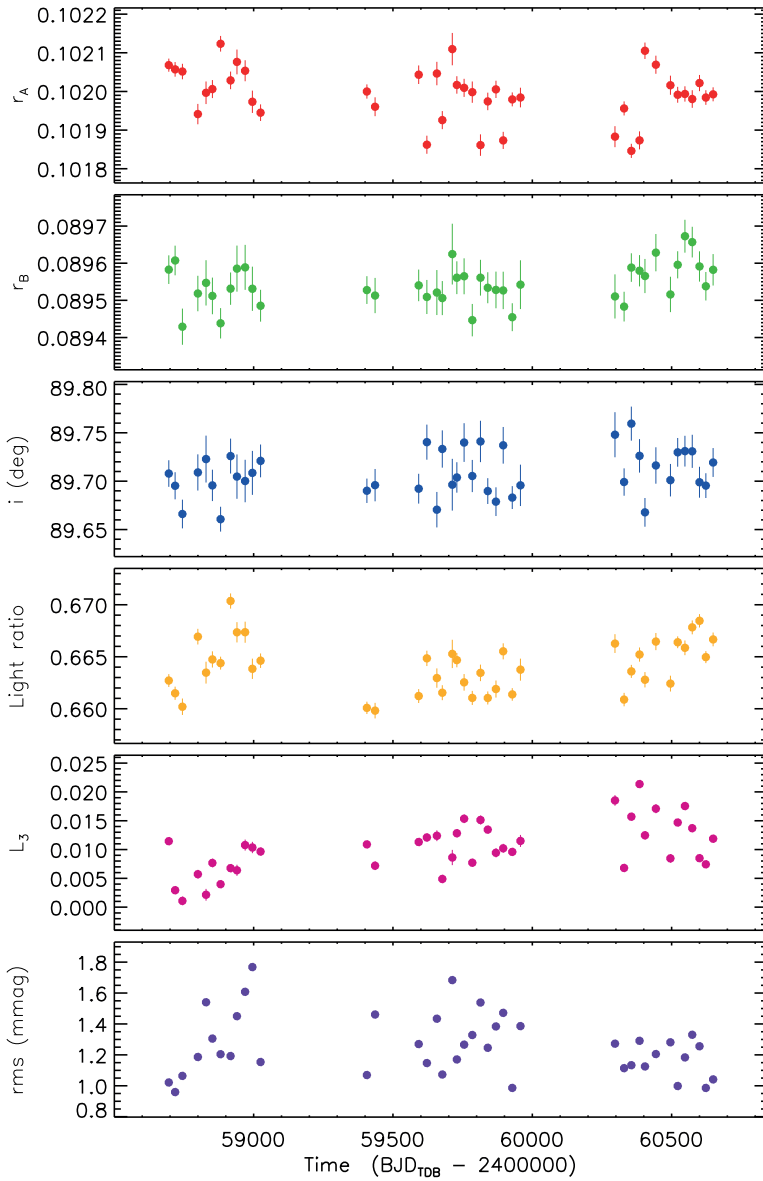


FIG. 3

The best fit to selected photometric parameters of UZ Dra from *TESS* sectors 1 to 86. The times used in the plot are those presented in the next section. The error bars are from Monte Carlo simulations.

TABLE II

*Photometric parameters of UZ Dra measured using JKTEBOP from the light-curves from all 41 TESS sectors. The error bars are standard deviations (not standard errors) of the results for individual sectors.*

Parameter	Value
<i>Fitted parameters:</i>	
Orbital inclination ( $^{\circ}$ )	$89.708 \pm 0.024$
Sum of the fractional radii	$0.19154 \pm 0.00009$
Ratio of the radii	$0.87795 \pm 0.00076$
Central-surface-brightness ratio	$0.8582 \pm 0.0051$
Third light	$0.0104 \pm 0.0045$
LD coefficient $c_A$	$0.611 \pm 0.013$
LD coefficient $c_B$	$0.0568 \pm 0.025$
LD coefficient $\alpha_A$	0.4984 (fixed)
LD coefficient $\alpha_B$	0.5237 (fixed)
<i>Derived parameters:</i>	
Fractional radius of star A	$0.10199 \pm 0.00007$
Fractional radius of star B	$0.08955 \pm 0.00006$
Light ratio $\ell_B/\ell_A$	$0.6641 \pm 0.0025$

No significant slow variations with time are apparent. The Monte Carlo error bars underestimate the true uncertainty in the light ratio, an issue which may be caused by the spot modulation in the light-curve. The third light is not expected to be the same between sectors due to the different pixel position of UZ Dra and pixel mask used each time the telescope is re-orientated.

### *Orbital ephemeris*

Our photometric analysis above yielded a measurement of the mean time of primary eclipse for each *TESS* sector. We fitted a linear ephemeris to these times, obtaining

$$\text{Min I} = \text{BJD}_{\text{TDB}} 2459677.038365(4) + 3.261303037(20)E \quad (1)$$

in the barycentric rest frame, where  $E$  is the number of cycles since the reference time of minimum and the bracketed quantities indicate the uncertainty in the final digit of the previous number. The scatter around the best fit is larger than the error bars suggest, with  $\chi^2_{\nu} = 25.4$ , likely due to the weak spot activity visible outside eclipse in most *TESS* sectors. The uncertainties in the ephemeris have been multiplied by  $\sqrt{\chi^2_{\nu}}$  to account for this. The individual timings are given in Table III.

The deep eclipses combined with the high quality of the available data yield a very precise ephemeris: the r.m.s. scatter around the best fit is only 2.2 s, and the period is measured to within  $\pm 2$  ms. We extrapolated it back to the ephemeris given by Gülmen *et al.*<sup>19</sup> (HJD 2446227.4238) and found that it matched to within 18 s, after correcting the HJD to BJD and converting to the TDB timescale<sup>34</sup>. Based on this and our timings, we see no evidence for nonlinearity in the orbital ephemeris. A more robust approach would require assembling the many published times of minimum for UZ Dra, which is beyond the scope of the current work.

TABLE III

*Times of mid-eclipse for UZ Dra and their residuals versus the fitted ephemeris.*

<i>Orbital cycle</i>	<i>Eclipse time (BJD<sub>TDB</sub>)</i>	<i>Uncertainty (d)</i>	<i>Residual (d)</i>	<i>TESS sector</i>
-301.0	2458695.386152	0.000004	0.000001	14
-294.0	2458718.215246	0.000005	-0.000026	15
-286.0	2458744.305680	0.000006	-0.000016	16
-269.0	2458799.747840	0.000006	-0.000008	18
-260.0	2458829.099615	0.000006	0.000040	19
-253.0	2458851.928689	0.000006	-0.000007	20
-244.0	2458881.280400	0.000005	0.000024	21
-233.0	2458917.154773	0.000005	0.000016	22
-226.0	2458939.983865	0.000007	0.000013	23
-217.0	2458969.335652	0.000006	0.000046	24
-209.0	2458995.426050	0.000007	0.000020	25
-200.0	2459024.777740	0.000005	0.000017	26
-83.0	2459406.350163	0.000004	0.000050	40
-74.0	2459435.701982	0.000005	0.000042	41
-26.0	2459592.244467	0.000005	0.000019	47
-17.0	2459621.596224	0.000005	0.000011	48
-6.0	2459657.470594	0.000007	0.000048	49
0.0	2459677.038369	0.000005	-0.000004	50
11.0	2459712.912675	0.000011	0.000023	51
16.0	2459729.219231	0.000005	0.000018	52
24.0	2459755.309623	0.000006	-0.000014	53
33.0	2459784.661343	0.000005	0.000022	54
42.0	2459814.013130	0.000006	0.000038	55
50.0	2459840.103558	0.000004	-0.000042	56
59.0	2459869.455257	0.000005	-0.000013	57
67.0	2459895.545631	0.000005	-0.000037	58
77.0	2459928.158697	0.000004	-0.000001	59
86.0	2459957.510395	0.000008	-0.000031	60
190.0	2460296.685987	0.000007	-0.000045	73
200.0	2460329.298995	0.000004	-0.000023	74
208.0	2460355.389387	0.000004	-0.000009	75
217.0	2460384.741110	0.000005	-0.000014	76
223.0	2460404.308962	0.000005	-0.000020	77
235.0	2460443.444577	0.000005	-0.000001	78
251.0	2460495.625437	0.000005	-0.000010	80
259.0	2460521.715823	0.000004	-0.000028	81
267.0	2460547.806279	0.000004	-0.000004	82
275.0	2460573.896693	0.000005	-0.000007	83
283.0	2460599.987162	0.000005	-0.000038	84
290.0	2460622.816217	0.000004	-0.000028	85
298.0	2460648.906647	0.000005	-0.000022	86

*Radial-velocity analysis*

Two prior spectroscopic studies of UZ Dra exist: that by Imbert<sup>20</sup> and L89. The former obtained and analysed 40 RVs for star A and 39 for star B, using the *Coravel* spectrometer. The latter found that Imbert's results were slightly but significantly discrepant with their own measurements, based on 16 high-resolution spectra. This claimed disagreement is sufficient justification for us to revisit the RVs, both sets of which are tabulated in the respective papers.

We first digitized the Imbert RVs then performed two fits with JKTEBOP, one with the same systemic velocity for both stars ( $V_\gamma$ ) and one with a systemic velocity per star ( $V_{\gamma A}$  and  $V_{\gamma B}$ ). In both cases we fitted for  $K_A$ ,  $K_B$ , and an

TABLE IV

*Spectroscopic orbits for UZ Dra from the literature and from the current work. In each case two sets of orbits are given: where the systemic velocity for the two stars are forced to be the same or allowed to differ. The adopted result is based on all RVs and different systemic velocities. All velocities are given in  $\text{km s}^{-1}$ .*

Source	$K_A$	$K_B$	$V_\gamma$	$V_{\gamma,A}$	$V_{\gamma,B}$	$\sigma_A$	$\sigma_B$
Imbert <sup>20</sup>	$92.73 \pm 0.46$	$100.51 \pm 0.46$	$-15.29 \pm 0.25$			1.6	2.5
L89	$94.3 \pm 0.5$	$102.6 \pm 0.7$		$-15.6 \pm 0.4$	$-16.8 \pm 0.6$	1.4	2.0
This work (Imbert RVs)	$92.87 \pm 0.34$	$100.50 \pm 0.54$	$-15.45 \pm 0.22$			1.63	2.57
This work (Imbert RVs)	$92.87 \pm 0.36$	$100.52 \pm 0.55$		$-15.71 \pm 0.26$	$-14.80 \pm 0.40$	1.61	2.48
This work (L89 RVs)	$93.96 \pm 0.46$	$102.05 \pm 0.64$	$-15.99 \pm 0.31$			1.30	1.97
This work (L89 RVs)	$94.02 \pm 0.48$	$102.55 \pm 0.68$		$-15.64 \pm 0.37$	$-16.73 \pm 0.56$	1.28	1.87
This work (all RVs)	$93.43 \pm 0.28$	$101.13 \pm 0.43$	$-15.69 \pm 0.20$			1.61	2.55
This work (all RVs, adopted)	$93.40 \pm 0.30$	$101.03 \pm 0.44$		$-15.84 \pm 0.21$	$-15.33 \pm 0.34$	1.60	2.50

offset from our ephemeris above (which turns out to be negligible), and assumed a circular orbit. All error bars were obtained using 1000 Monte Carlo simulations<sup>35</sup>; the error bars in the systemic velocities do not account for any systematic bias due to transformation onto a standard system. The two solutions are very similar (Table IV), and confirm the numbers presented by Imbert<sup>20</sup>.

We then undertook the same analysis for the RVs from L89. An identical picture emerged: a good agreement between our two solutions and the values given by L89. The phase offset was also negligible, a relevant point because the time-stamps of the RVs are tabulated to only three decimal places (a precision of 86 s) in L89. We therefore confirmed the small but significant discrepancy between the two sets of measurements.

Faced with this choice, L89 opted to use only their own RVs on the basis that previous work by these authors had given results in good agreement with independent measurements for several dEBs. We have used RVs from Claud Lacy several times in the current series of papers: for ZZ UMa<sup>36,37</sup>, IT Cas<sup>38,39</sup>, IQ Per<sup>40,41</sup>, and MU Cas<sup>42,43</sup>. Similarly, we have in the past been happy to adopt RVs from Imbert for AN Cam<sup>44,45</sup> and ZZ UMa<sup>46,37</sup>; the two sources agreed well in the case of ZZ UMa.

We have therefore chosen to adopt spectroscopic orbits from the combined RVs for the remainder of our analysis. Neither source gives uncertainties for their RVs, so we specified uncertainties that give  $\chi^2_\nu = 1.0$  for each of the four data sets (two per star). Our adopted fit has separate systemic velocities for the two stars, is shown in Fig. 4, and its parameters are given in Table IV. It is, unsurprisingly, intermediate between the spectroscopic orbits from Imbert<sup>20</sup> and L89.

#### *Physical properties and distance to UZ Dra*

We calculated the physical properties of UZ Dra using the JKTEBDDIM code<sup>48</sup> with the photometric properties from Table II, and the  $K_A$  and  $K_B$  from the previous section. The orbital period was corrected to the rest frame of the system using a systemic velocity of  $-15.5 \text{ km s}^{-1}$ . The masses are measured to 0.9% precision, and the radii to 0.3%. The radii agree to within approximately  $1\sigma$  with the measurements from L89, but the masses are slightly lower due to the choices made in the RV analysis. We adopted the effective temperatures of

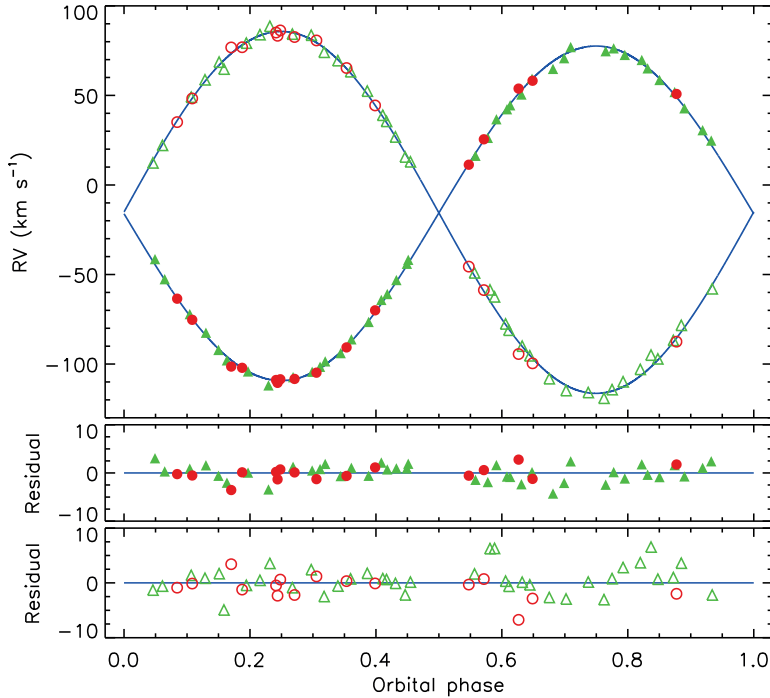


FIG. 4

RVs of UZ Dra compared to the best fit from JKTEBOP (solid blue lines). The RVs for star A are shown with filled symbols, and for star B with open symbols. The residuals are given in the lower panels separately for the two components. RVs from Imbert<sup>20</sup> are shown with green triangles, and those from L89 with dark-red circles.

the stars of  $6450 \pm 120$  K and  $6170 \pm 120$  K, from Graczyk *et al.*<sup>23</sup>. These are significantly higher than the  $6200 \pm 120$  and  $5985 \pm 110$  K given by L89 (see below for justification). For both sets of temperatures, their ratio is in good agreement with the central-surface-brightness ratio in Table II.

The synchronous rotational velocities in Table V are consistent with the projected rotational velocities measured by L89. Inspection of the residuals of the JKTEBOP fits shows that the spot modulation occurs on the orbital period of the system (see next section). We conclude that the system is tidally circularized and rotationally synchronized. There is no evidence for pulsations in the available data.

We determined the distance to UZ Dra using the  $BV$  magnitudes from *Tycho*<sup>8</sup> catalogue and  $JHK_s$  magnitudes from 2MASS<sup>9</sup> given in Table I. We used the surface-brightness calibrations from Kervella *et al.*<sup>49</sup> and found that an interstellar reddening of  $E(B - V) = 0.02 \pm 0.01$  mag was needed to bring the  $BV$ -based distance measurements into agreement with those from  $JHK_s$ . The best distance estimate is  $185.7 \pm 2.4$  pc, which is in excellent agreement with the

TABLE V

*Physical properties of UZ Dra defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 47).*

Parameter	Star A	Star B
Mass ratio $M_B/M_A$	0.9244 ± 0.0050	
Semi-major axis of relative orbit ( $R_\odot^N$ )	12.533 ± 0.0034	
Mass ( $M_\odot^N$ )	1.291 ± 0.012	1.193 ± 0.009
Radius ( $R_\odot^N$ )	1.2783 ± 0.0036	1.1224 ± 0.0032
Surface gravity (log[cgs])	4.3356 ± 0.0020	4.4145 ± 0.0015
Density ( $\rho_\odot$ )	0.6178 ± 0.0020	0.8438 ± 0.0029
Synchronous rotational velocity (km s <sup>-1</sup> )	19.830 ± 0.056	17.411 ± 0.049
Effective temperature (K)	6450 ± 120	6170 ± 120
Luminosity log( $L/L_\odot^N$ )	0.406 ± 0.032	0.216 ± 0.033
$M_{\text{bol}}$ (mag)	3.724 ± 0.081	4.200 ± 0.085
Interstellar reddening $E(B-V)$ (mag)	0.02 ± 0.01	
Distance (pc)	185.7 ± 2.4	

185.39 ± 0.39 pc from the *Gaia* DR3 parallax<sup>10</sup>. In contrast, the temperatures from L89 give a shorter distance and need a slightly negative interstellar reddening to equalize the optical and IR distances.

We compared the measured masses, radii, and temperatures of the stars to theoretical predictions from the PARSEC 1.2 evolutionary models<sup>50</sup>. The best match occurs for an age of 600 ± 200 Myr and a slightly super-solar metal abundance of  $Z = 0.020$ . Thus UZ Dra is a relatively young dEB.

#### Stellar activity

We obtained a spectrum of the Ca II *H* and *K* lines of UZ Dra to search for evidence of emission caused by chromospheric activity, with the *Intermediate Dispersion Spectrograph* (IDS) at the Cassegrain focus of the *Isaac Newton Telescope* (INT). A single observation with an exposure time of 500 s was obtained on the night of 2022/06/07 in excellent weather conditions. We used the 235-mm camera, H2400B grating, EEV10 CCD, and a 1-arcsec slit and obtained a resolution of approximately 0.05 nm. A central wavelength of 4050 Å yielded a spectrum covering 373–438 nm at a reciprocal dispersion of 0.023 nm px<sup>-1</sup>. The data were reduced using a pipeline currently being written by the author<sup>53</sup>, which performs bias subtraction, division by a flat-field from a tungsten lamp, aperture extraction, and wavelength calibration using copper-argon and copper-neon arc lamp spectra.

The spectrum (Fig. 5) was obtained at orbital phase 0.887, when the RV difference of the two stars was 126 km s<sup>-1</sup> (0.17 nm). When compared to a composite synthetic spectrum without chromospheric activity<sup>51,52</sup>, the infilling of the *H* and *K* lines is clear. The velocity difference of the two stars is resolved and both show chromospheric emission, most obviously in the *K* line at 393.4 nm.

The *TESS* light-curves show brightness modulations due to starspot activity, visualized in Fig. 6. It can be seen that the variations are on a period consistent with the orbital period of the system, which in the previous section was interpreted as an indicator of rotational synchronization. The variations evolve on a time-scale of roughly two to three times the orbital period and have an amplitude of up to 0.006 mag.

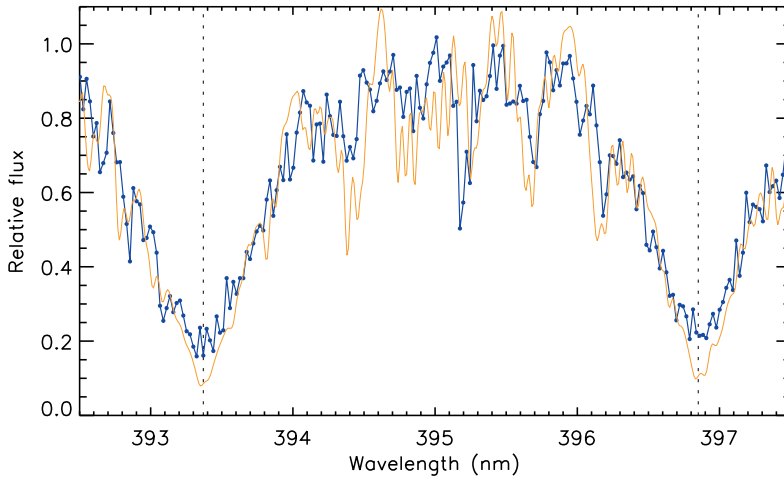


FIG. 5

Comparison between the observed spectrum of UZ Dra and a synthetic spectrum around the Ca II *H* and *K* lines. The observed spectrum has been shifted to zero velocity and normalized to approximately unit flux (blue line with points). The synthetic spectrum is for  $T_{\text{eff}} = 6450$  K,  $\log g = 4.3$ , and solar metallicity from the BT-Settl model atmospheres<sup>51,52</sup> (orange line). A composite synthetic spectrum has been made by duplicating and shifting the original one to the velocities of the two components of UZ Dra then adding them using the light ratio from Table II.

### Summary and conclusions

UZ Dra is a dEB containing two late-F stars in a circular orbit with a period of 3.261 d. The most interesting features are total eclipses and a plethora of photometry from *TESS*, which together allow the radii of the stars to be obtained to very high precision. The light-curves also show starspot modulation on the orbital period, indicating the stars are tidally synchronized. We see no evidence for pulsations, orbital eccentricity, or changes in the orbital period.

Two sets of RVs have been published for UZ Dra, and they lead to slightly different measurements for the masses of the components. We are not aware of a reason to prefer one set over the other, so instead combined them to obtain spectroscopic orbits intermediate between the two sets. The uncertainties in  $K_A$  and  $K_B$  dominate those in both the mass and radius measurements. *Gaia* Data Release 4 (DR4\*) is expected to provide extensive new RVs and thus a casting vote over which set of RVs to use (if either).

The photometric properties of UZ Dra are now extremely well-determined, although the spectroscopic orbits are not. New spectroscopic observations would be useful in determining the photospheric temperatures and chemical abundances of the component stars. The duration of totality is approximately 17 minutes, so a carefully-scheduled observation at secondary eclipse could record the spectrum of star A without contamination by star B.

\*<https://www.cosmos.esa.int/web/gaia/data-release-4>

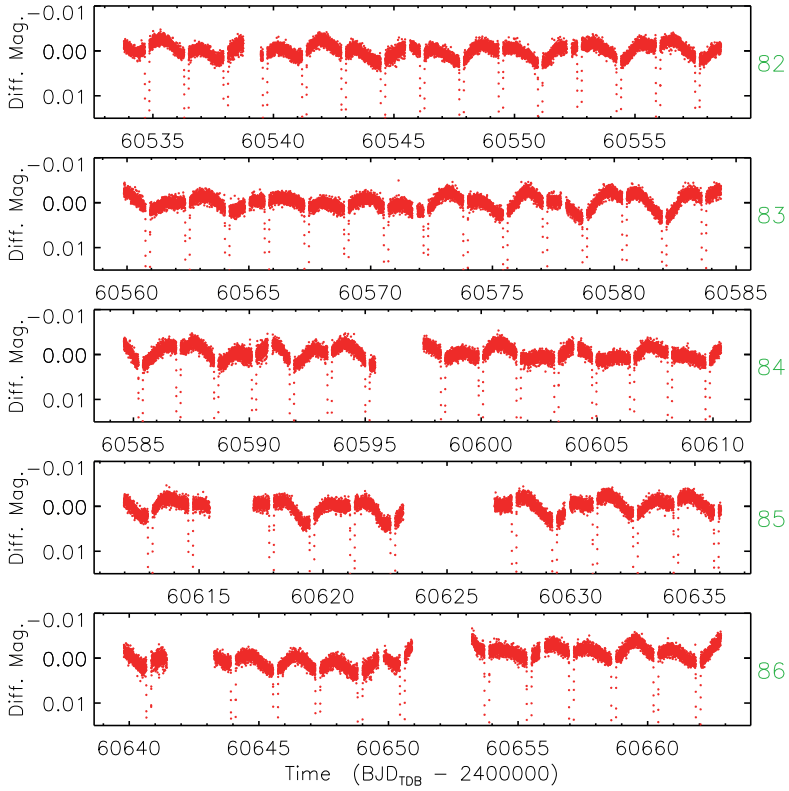


FIG. 6

Differential-magnitude light-curve of UZ Dra from sectors 82 to 86 (labelled on the right of each panel). The  $y$ -axis has been chosen so the out-of-eclipse variation due to starspots is clear.

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This paper includes observations made with the *Isaac Newton Telescope* operated on the island of La Palma by the Isaac Newton Group of Telescopes in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

This work has made use of data from the European Space Agency (ESA) mission *Gaia*<sup>\*</sup>, processed by the *Gaia* Data Processing and Analysis Consortium (DPAC)<sup>†</sup>. Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. The following resources were used in the course of this work: the NASA Astrophysics Data System; the *Simbad* database operated at CDS, Strasbourg, France; and the arXiv scientific paper preprint service operated by Cornell University.

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## REVIEWS

**Einstein in Oxford**, by Andrew Robinson (Bodleian Library Publishing), 2024. Pp. 96, 20.5 × 13.5 cm. Price £16.99 (hardbound; ISBN 978 1 85124 638 0).

Ulm, Zurich, Bern, Prague, Berlin, Princeton. Most readers will immediately think of Einstein when encountering the names of those cities in which he lived. But Oxford? Einstein never lived in Oxford, but it is a place which he visited several times, first on his first trip to England in 1921 when he lectured in Manchester and London but also visited Oxford due to the invitation of Frederick Lindemann, professor of experimental philosophy (*i.e.*, physics). He returned at Lindemann's invitation in 1931, 1932, and 1933. Born in Germany, Lindemann was brought up and educated in England, though he returned temporarily to Germany in his teens for some schooling. He thought of himself as more English than the English and, in contrast to Einstein, had very conservative political views, but at the same time great respect for Einstein's science and for him as a person. On the same day I bought this book, just across the street I also saw the famous Einstein blackboard (which contains some mistakes) in the History of Science Museum (whose director, Silke Ackermann, one of many German-born English residents mentioned in this review, provides a foreword), which dates from his Rhodes Lecture in 1931 (which finally took place after several attempts since 1927 to attract Einstein back for a second visit); during that visit Einstein also received an honorary doctorate (with an oration in Latin, putting him into a similar situation as that of those who couldn't understand his lectures in German). The book's preface discusses the blackboard and the first chapter Lindemann and his invitations.

Chapter two discusses aspects of Einstein's work relevant to his 1933 Herbert Spencer lecture. When visiting Oxford, Einstein (sometimes living in Lewis Carroll's former quarters) also indulged his interests besides science, especially music. As the third chapter describes, that was well documented by Margaret Deneke (whose parents had been born in Germany; her mother was also a close friend of Clara Schumann). In addition to playing a borrowed violin, Einstein also sat for a portrait and, in 1933, gave the Deneke lecture on atomic theory. The fourth chapter explores other aspects of Einstein in Oxford, such as writing a (perhaps Carroll-inspired) poem about himself, appearing in a stained-glass window, and Lindemann's attempts to get Einstein elected as a Fellow of Christ