

Professor Richard Ellis. The mass gap between the neutron stars and black holes: I presume that we understand it at some level but recently there were some claims that there was an object within the gap. I think it is a neutron star. Do we understand that object?

Dr. El-Badry. It's debatable whether we understand the gap but there are some reasons why we should get a gap. At the end of the star's life you have a core collapse and then you have a supernova, or your supernova fails and a bit of material falls on the star and that is why you get a gap. There are objects that are $2\text{--}3 M_{\odot}$ stellar objects in a globular cluster and we have radio timing of the companion. It could be a massive neutron star or it could be a low-mass black hole. I guess it's a massive neutron star. From the gravitational waves we have a better-sampled mass function so the answer is probably not that there is nothing in the gap but just an order of magnitude fewer objects in the gap than there are on either side. Nature usually finds a way to make objects in all areas of parameter space, it's just that some parts work better than others.

Professor Phil Charles. I was most intrigued by the enhanced Li in some of your neutron stars. That happens to be related to the formation from the SN event but the Li will actually be absorbed and decay with time which implies that those are young objects. Have you looked for radio SN remnants or faint examples of that to support the idea of the recent production?

Dr. El-Badry. We have looked in the radio and not seen anything. We think that those are pretty old stars because they are metal-poor and we didn't find any young stars with those values. Because they are metal-poor they have very thin convective envelopes so anything you dump on the surface effectively stays on the surface, it doesn't get mixed in, and we think the Li will survive for a long time. You can produce Li in a SN in a super AGB star. Young NSs produce high-energy particles which will bombard the surface of the companion and those high-energy particles can make carbon and oxygen by spallation.

The President. Thank you again for a wonderful lecture. [Applause.] To close, nobody in Washington is measuring how thick your hair is! [Laughter.]

I give notice that the AGM will be here on May 8 and the next A&G meeting will be on April 10th in Bristol. Thank you again for the wonderful talks.

REDISCUSSION OF ECLIPSING BINARIES. PAPER 32: THE ECCENTRIC F-TYPE SYSTEM EY CEPHEI

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EY Cep is a detached eclipsing binary containing two Fo V stars in an orbit with a period of 7.97 d and an eccentricity of 0.440 . We determine the physical properties of the system using light-curves from the *Transiting Exoplanet Survey Satellite* and published spectroscopic measurements. We find masses of $1.523 \pm 0.008 M_{\odot}$ and $1.494 \pm 0.014 M_{\odot}$, radii of $1.491 \pm 0.004 R_{\odot}$ and $1.446 \pm 0.004 R_{\odot}$, and temperatures of 7070 ± 170 K and 6990 ± 150 K. We calculate the system's distance to be 300.3 ± 3.8 pc, in excellent agreement with the *Gaia* DR3 parallax, and estimate its age to be 220 Myr. We find no evidence for pulsations, but there are hints of variation in the eclipse times potentially attributable to a third body on a longer-period eccentric orbit.

Introduction

Eclipsing binary star systems (EBs) are of fundamental importance to astrophysics as a direct source of mass and radius measurements of normal stars. Detached eclipsing binaries (dEBs) are particularly useful as their components have evolved as single stars so can be used to check and calibrate theoretical models of single-star evolution^{1,2}. The current work is part of a series of papers³ in which primarily space-based light-curves⁴ are used to refine the properties of known dEBs. The properties of those objects are collected in the *Detached Eclipsing Binary Catalogue*⁵ (DEBCat^{*}).

In this work we present an analysis of EY Cephei (see Table 1), which contains two Fo V stars on an eccentric orbit. The target was originally chosen as possibly containing pulsating stars, although that was not confirmed. We summarize the observational history of the system, present the new observational material, analyse the available light- and radial-velocity (RV) curves, and determine the physical properties and age of the component stars.

EY Cephei

Eclipses in the EY Cep system were reported in 1958 by Strohmeier⁶. Strohmeier⁷ gave an orbital period of 5.51672 d, which has turned out to be incorrect. Lacy^{8,9} reported the discovery of double lines in the spectrum of EY Cep, with the lines from the two stars having approximately equal widths and depths. Lacy¹⁰ measured its *V* magnitude, and *B* – *V* and *U* – *B* colour indices outside eclipse. Lacy¹¹ provided magnitudes and colour indices in the *uvby* system.

Lacy *et al.*¹² (hereafter Lo6) presented the only detailed analysis of EY Cep published so far, including a revision and confirmation of the orbital period of 7.971 d. Their spectrographic material comprised five spectra from the 2.1-m telescope and coude spectrometer at the Kitt Peak National Observatory (KPNO), and 47 from the 1.5-m Tillinghast reflector, échelle spectrograph, and Reticon detector at the Fred Lawrence Whipple Observatory (FLWO). Each yielded RV measurements for both stars. The projected rotational velocities were found to be $10 \pm 1 \text{ km s}^{-1}$ for both stars. From the *UBV* and *uvby* photometry Lo6 deduced spectral types of Fo V for both components, a temperature of $T_{\text{eff,A}} = 7090 \pm 150 \text{ K}$ for star A (the star eclipsed at phase zero), and a temperature of $T_{\text{eff,B}} = 6970 \pm 150 \text{ K}$ for star B (its companion).

Lo6 obtained light-curves comprising 6907 measurements in the *V*-band using a 28-cm telescope and modelled using the EBOP code^{18,19}. They found night-to-night magnitude offsets in those data, concluded that they were likely of instrumental origin, and removed them before analysis. They determined the physical properties of the component stars and found them to be consistent with theoretical predictions for a solar metallicity and a young age (40 Myr but with a large uncertainty). Finally, they suspected δ Scuti pulsations in star A due to the night-to-night offsets and its much larger scatter in the RVs compared to those for star B.

EY Cep has been mentioned in several other works, and additional times of mid-eclipse have been published. However, Lo6 remains the only detailed analysis of the system prior to the current work.

Photometric observations

EY Cep was observed by the *Transiting Exoplanet Survey Satellite* (TESS²⁰) mission during eight sectors. Light-curves from the TESS Science Processing Center (SPOC²¹) at a cadence of 120 s are available for seven of the sectors (19, 25, 53, 59, 60, 73, and 79). Quick Look Pipeline (QLP²²) data at 200-s cadence are available for the last sector (86).

^{*}<https://www.astro.keele.ac.uk/jkt/debcats/>

TABLE I

Basic information on EY Cephei. The *BV* magnitudes are each the mean of 115 individual measurements¹³ distributed approximately randomly in orbital phase. The *JHK_s* magnitudes from 2MASS¹⁴ were obtained at an orbital phase of 0.947, which is close to but confidently before the beginning of primary eclipse.

Property	Value	Reference
Right ascension (J2000)	03 ^h 40 ^m 04 ^s .07	15
Declination (J2000)	+81°1′9″.0	15
<i>Gaia</i> DR3 designation	568183560050534016	16
<i>Gaia</i> DR3 parallax (mas)	3.3202 ± 0.0135	16
<i>TESS</i> Input Catalog designation	TIC 297899564	17
<i>U</i> magnitude	10.126 ± 0.010	10
<i>B</i> magnitude	10.162 ± 0.009	10
<i>V</i> magnitude	9.795 ± 0.007	10
<i>J</i> magnitude	9.035 ± 0.030	14
<i>H</i> magnitude	8.977 ± 0.031	14
<i>K_s</i> magnitude	8.841 ± 0.020	14
Spectral type	F0 V + F0 V	12

We downloaded those data from the *Mikulski Archive for Space Telescopes (MAST*)* using the *LIGHTKURVE* package²³, with the ‘hard’ flag to reject data of lower quality. The light-curve from each sector was then converted into differential magnitudes and the median magnitude was subtracted to normalize the data to zero outside eclipse. The light-curves are shown in Fig. 1.

We queried the *Gaia* DR3 database[†] for sources within 2 arcmin of EY Cep, finding 41 including the dEB itself. The brightest of those is 5.3 mag fainter than EY Cep in the *G_{RP}* band, suggesting that contamination of the *TESS* light-curve by nearby stars is negligible.

Light-curve analysis

The *TESS* light-curves for each sector all have full coverage of at least two primary and two secondary eclipses, with the exception of sector 73 for which there are two primary but only one secondary eclipse. We therefore modelled the light-curves from each sector independently. Prior to that, we extracted the data for each fully-observed eclipse from the *TESS* light-curves in order to reject data which were not useful but would still incur computational overhead. We included an additional 0.2 d of data before the start and after the end of each eclipse, to which we fitted a straight line. That fit was then subtracted from the data to normalize each eclipse to zero differential magnitude.

The light-curve for each sector was then modelled using version 45 of the *JKTEBOP*[‡] code^{24,25}. We fitted for the orbital period (*P*), a reference time of primary minimum (*T*₀) selected as the primary eclipse closest to the midpoint of the sector, the sum and ratio of the fractional radii (*r*_A + *r*_B and *k* = *r*_B/*r*_A), the central-surface-brightness ratio (*J*), third light (*L*₃), and orbital inclination (*i*). We included orbital eccentricity (*e*) by fitting for *e* cos ω and *e* sin ω , where ω is the argument of periastron.

Limb darkening (LD) was incorporated using the power-2 law^{26–28}. The two stars have very similar properties so we used the same LD coefficients for both. We fitted for the linear coefficient (*c*) and fixed the nonlinear coefficient (α) at a theoretical value^{29,30}. The best fit

*<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>

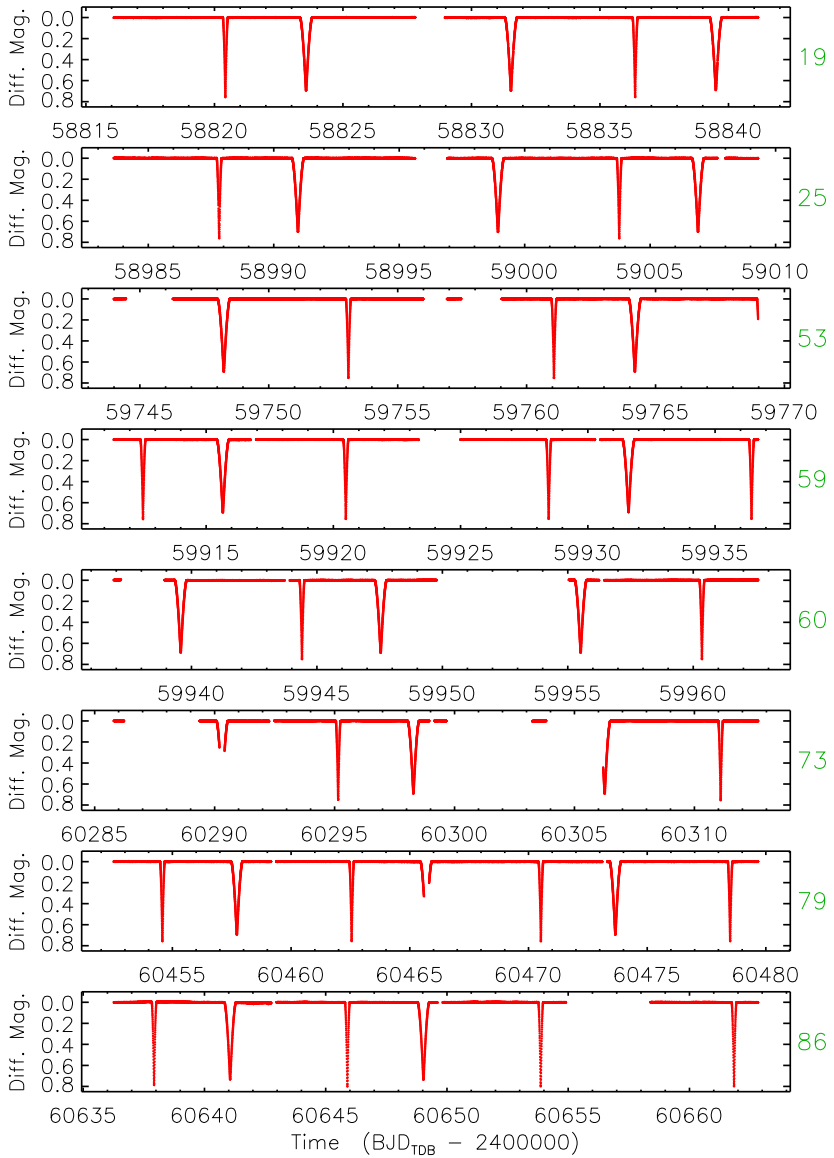


FIG. 1

Light-curves of EY Cep from all eight *TESS* sectors. The flux measurements have been converted to magnitude units and the median subtracted.

for the data from sector 19 is shown in Fig. 2; other sectors are similar. The fitted parameters are given in Table II and are the unweighted mean of the individual values for each parameter.

We determined three sets of uncertainties for the fitted and derived parameters. The first

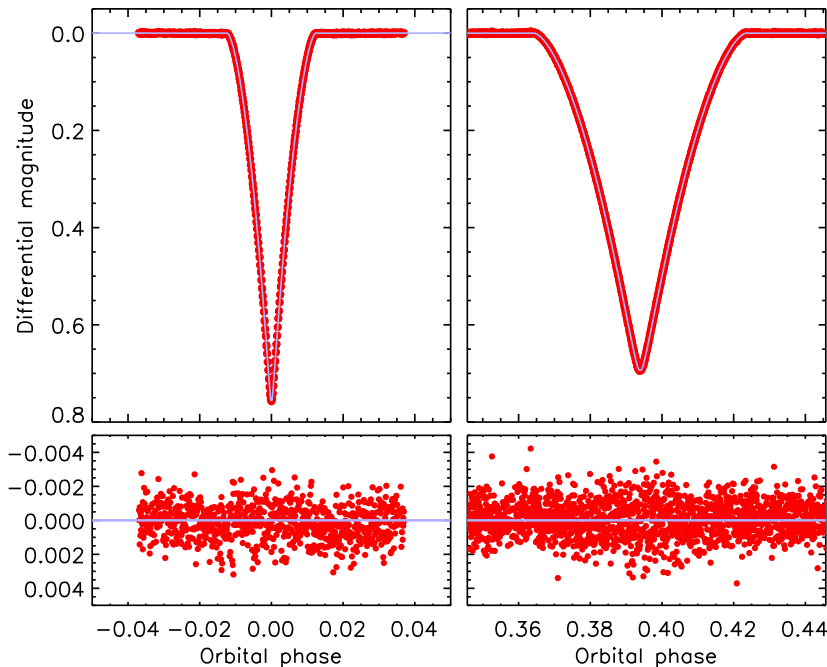


FIG. 2

JKTEBOP best fit to the light-curve of EY Cep from *TESS* sector 19 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.

TABLE II

Photometric parameters of EY Cep measured using *JKTEBOP* from the *TESS* light-curves. The error bars are 1σ and are the largest of three options calculated for each parameter. Values from Lo6 (their table 6) are shown for comparison; the two bracketed quantities came instead from their table 5.

Parameter	This work	Lo6
<i>Fitted parameters:</i>		
Orbital inclination ($^{\circ}$)	89.903 ± 0.013	89.89 ± 0.03
Sum of the fractional radii	0.12102 ± 0.00008	
Ratio of the radii	0.9701 ± 0.0017	1.005 ± 0.012
Central-surface-brightness ratio	-0.9577 ± 0.0010	0.931 ± 0.005
Third light	-0.0001 ± 0.0149	
$e \cos \omega$	-0.15291 ± 0.00028	-0.14897 ± 0.00013
$e \sin \omega$	0.41275 ± 0.00037	0.4224 ± 0.0017
LD coefficient c	0.597 ± 0.014	
LD coefficient α	0.4555 (fixed)	
<i>Derived parameters:</i>		
Fractional radius of star A	0.06143 ± 0.00006	0.0603 ± 0.0004
Fractional radius of star B	0.05959 ± 0.00008	
Light ratio ℓ_B/ℓ_A	0.9013 ± 0.0028	0.961 ± 0.026
Orbital eccentricity	0.44017 ± 0.00035	(0.4415 ± 0.012)
Argument of periastron ($^{\circ}$)	110.328 ± 0.041	(109.78 ± 0.07)

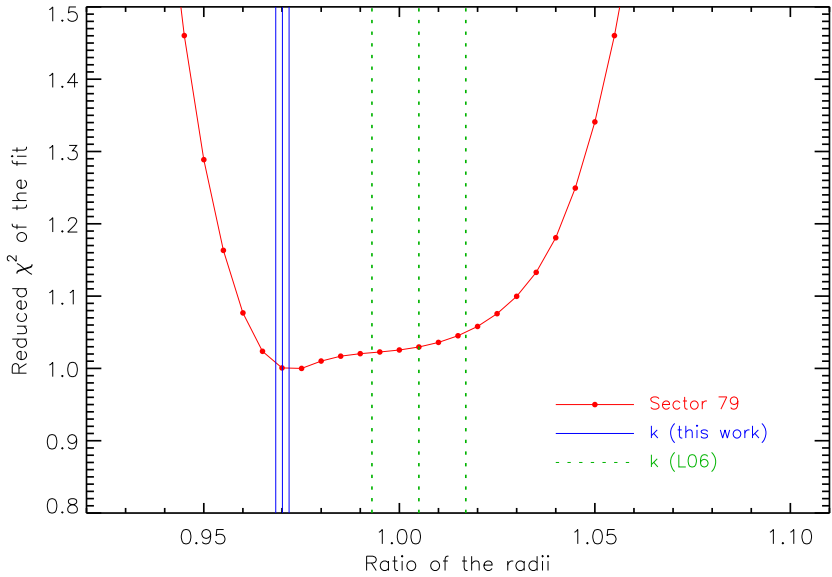


FIG. 3

Quality of the fit, χ^2_ν , to the *TESS* sector 79 light-curve of EY Cep as a function of ratio of the radii, k (red lines and filled circles). The blue solid lines indicate the value and its uncertainty from the current work (based on all eight *TESS* sectors, not just sector 79), and the green dotted lines show the best value and uncertainty found by Lo6.

set is the r.m.s. scatter of the fitted values from the different sectors, the second set was obtained by running 1000 Monte Carlo simulations for each sector, and the third set was from running residual-permutation simulations for each sector³¹. We took the largest of the three options for each parameter, which in most cases was from the scatter of the fitted values. Those are also given in Table II. We did not divide by $\sqrt{8}$ to obtain the standard error because that led to error bars which are smaller than the limits to which our modelling code has been proven³².

The parameter values we measured are significantly different from those of Lo6. The latter are collected in Table II for convenience, along with our own. The most obvious discrepancies are for k and the light ratio, which of course are physically related. We investigated that by running a set of JKTEBOP fits to the data from *TESS* sector 79, with k fixed at a grid of values between 0.6 and 1.5. The quality of the fit is shown in Fig. 3, together with the k found in this work and by Lo6 (Table II). It can be seen that our k measurement is much more precise and also significantly different from that of Lo6, driven primarily by the much better quality of the *TESS* data.

The light ratio we find (0.901 ± 0.003) does not match either of the spectroscopic light ratios measured by Lo6 (1.06 ± 0.06 from their KPNO spectra and 1.32 ± 0.02 from their FLWO spectra). It is also moderately different from Lo6's photometric value (0.96 ± 0.03), which can be attributed to the different k we obtain as discussed above. The two spectroscopic light ratios are inconsistent with each other and with the photometric values, as noted by Lo6. A plausible explanation would be that one component is a metallic-lined star, thus the ratio of spectral-line strengths differs from the continuum light ratio, but that is ruled out by Lo6's observation that the two stars are chemically normal. The discrepancy remains unexplained.

TABLE III

Times of mid-eclipse for EY Cep and their residuals versus the fitted ephemeris.

<i>Orbital cycle</i>	<i>Eclipse time (BJD_{TDB})</i>	<i>Uncertainty (d)</i>	<i>Residual (d)</i>	<i>TESS sector</i>
−139.0	2458836.367724	0.000012	0.000057	19
−118.0	2459003.768820	0.000014	−0.000003	25
−23.0	2459761.059727	0.000012	−0.000039	53
−2.0	2459928.460878	0.000007	−0.000043	59
0.0	2459944.403874	0.000012	−0.000015	60
44.0	2460295.149249	0.000012	0.000082	73
66.0	2460470.521820	0.000007	0.000013	79
89.0	2460653.865933	0.000010	0.000003	86

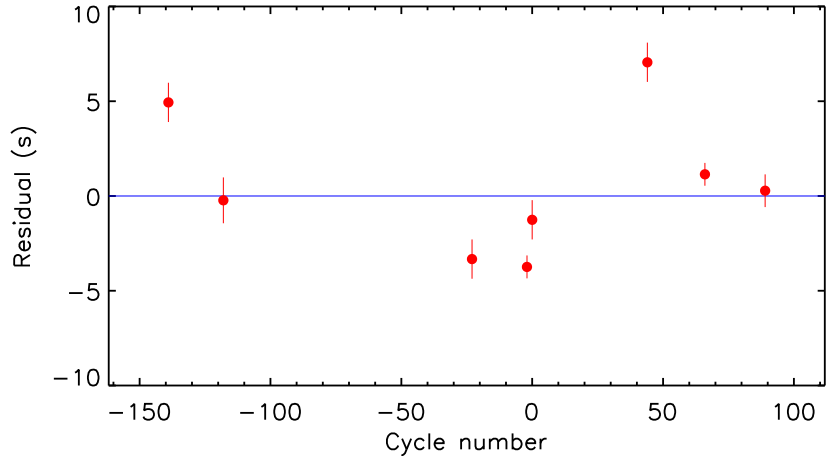


FIG. 4

Residuals of the times of minimum light from Table III versus the best-fitting ephemeris. Red open circles indicate the values calculated from *TESS* data in the current work. The blue solid line indicates a residual of zero.

Orbital ephemeris

We determined a new orbital ephemeris for EY Cep using the times of effective primary eclipse found in the fits to the individual *TESS* sectors above. A straight line fitted to these data gives the ephemeris

$$\text{Min I} = \text{BJD}_{\text{TDB}}\ 2459944.403889(14) + 7.97148361(20)E \tag{1}$$

where *E* is the number of cycles since the reference time of minimum and the bracketed quantities indicate the uncertainty in the final digits of the previous number. The times of minimum and residuals of the fit are reported in Table III.

The residuals of the fit are plotted in Fig. 4 and show a scatter which is small in absolute terms (the r.m.s. is 3.6 s) but bigger than the error bars. The reduced χ^2 of the fit is 15.3 and there are hints of a periodic variation which could be explained by the light-time effect due to a third body on an eccentric orbit. The uncertainties in the ephemeris above have been

increased by $\sqrt{15\cdot3}$ to account for that excess scatter. Further measurements are required to investigate the possible light-time effect.

We tested including eclipse timings from the literature to see if those might support the third-body hypothesis. The measurement errors from the seven individual timings given by Lo6 are too large to constrain the solution, given the high quality of the *TESS* data. The time system used for those timings is also not clear: they are labelled as HJD but without indication of whether they are UTC or TDB*. The difference between those two time systems is much larger than the size of the prospective light-time effect. Five more timings exist in the literature^{33–37} but all are for secondary eclipses and have a larger measurement error than the Lo6 timings. We thus leave confirmation or refutation of that effect to future work.

Radial-velocity analysis

Lo6 tabulated RVs for both components of EY Cep from their five KPNO spectra and 47 FLWO spectra. We reanalysed the RVs using *КТЕВОР*, fixing the values of P , T_0 , $e \cos \omega$, and $e \sin \omega$ to those in Table II. We fitted for the velocity amplitudes (K_A and K_B) and the systemic velocities ($V_{\gamma,A}$ and $V_{\gamma,B}$) of the two stars. We also allowed for an orbital-phase offset, which in all cases was very small and consistent with the difference between the TDB time-scale used in the current work and the UTC time-scale probably used by Lo6. We calculated orbits based on only the FLWO RVs, and on all RVs assuming the two sources are on a consistent velocity scale. The results are given in Table IV and a representative orbit is plotted in Fig. 5

All spectroscopic orbits in Table IV agree within their uncertainties, making it unimportant which is adopted for the rest of the analysis. We chose to use the orbits based on only the FLWO data — to avoid exposure to any velocity offsets between the two spectrographs — and with separate systemic velocities for the two stars. Our results confirm the observation of Lo6 that the scatter of the RVs for star A is much larger than that for star B.

Physical properties and distance to EY Cep

We calculated the physical properties of EY Cep using our usual method: the *КТАБС-ДИМ* code³⁸ fed with the results of the photometric and spectroscopic analyses above. The properties are collected in Table V. The masses of the two stars are measured to 0.5% and 0.9% precision, respectively, and agree very well with the values from Lo6 (as expected). The radii are measured to 0.3% precision and do not agree with those from Lo6 because we found a smaller k (as discussed above).

Lo6 found a mean effective temperature of the system of 7030 ± 150 K. We determined individual temperatures from that, the radius and surface-brightness ratios, and the equations derived in our study of V454 Aur³⁹. The values are also given in Table II.

Table V also reports the synchronous and pseudo-synchronous rotational velocities of the stars. The former is the rotational velocity giving one stellar rotation per orbital period. The latter is the rotational velocity resulting in synchronous rotation at periastron, calculated using equation (44) from Hut⁴¹. Because tidal effects are strongest at periastron (as that is when the stars are closest), it is expected that the stars are rotating pseudo-synchronously. However, their measured rotational velocities are consistent with synchronous rather than pseudo-synchronous rotation. The reason for that is unclear. The age of the system (see below) puts it much older than the rotational synchronization time-scale (40 Myr) but much younger than the orbital circularization time-scale (20 Gyr) according to the theory of Zahn⁴².

We determined the distance to the system using the *UBV* magnitudes from Lacy¹⁰, the *JHK_s* magnitudes from 2MASS¹⁴ transformed onto the Johnson system, and the bolometric corrections from Girardi *et al.*⁴³. A small interstellar reddening of $E(B - V) = 0.025 \pm 0.015$

*TDB stands for *Temps Dynamique Barycentrique*, Barycentric Dynamical Time.

Spectroscopic orbits for EY Cep from the literature and from the current work. All quantities are given in km s^{-1} . We give both sets of orbits from Lo6 (a) based on all (KPNO and FLWO) RVs; (b) based on all RVs and times of minimum light. The orbits from the current work were calculated using either the FLWO RVs or all RVs.

TABLE IV							
Source	K_A	K_B	V_γ	$V_{\gamma,A}$	$V_{\gamma,B}$	σ_A	σ_B
Lo6 (a)	85.27 ± 0.41	86.64 ± 0.15	-6.79 ± 0.10			2.07	0.64
Lo6 (b)	85.23 ± 0.39	86.62 ± 0.14	-6.77 ± 0.10				
This work (FLWO)	84.94 ± 0.39	86.57 ± 0.13		-6.28 ± 0.28	-6.90 ± 0.09	1.91	0.65
This work (FLWO)	85.06 ± 0.42	86.58 ± 0.14	-6.84 ± 0.09			2.00	0.65
This work (KPNO + FLWO)	85.07 ± 0.38	86.56 ± 0.13		-6.27 ± 0.27	-6.89 ± 0.10	1.88	0.76
This work (KPNO + FLWO)	85.22 ± 0.38	86.58 ± 0.13	-6.83 ± 0.09			1.96	0.76

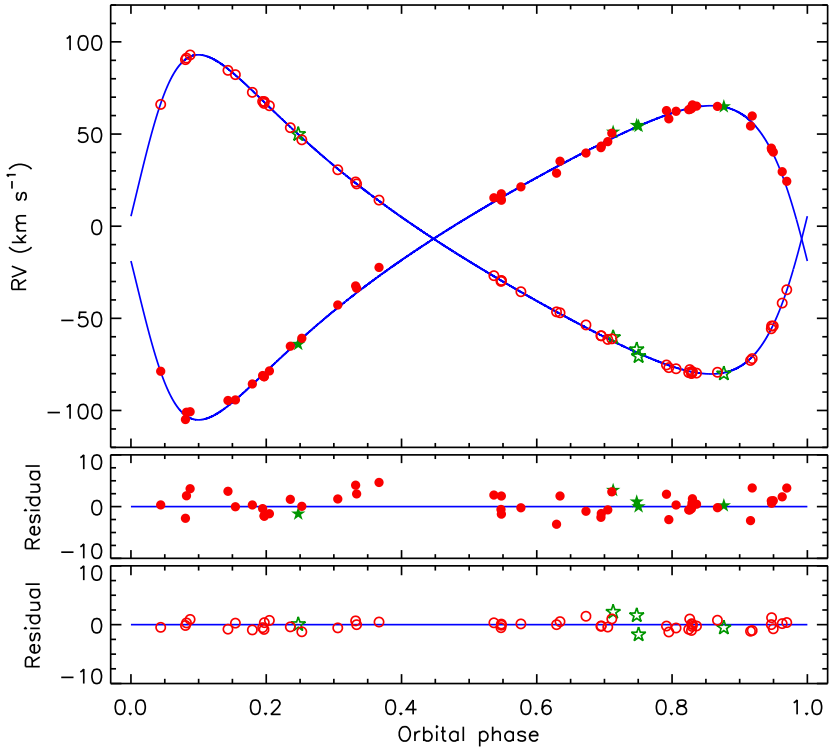


FIG. 5

RVs of EY Cep from Lo6 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 RVs from the FLWO spectra are shown as red circles, and from the KPNO spectra as green stars. The residuals are given in the lower panels separately for the two components.

was needed to bring the optical distances into agreement with the infrared ones. Our final distance measurement is from the K -band and is 300.3 ± 3.8 pc, which is in excellent agreement with the distance of 301.2 ± 1.2 pc from inverting the *Gaia* DR3 parallax.

We compared the masses, radii, and temperatures of the components of EY Cep to the predictions of the PARSEC 1.2 evolutionary models⁴⁴. The mass–radius relation defined by the two stars is steeper than that predicted by the models, but agreement within 1σ can be obtained for a metal abundance fraction by mass of $Z = 0.020$ and an age of 220 Myr. The predicted temperatures for that age and Z are approximately 50 K higher than observed, so are well within the error bars. Our results here differ from those of Lo6, who required the system to be on or around the zero-age main sequence in order to explain their measurement of a larger radius and lower surface gravity for star B *versus* star A.

Summary and conclusions

EY Cep is a dEB containing two Fo V stars in an orbit of period 7.97 d and eccentricity 0.44. We have determined the physical properties of the component stars using light-curves from eight *TESS* sectors and the RVs from Lo6. The masses are measured to 1% and the

TABLE V

Physical properties of EY Cep defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 40).

Parameter	Star A	Star B
Mass ratio M_B/M_A	0.9811 ± 0.0047	
Semimajor axis of relative orbit ($\mathcal{R}_\odot^N$)	24.265 ± 0.058	
Mass ($M_\odot^N$)	1.523 ± 0.008	1.494 ± 0.014
Radius ($\mathcal{R}_\odot^N$)	1.4906 ± 0.0039	1.4460 ± 0.0040
Surface gravity (log[cgs])	4.2740 ± 0.0011	4.2921 ± 0.0023
Density ($\rho_\odot$)	0.4600 ± 0.0017	0.4942 ± 0.0023
Synchronous rotational velocity (km/s)	9.461 ± 0.025	9.177 ± 0.025
Pseudo-synchronous rotational velocity (kms/s)	27.104 ± 0.073	26.293 ± 0.076
Effective temperature (K)	7070 ± 150	6990 ± 150
Luminosity log($L/L_\odot^N$)	0.699 ± 0.037	0.653 ± 0.037
M_{bol} (mag)	2.99 ± 0.09	3.11 ± 0.09
Interstellar reddening $E(B - V)$ (mag)	0.025 ± 0.015	
Distance (pc)	300.3 ± 3.8	

radii to 0.3%. We find the less massive star to have a smaller radius than its companion, as expected from stellar-evolution theory, resolving a discrepancy found in previous work. Our measured distance to the system agrees well with that from the *Gaia* DR3 parallax. The properties of the stars are consistent with theoretical predictions for a slightly super-solar metallicity and an age of 220 Myr. There is a hint of periodic variation in the times of minimum light suggestive of the light-time effect from a third component on an eccentric orbit.

Our original interest in this object was piqued by the possibility of pulsations in its light-curve. We investigated that by fitting the most suitable dataset, *TESS* sectors 59 and 60, with *ЖТЕВОР* and calculating a periodogram of the residuals. The highest frequency in the amplitude spectrum was at 0.546 d⁻¹ and had an amplitude of 0.26 mmag and a signal-to-noise ratio of 4.4. That signal-to-noise ratio is below that required for the detection to be significant⁴⁵. We therefore analysed the data from sectors 79 and 86 as well to see if they could confirm the detection. We did not find the signal present in either sector. We conclude that pulsations are not detectable in the currently available data of EY Cep.

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^{*}<https://www.cosmos.esa.int/gaia>

[†]<https://www.cosmos.esa.int/web/gaia/dpac/consortium>

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