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REDISCUSSION OF ECLIPSING BINARIES. PAPER 22: THE B-TYPE SYSTEM MU CASSIOPEIAE

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MU Cas is a detached eclipsing binary containing two B5 V stars in an orbit of period 9·653 d and eccentricity 0·192, which has been observed in seven sectors using the *Transiting Exoplanet Survey Satellite* (*TESS*). We use these new light-curves together with published spectroscopic results to measure the physical properties of the component stars, finding masses of 4·67 ± 0·09 $M_{\odot}$ and 4·59 ± 0·08 $M_{\odot}$, and radii of 4·12 ± 0·04 $R_{\odot}$ and 3·65 ± 0·05 $R_{\odot}$. These values agree with previous results save for a change in which of the two stars is designated the primary component. The measured distance to the system, 1814 ± 37 pc, is 1·8σ shorter than the distance from the *Gaia* DR3 parallax. A detailed spectroscopic analysis of the system is needed to obtain improved temperature and radial-velocity measurements for the component stars; a precise spectroscopic light ratio is also required for better measurement of the stellar radii. MU Cas matches the predictions of theoretical stellar-evolutionary models for a solar chemical composition and an age of 87 ± 5 Myr. No evidence for pulsations was found in the light-curves.

Introduction

The study of detached eclipsing binaries (dEBs) allows the direct and high-precision measurement of the masses and radii of stars[1,2], which can be used to confirm and improve the predictions of theoretical models of stellar evolution[3–5]. The recent plethora of space-based telescopes has revolutionized this work[6] by providing light-curves of previously unattainable quality for a large number of dEBs. In the current series of papers[7] we are using this opportunity to improve and update measurements of known dEBs to increase the number with mass and radius measurements to 2% precision and accuracy[8].

In this work we study the system MU Cassiopeiae⋆ an EB containing two B5 V stars on an eccentric orbit with a period of 9·653 d (Table I). Our analysis relies on new high-quality space-based photometry and on spectroscopic results available in the literature. Our decision to study this object was partly motivated by the recent acquisition of extensive light-curves using the *TESS* mission, and partly by the possibility of including it in an unrelated project (in preparation).

Table I

Basic information on MU Cassiopeiae. The BV magnitudes are each the mean of 122 individual measurements[12] *distributed approximately randomly in orbital phase, and agree well with the out-of-eclipse values from Lacy*[13]*. The JHK_s magnitudes are from 2MASS*[14] *and were obtained at orbital phase 0·268.*

Property	*Value*	*Reference*
Right ascension (J2000)	$00^{\mathrm{h}}15^{\mathrm{m}}51^{\mathrm{s}}{\cdot}56$	15
Declination (J2000)	$+60^{\circ}25'53''{\cdot}6$	15
Gaia DR3 designation	429158427924463872	16
Gaia DR3 parallax	0·5133 ± 0·0191 mas	16
TESS Input Catalog designation	TIC 83905462	17
B magnitude	11·12 ± 0·05	12
V magnitude	10·80 ± 0·06	12
J magnitude	10·127 ± 0·022	14
H magnitude	10·083 ± 0·021	14
K_s magnitude	10·021 ± 0·016	14
Spectral type	B5V + B5V	10

The variability of MU Cas was discovered by Hoffmeister[9], and subsequent work has been summarized by Lacy, Claret & Sabby[10] (hereafter LCS04). LCS04 were the first to determine the orbital period of the system correctly, and also measure the properties of the component stars from extensive V-band light-curves and a set of radial velocities (RVs) from high-resolution spectra.

⋆Note that entering "mu cas" into databases such as *Simbad* returns information for the bright star μ Cas. The results for the eclipsing binary can sometimes be obtained by searching for "MU Cas" (note capitalization), but in other cases "V⋆ MU Cas" or alternative designations such as "HIP 1263" are more reliable.

Claret *et al.*[11] measured the apsidal motion of the system, which is slow, and did not use it as it lacked sufficient precision for their analysis. Aside from this work, MU Cas has been mentioned in a multitude of catalogue papers and lists of observed times of minimum brightness which need not be itemized here.

LCS04 deduced photometric spectral types of B5 V for both components of MU Cas based on *UBV* photometry. We define star A to be the star eclipsed at the primary (deeper) eclipse, and star B to be its companion. By this definition, star A turns out to be the larger and more massive of the two, but has evolved to a cooler effective temperature ($T_{\rm eff}$).

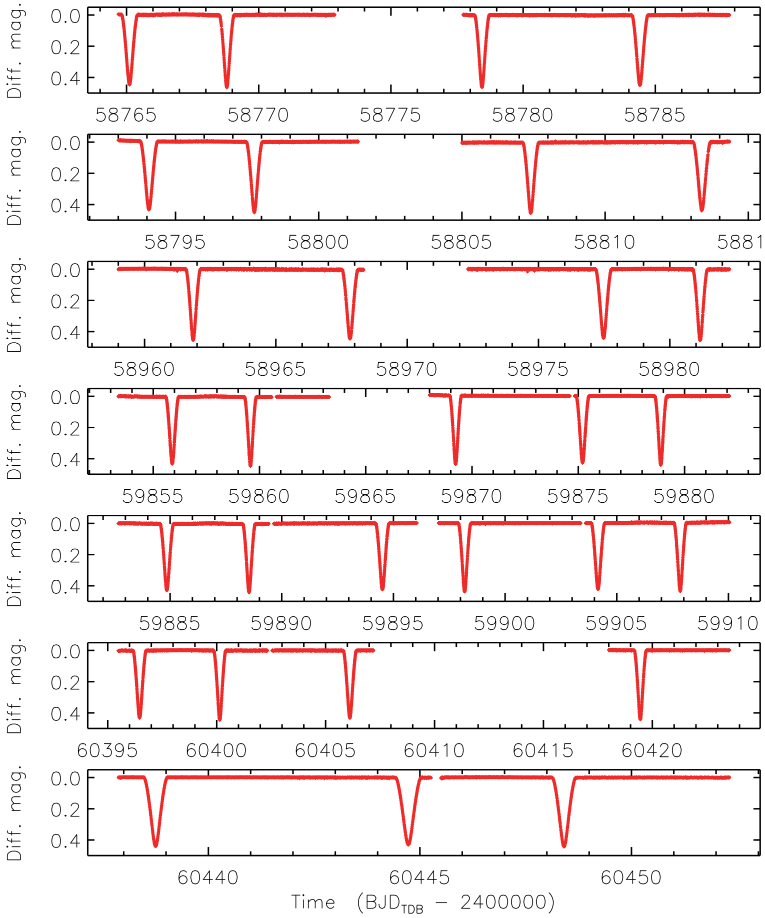

Fig. 1

TESS short-cadence SAP photometry of MU Cas from sectors 17, 18, 24, 57, 58, 77, and 78 (top to bottom panels). The flux measurements have been converted to magnitude units then rectified to zero magnitude by subtraction of the median.

Photometric observations

A profusion of photometric data exists for MU Cas, as it has been observed at 120-s cadence in sectors 17, 18, 24, 57, 58, 77, and 78 by *TESS*. We downloaded all these data from the NASA Mikulski Archive for Space Telescopes (MAST*) using the LIGHTKURVE package[18] and the quality flag "hard". The simple aperture photometry (SAP) light-curves from the SPOC data-reduction[19] pipeline were used, converted into differential magnitudes and with the median magnitude subtracted for each sector.

The light-curves are shown in Fig. 1. Some gaps in coverage exist due to pauses in observation by the spacecraft, or where the quality threshold was not met, and a few instrumental jumps or trends are discernible. There is a total of 105 609 data points within these sectors. We trimmed a further set of data points where slow instrumental trends were clear, leaving behind 97 571 data points.

A query of the *Gaia* DR3 database† returns a total of 282 sources within 2 arcmin of MU Cas, as expected due to the faint limiting magnitude of *Gaia* and the proximity of our target to the Galactic plane. MU Cas is the brightest star within this sky region, the second-brightest is distant by 1·33 arcmin and fainter by 1·33 mag in the *Gaia* $G_{\rm RP}$ band, and the next-brightest is at 1·79 arcmin and fainter by 2·62 mag in the same band. As the pixel size and point-spread functions of *TESS* are large, at 21 arcsec and 84 arcsec (90% encircled energy) respectively, these nearby stars will contribute a small amount of contaminating light to the *TESS* observations of MU Cas.

Light-curve analysis

Our first approach was to isolate the data near eclipse. We extracted the data within 1·1 d of each eclipse midpoint, and renormalized them to zero differential magnitude by fitting a straight line or quadratic function to the data outside eclipse. On inspection of the results it was found that the eclipse depths change slightly between sectors — the primary eclipses vary from a depth of 0·463 mag (sector 17) to 0·440 mag (sector 58). We attribute this to varying amounts of contaminating light, as the sectors of data were obtained with different spacecraft orientations and pixel masks in the photometry pipeline. We therefore decided to model the sectors individually and combine the results afterwards.

The components of MU Cas are well-separated, so the system is suitable for analysis with the JKTEBOP‡ code[20,21] (version 43). We fitted the following parameters for each *TESS* sector: the fractional radii of the stars ($r_{\rm A}$ and $r_{\rm B}$), expressed as their sum ($r_{\rm A} + r_{\rm B}$) and ratio ($k = r_{\rm B}/r_{\rm A}$), the central-surface-brightness ratio (J), third light (L_3), orbital inclination (i), orbital period (P), reference time of primary minimum (T_0), the orbital eccentricity (e), and the argument of periastron (ω) expressed as their Poincaré combinations ($e \cos \omega$ and $e \sin \omega$), one limb-darkening coefficient (see below), and a linear trend for the out-of-eclipse brightness for each *TESS* half-sector.

Limb darkening (LD) was included using the power-2 approximation[22–24] and the similarity of the stars allowed the use of the same LD coefficients for both stars. We fitted for the linear coefficient (c) but fixed the non-linear coefficient

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*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

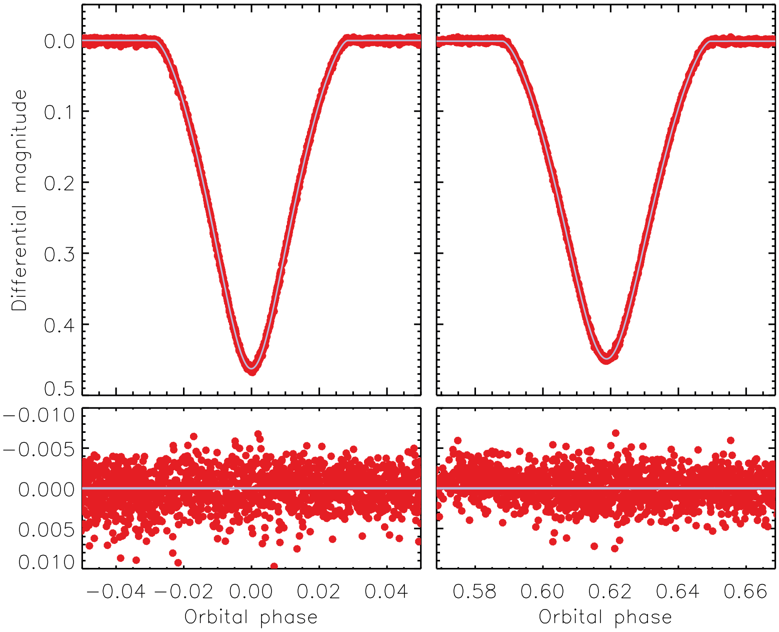

FIG. 2

JKTEBOP best fit to the 120-s cadence light-curves of MU Cas from *TESS* sector 17. 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 panel.

(α) to a suitable theoretical value[25,26]. The strong correlation between *c* and α, and the inclusion of *c* in the list of fitted parameters, means our results are effectively independent of stellar theory.

The best fit to the data from sector 17 is good, is shown in Fig. 2, and is representative of the results for the other sectors. Once the fits to each of the sectors were established, we ran Monte Carlo and residual-permutation solutions[27] to obtain error bars for the measured parameters[28]. The immediate outcome of this process was that the results between sectors agree well with each other, but not within the uncertainties. For our final results we therefore provide the unweighted mean for each parameter, with uncertainties calculated by dividing the standard deviation of the values by the square-root of the number of sectors. These numbers are collected in Table II.

We find that some parameters are determined extremely well; these include the orbital inclination (±0°·03), the sum of the fractional radii (fractional uncertainty of 0·3%), the central-surface-brightness ratio (0·2%), and $e \cos \omega$. However, the ratio of the radii and the light ratio are relatively poorly determined and strongly correlated with other parameters. This effect is common in the analysis of the light-curves of dEBs with eclipses that are not total (*e.g.*, ref. 29) and is due to changes in the ratio of the radii having little effect on the shape of the light-curve.

TABLE II

Photometric parameters of MU Cas measured using JKTEBOP. *The value for each parameter is the unweighted mean of the individual values per TESS sector, and its uncertainty is the standard deviation of the values divided by the square-root of the number of sectors.*

Parameter	*Value*
Fitted parameters:	
Orbital inclination (°)	87·110 ± 0·033
Sum of the fractional radii	0·19395 ± 0·00027
Ratio of the radii	0·888 ± 0·016
Central-surface-brightness ratio	1·0178 ± 0·0008
Third light	0·0334 ± 0·0061
LD coefficient c	0·519 ± 0·027
LD coefficient α	0·3811 (fixed)
$e\cos\omega$	0·18728 ± 0·00008
$e\sin\omega$	0·04215 ± 0·00054
Derived parameters:	
Fractional radius of star A	0·10275 ± 0·00075
Fractional radius of star B	0·09119 ± 0·00099
Light ratio ℓ_B/ℓ_A	0·804 ± 0·029
Orbital eccentricity	0·19197 ± 0·00011
Argument of periastron (°)	12·68 ± 0·16

To visualize this we have constructed a set of correlation plots in Fig. 3. Panel (*a*) shows that the fractional radii of the stars are strongly anti-correlated, as expected when their sum is much better determined than their ratio. Panels (*b*) and (*c*) show that the surface-brightness ratio is well-constrained (by the relative depths of the eclipses) and thus the uncertainty in the ratio of the radii manifests as a large uncertainty in the light ratio. Panel (*d*) shows that the correlation is much weaker for the orbital inclination, and panels (*e*) and (*f*) that it has no significant effect on the Poincaré quantities.

Panel (*b*) shows that a direct measurement of the light ratio of the two stars, either from a composite spectrum or high-resolution imaging (*e.g.*, refs. 30 and 31), could solve this problem by specifying the allowed range of values of the ratio of the radii. To demonstrate this we reran the JKTEBOP fit of the sector-78 light-curve with the imposition of the spectroscopic light ratio of 0·79±0·04 reported by LCS04. The uncertainties in the fractional radii were decreased by roughly a factor of 1·5 with respect to the solution without the light ratio, and application to all sectors results in a tighter clustering of parameter values.

Our results are in good agreement with the spectroscopic light ratio, but are independent of it; our tests show that a more precise light ratio than this is needed to measure the radii of the stars better.

Radial-velocity analysis

The *TESS* observations allow a more precise photometric model of the system, specifically for the orbital eccentricity and ephemeris. The eccentricity has been precisely measured above, but the ephemeris has not. We therefore fitted the light-curve containing each fully-observed eclipse (see above) with JKTEBOP to determine a precise ephemeris. We did not include published times of minimum because MU Cas experiences apsidal motion and analysis of that effect is outside the scope of the current work. The resulting ephemeris is

$$\text{Min I} = \text{BJD}_{\text{TDB}}\ 2459869{\cdot}229815(31) + 9{\cdot}65295307(29)E \qquad (1)$$

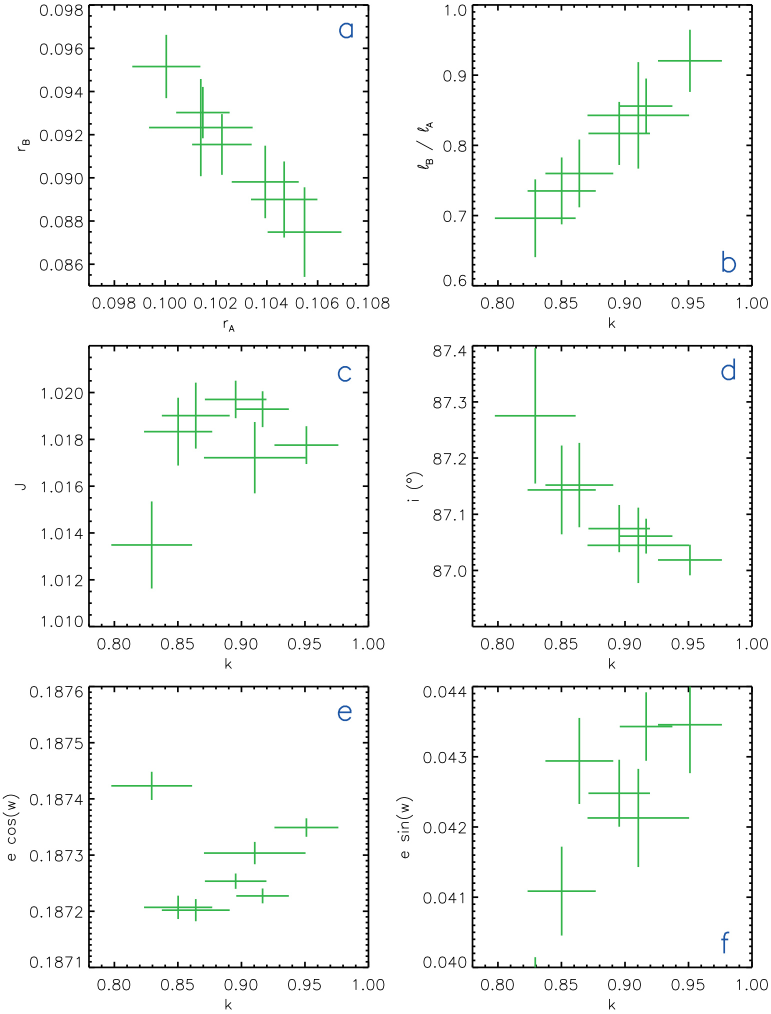

Fig. 3

Correlation plots from the JKTEBOP fits to the individual *TESS* sectors. The error bars in each case are the uncertainties obtained from Monte Carlo simulations.

where *E* is the number of cycles elapsed since the reference time.

Armed with this new information, it is worthwhile revisiting the spectroscopic orbit of the system. LCS04 obtained and presented 29 spectroscopic RV measurements for each star, which they fitted together with their photometric observations. We obtained the RVs from their table 2 and performed an independent fit with JKTEBOP. We fixed the parameters of the system except for the argument of periastron (to allow for possible apsidal motion), and the velocity amplitudes (K_A and K_B) and systemic velocities ($V_{\gamma,A}$ and $V_{\gamma,B}$) of the stars. We did not force $V_{\gamma,A}$ to equal $V_{\gamma,B}$ but their fitted values agree well. We also allowed for a phase offset *versus* the orbital ephemeris above, to account for shifts due to apsidal motion or time-conversion errors. The data were not provided with error bars so we adopted a single uncertainty for all RVs per star and adjusted it to force a reduced χ^2 of unity for each star.

The best fit to the LCS04 RVs is shown in Fig. 4 and is practically identical to that presented in fig. 1 of LCS04. We found $K_A = 105{\cdot}83 \pm 0{\cdot}85$ km s^{-1}, $K_B = 107{\cdot}86 \pm 0{\cdot}95$ km s^{-1}, $V_{\gamma,A} = -35{\cdot}57 \pm 0{\cdot}55$ km s^{-1} and $V_{\gamma,B} = -35{\cdot}49 \pm 0{\cdot}66$ km s^{-1}. The argument of periastron ($\omega = 10^\circ{\cdot}8 \pm 1^\circ{\cdot}4$) agrees with the photometric value in Table II, and the phase offset [$\Delta\phi = (8 \pm 9) \times 10^{-5}$] is consistent with zero. The error bars quoted here were obtained from Monte Carlo simulations[32].

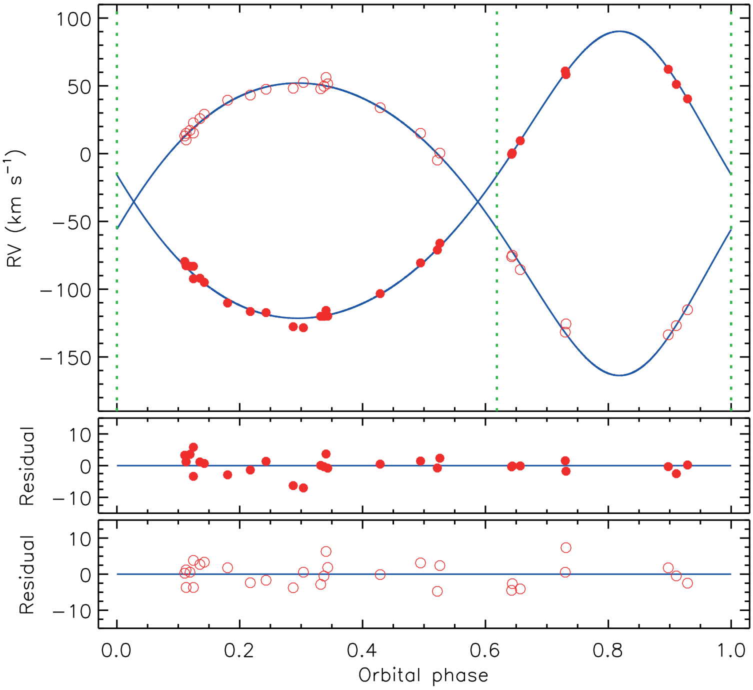

FIG. 4

RVs of MU Cas from LCS04 (filled red circles for star A and open red circles for star B), compared to the best fit from JKTEBOP (solid blue lines). The times of eclipse are given using vertical green dotted lines. The residuals are given in the lower panels separately for the two components.

Physical properties and distance to MU Cas

We determined the physical properties of MU Cas using the JKTABSDIM code[34] and the results from the light- and RV-curve analyses given above. The masses are measured to 1·9% precision and the radii to 0·9% (star A) and 1·2% (star B) precision. When comparing to LCS04 we find our results are in good agreement but with the identities of the two stars interchanged. The pseudo-synchronous rotational velocities of the stars are consistent with the values of 22 ± 2 km s^{-1} and 21 ± 2 km s^{-1} measured by LCS04.

The photometric analysis of LCS04 proceeded with the primary (deeper) eclipse being at phase zero; the secondary eclipse was at phase 0·62 in agreement with the current work. They then chose to swap the two stars to make the primary the hotter of the two; this also made it the smaller, less-massive, and less-luminous component. Our analysis proceeded in the same way but without the swap, so our star A is the larger, cooler, and more-massive object. The primary eclipse is deeper than the secondary eclipse, despite the inverted $T_{\rm eff}$ ratio, because a larger projected stellar area is eclipsed at primary than secondary. A good example of this situation can be found in our recent analysis of V454 Aur[35].

LCS04 settled on a mean $T_{\rm eff}$ for the system of 14 900 ± 500 K from a set of calibrations based on *UBV* and *uvby* photometry, which is consistent with but slightly below the expected value for B5 V stars[36,37]. Combining this value with the ratios of the surface brightnesses and radii from Table II, and equations 5 and 6 from Southworth[35], gives $T_{\rm eff}$ values of 14 870 ± 500 and 14 940 ± 500 K for stars A and B, respectively. These values are given in Table III and are much closer together than those measured by LCS04, as expected from the surface-brightness ratio being only slightly above unity.

We used the results in Table III, combined with the *BV* and JHK_s apparent magnitudes from Table I and the bolometric corrections from Girardi *et al.*[38], to determine the distance to MU Cas. The 2MASS JHK_s observations were taken at orbital phase 0·268 so correspond to the out-of-eclipse brightness of the system. An interstellar reddening value of $E(B-V)$ = 0·44 ± 0·05 mag is needed to align the *BV* and JHK_s distances, in good agreement with the $E(B-V)$ = 0·50 ± 0·08 mag suggested by the STILISM reddening maps[★][39]. The most precise distance estimate from this work is in the K_s band and is 1814 ± 37 pc, slightly shorter than the *Gaia* DR3[16] value of 1948 ± 73 pc (a difference of 1·8σ). We are confident in our measurement of the radii of the stars — especially in their sum, which is more important than the ratio for distance measurement — so the discrepancy could indicate that the $T_{\rm eff}$ values of the stars are higher than inferred by LCS04. We experimented with adding a plausible 1000 K to the $T_{\rm eff}$ values, finding that this required an extra 0·01 mag of $E(B-V)$ and gave a distance larger by 54 pc. This partial solution to the issue could be checked by obtaining a spectroscopic estimate of the $T_{\rm eff}$ values of the stars.

TABLE III

Physical properties of MU Cas defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 33).

Parameter	*Star A*	*Star B*
Mass ratio $M_{\rm B}/M_{\rm A}$	0·981 ± 0·012	
Semi-major axis of relative orbit ($\mathcal{R}^{\rm N}_{\odot}$)	40·06 ± 0·23	
Mass ($\mathcal{M}^{\rm N}_{\odot}$)	4·674 ± 0·091	4·586 ± 0·084
Radius ($\mathcal{R}^{\rm N}_{\odot}$)	4·117 ± 0·039	3·653 ± 0·045
Surface gravity (log[cgs])	3·879 ± 0·007	3·974 ± 0·010
Density ($\rho_{\odot}$)	0·0670 ± 0·0015	0·0940 ± 0·0031
Synchronous rotational velocity (km s^{-1})	21·57 ± 0·20	19·15 ± 0·24
Effective temperature (K)	14870 ± 500	14940 ± 500
Luminosity $\log(L/\mathcal{L}^{\rm N}_{\odot})$	2·873 ± 0·059	2·778 ± 0·059
$M_{\rm bol}$ (mag)	−2·44 ± 0·15	−2·20 ± 0·15
Interstellar reddening $E(B-V)$ (mag)	0·44 ± 0·05	
Distance (pc)	1814 ± 37	

[★] https://stilism.obspm.fr/

Summary and conclusions

MU Cas is a dEB containing two B5 V stars in an orbit of period 9·653 d and eccentricity 0·192. We used light-curves from seven sectors of observations using *TESS*, combined with spectroscopic results from LCS04, to determine the physical properties of the system. Our results are in good agreement with those of LCS04 save for an interchange of the identities of the two stars: the primary star in the current work is the larger and more massive of the two, but has evolved to be the cooler component. That the primary (deeper) eclipse corresponds to the obscuration of the cooler star is a result of the orientation of the eccentric orbit, which causes a greater stellar area to be eclipsed during primary than secondary eclipse. The precision of our results is limited by the ratio of the radii, which is poorly measured from the deep but partial eclipses produced by the system, and the scatter in the available RVs.

We find a distance to the system of 1814 ± 37 pc, 1·8σ shorter than the distance of 1948 ± 73 pc from the *Gaia* DR3 parallax. A possible solution to this difference is that the stars are hotter than given in Table III. The system deserves detailed spectroscopic study in order to check and confirm the $T_{\rm eff}$ values, measure more precise RVs to help the determination of the masses, and obtain a new spectroscopic light ratio to determine the radii of the stars better.

We compared the measured properties of MU Cas to the predictions of the PARSEC theoretical stellar-evolutionary models[40] to check the level of agreement between observation and theory, and to infer the age of the system. A metal abundance of $Z = 0{\cdot}017$ and an age of 87 ± 5 Myr provides excellent agreement with the measured $T_{\rm eff}$ values and acceptable agreement with the measured radii.

The properties of both components are in the range where slowly-pulsating B-stars are found[41–43], prompting us to conduct a search for pulsations. The data from *TESS* sectors 57 and 58 were chosen as they provide the longest quasi-contiguous temporal coverage, a JKTEBOP fit was performed, and the residuals of the fit fed to the PERIOD04 code[44]. No significant periodicities were found, with 3σ limits of 0·2 mmag for frequencies from 0·4 d^{-1} to the Nyquist limit (359 d^{-1}) and 1 mmag for frequencies of 0·0–0·4 d^{-1}.

A final remark is that our work has failed to improve significantly the measurements of the properties of MU Cas from the previous analysis by LCS04. The huge advance in the quality of the available light-curves was not useful because the ratio of the stellar radii remains poorly determined due to degeneracies between fitted parameters. A detailed spectroscopic analysis is recommended instead, and the reader is reminded that it is good scientific practice to publish results even if they are uninteresting[45], especially if they act as independent confirmation of existing work[46] (see also the *Journal of Trial & Error**).

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*https://journal.trialanderror.org/

Space Agency (ESA) mission *Gaia*[⋆], processed by the *Gaia* Data Processing and Analysis Consortium (DPAC[†]). 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 arχiv scientific paper preprint service operated by Cornell University.

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CORRESPONDENCE

To the Editors of 'The Observatory'

Rosse versus Herschel: Rivalry among Great-Telescope Families.

In 2023 the dispersal began through an Irish auction-house of part of the Birr Castle astronomical library of printed books. This will no doubt come as a surprise to some readers of this letter. The writer was thus fortunate to acquire two lots in the sale, including the Birr copy of Captain Smyth's *Cycle of Celestial Objects* 1844. The point of interest which prompts this letter is one of the marginal annotations in an evidently mid-19th Century hand[*] added by a previous owner, presumably the third Earl of Rosse, in Volume 2 of the *Bedford Catalogue*.

Appended to Smyth's entry for θ^1 Orionis on page 130 of that volume where Smyth remarks on the non-discovery of the fifth star 'E' by earlier observers in the words "Now when we consider the eye of Herschel,…" there is the following marginal comment in extremely faint pencil: "And his ill-defining telescopes, the non-appearance of this star in the 40 foot proves the utter worthlessness of that gigantic humbug" (Fig. 1). There may be some justice in this uncharitable assessment of the optical quality of Herschel's 40-foot, which was in any case never routinely used by its maker as a working instrument in his major observational programmes. The remark is, however, totally unfounded with respect to Herschel's smaller telescopes, as for instance amply proven by the astonishing performance of the '7-foot' of only 6·2-inches aperture[†] on close double stars: on that instrument the great binastrist not infrequently used magnifications of ×932 or even higher as standard working powers and discovered a number of binaries when at 1-arc-second separation or even less — ζ Cancri AB, *ω* Leonis, η Coronae, ξ Scorpii AB, *et al*…[‡].

[*] For instance, using the archaic long 'S'. In fact, the style of hand bears a very close similarity to that of the caption on Rosse's original 1845 April sketch of M51 Canum Venaticorum as reproduced on page 233 of C. Mollan's *William Parsons, 3rd Earl of Rosse* (Manchester University Press), 2014.

[†] The 'Uranus' 7-foot telescope.

[‡] These were all discovered with the 7-foot in 1780–82 during Herschel's early single-handed 'Second Review' of the heavens, a specifically high-power examination of individual bright stars. Contrary to a widespread myth this work was not conducted jointly with Caroline at the much larger 20-foot, which instrument contributed negligibly to this systematic search for very close double stars. The famous 20-foot 'Sweeps' performed by the Caroline & William partnership were a completely separate research programme commenced in 1784 and using far lower powers.