certain assumptions that you are taking that lead to errors in the areas that you are looking for, or is it other assumptions that you are finding through SPI which leads to those things? It is a very complex situation.

Dr. Lovell. To first order it is the environment. These FLARES regions are large enough that they are capturing cosmological representatives of populations of galaxies. They are rare enough that they are producing rare galaxies but you are right, for a given over-density there is still a lot of scatter in the predicted properties when you add in the galaxy attributes. For certain regions that you think will be very rare there is actually a spread in the rarity of these objects. Otherwise, as you add in the forward modelling that also increases the variance as well so it's not a case of a very simple one-to-one mapping on just the over-density.

The President. One more question.

Reverend Barber. Can you model the very early objects we see with the *James Webb Space Telescope* — the massive black holes, *etc.*?

Dr. Lovell. Yes, is the short answer. We essentially stop the simulations at a redshift of five, so FLARES is very much focussed on *JWST* and early galaxies and it has already been used to explore and place some limits on those very early galaxies. FLARES seems to do quite well at matching some of these early results that suggested attention with our previous understanding of abundances and masses of galaxies. FLARES does slightly better than some other models and we believe that part of that is due to our simulation approach — we are actually catching these rare objects that *JWST* is seeing and other models are able to probe but they don't have the volume to do it. With that said, there have been a few papers in the past few weeks where FLARES is still struggling to produce enough of these very massive things. FLARES is not the end of the story but it is an important contribution.

The President. With that I fear I have to wrap up. Everything you have heard today was beautifully presented and absolutely fascinating and I think we should give a big round of applause to all our speakers [applause]. I should say that Dr. Siân Prosser has produced an exhibition in the Library about Chandrasekhar and Eddington. The next meeting will be on the second Friday of February (14th).

REDISCUSSION OF ECLIPSING BINARIES. PAPER 25: THE CHEMICALLY-PECULIAR SYSTEM AR AURIGAE

By John Southworth

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AR Aur is a detached eclipsing binary containing two late-B stars which are chemically peculiar, on a circular orbit of period 4·135 d. The primary is a HgMn star which shows temporal changes in its chemical abundances and spectral-line profiles, whilst the secondary is a likely weak Am star. Published analyses of the system have used spectroscopic light ratios to constrain the eclipse models and found that the secondary star is larger than the primary. This unexpected outcome has been taken as an indication that the system is young and the secondary has yet to reach the main sequence. In this work we present the first analysis of the light-curve of the system obtained by the *Transiting Exoplanet Survey Satellite* (*TESS*), whose quality allows us to avoid using a spectroscopic light ratio to constrain the solution. When combined with literature spectroscopic results we obtain highly precise masses of $2{\cdot}544 \pm 0{\cdot}009\ M_\odot$ and $2{\cdot}366 \pm 0{\cdot}009\ M_\odot$ and radii of $1{\cdot}843 \pm 0{\cdot}002\ R_\odot$ and $1{\cdot}766 \pm 0{\cdot}003\ R_\odot$. The light ratio is inconsistent with spectroscopic determinations, confirming the suggestion of Takeda[1] that spectroscopic light ratios of the system are unreliable due the chemical peculiarity of the stars. The properties of the system are matched by theoretical predictions for a slightly super-solar metallicity and an age of 33 ± 3 Myr: both components are young main-sequence stars.

Introduction

The detached eclipsing binary system (dEB) AR Aurigae has been suggested to be a young object in which the secondary component is still a pre-main-sequence star[2]. This claim was based on the less-massive star having a larger radius and lower surface gravity, caused by using a spectroscopic light ratio (SLR) as a constraint in the eclipse modelling. A recent work by Takeda[1] questioned this claim because at least one of the stars is chemically peculiar, making light ratios from spectroscopic absorption lines unreliable. In this work we present an analysis of a new space-based light-curve which does not use an SLR as a constraint, confirms the suggestion by Takeda, and yields improved measurements of the physical properties of the AR Aur system.

The current work is presented in the context of our series of papers which revisit known dEBs[3] for which higher-quality light-curves are now available[4]. The ultimate aim is to measure the masses and radii of the component stars to 2% precision[5,6] and enable their inclusion in the *Detached Eclipsing Binary Catalogue*[7] (*DEBCat**).

AR Aurigae

AR Aur (Table I) has a long observational history, and was the first dEB known in which one component is a chemically-peculiar star of the HgMn type. The discovery of eclipses was made in 1931 by Pedersen & Steengaard[16], who subsequently measured an orbital period of $P_{\rm orb} = 2{\cdot}076$ d[17]. It was named AR Aurigae in Prager's Katalog of 1936. Spectroscopic observations by Harper[18] and Wyse[19] showed that the $P_{\rm orb}$ is double this, provided the first measurements of the velocity amplitudes of the two stars ($K_{\rm A}$ and $K_{\rm B}$), and yielded an SLR of approximately 0·9 from the 4481-Å and 4549-Å spectral lines. Nassau[20] confirmed that the primary and secondary eclipses have a slightly different depth, and obtained $P_{\rm orb} = 4{\cdot}134581$ d.

Photoelectric photometric studies were made by Huffer & Eggen[21], who adopted an SLR of $0{\cdot}86 \pm 0{\cdot}04$ in their analysis, and Johansen[22] using filters similar to the Strömgren *uvby* system. The data from these two papers were

* https://www.astro.keele.ac.uk/jkt/debcat/

modelled by Cester *et al.*[23] and similar results obtained. O'Connell[24] presented *UBV* photometry and found a change in P_{orb}. Adelman[25] obtained *uvby* photometry mostly outside eclipse and found no additional variability.

Nordström & Johansen[2] (hereafter NJ94) presented a detailed analysis of AR Aur using a precise SLR and the EBOP code to model the light-curves from O'Connell[24] and Johansen[22]. Radial-velocity (RV) measurements were taken from Harper[18] and Wyse[19]. The SLR was obtained by Dr. Graham Hill using the Mg II 4481-Å lines and based on seven spectra taken around quadrature phases. When corrected for the slow change of line strength with effective temperature (T_{eff}), an SLR of 0·866 ± 0·018 was found which gave the ratio of the radii to be $k = R_B/R_A = 1{\cdot}020 \pm 0{\cdot}015$. One outcome of their analysis was that the surface gravity of the secondary star (star B) was lower than that of the primary (star A); this was (with caveats) interpreted as indicating the system was young and star B was still in the final stages of contracting onto the zero-age main sequence.

TABLE I

Basic information on AR Aurigae. The BV magnitudes are each the mean of 111 individual measurements[8] distributed approximately randomly in orbital phase. The JHK$_s$ magnitudes are from 2MASS[9] and were obtained at an orbital phase of 0·23.

Property	*Value*	*Reference*
Right ascension (J2000)	$08^h18^m18^s.896$	10
Declination (J2000)	+33°46′02″·52	10
Bright Star Catalogue	HR 1728	11
Henry Draper designation	HD 34364	12
Hipparcos designation	HIP 24740	13
Tycho designation	TYC 2398-1311-1	8
Gaia DR3 designation	181983575426242944	14
Gaia DR3 parallax (mas)	7·0735 ± 0·0461	14
TESS Input Catalog designation	TIC 144085463	15
B magnitude	6·102 ± 0·014	8
V magnitude	6·144 ± 0·010	8
J magnitude	6·190 ± 0·019	9
H magnitude	6·254 ± 0·017	9
K_s magnitude	6·265 ± 0·023	9
Spectral type	B9 V + B9·5 V	2

Spectral characteristics

The chemical peculiarity of AR Aur was first shown by Wolff & Wolff[26] on the basis of an enhanced Hg II 3984-Å line in star A. More detailed analysis by Wolff & Preston[26] confirmed that star A is a HgMn star and found that star B did not show spectral peculiarities. Takeda *et al.*[27] found changes in the strength and profile of the 3984-Å line of star A and noted that star B appeared normal in their spectra. However, Stickland & Weatherby[28] found enhanced Hg II in *both* components. Khokhlova *et al.*[29] described star A as a typical HgMn star and found that star B showed a different type of chemical peculiarity. Zverko *et al.*[30] found Mn, Ba, and Pt to be overabundant in both stars.

Hubrig *et al.*[31] found line-profile variability for many chemical elements in star A, but none in star B. The projected rotational velocities for both components were measured as $V \sin i = 22 \pm 1$ km s^{-1}. In a subsequent analysis, Hubrig *et al.*[32] found both stars to have a weak magnetic field from spectropolarimetric observations. Those authors also used Doppler tomography to detect strong enhancements of Fe and Y in spots on the surface of star A. The presence of magnetic fields in HgMn stars has been controversial but several detections now exist[33,34].

Folsom *et al.*[35] presented an extensive analysis of atmospheric properties of AR Aur. They (re)confirmed the HgMn nature of star A and that star B shows weak features of being an Am star. They measured the $T_{\rm eff}$ values of the stars, an SLR consistent with that from NJ94, and precise $K_{\rm A}$ and $K_{\rm B}$ values.

Similar conclusions were obtained by Takeda *et al.*[36]. The detailed abundance measurements in this and papers mentioned above typically disagree by more than their uncertainties, suggesting that the measured abundances are variable over time. Takeda[1] presented further abundance measurements, obtained precise $T_{\rm eff}$ values, and pointed out that the SLRs found in previous work may be unreliable as both stars are chemically peculiar; it was this work that prompted the current analysis.

Nearby stars

The multiplicity of AR Aur is of interest. Firstly, it is a member of the Auriga OB1 association[37]. Secondly, it forms a common-proper-motion pair with the A0p star HR 1732 (IQ Aur). This was originally found by W. P. Bidelman, reported by Hoffleit[37] in the Third Revised Edition of her *Catalogue of Bright Stars*, and confirmed by Sargent & Eggen[38]. Thirdly, there is a third component on a wider orbit in the system which manifests as changes in the observed $P_{\rm orb}$ of the inner binary.

Guarnieri *et al.*[39] found $P_{\rm orb}$ to be variable from an $O-C$ (observed minus calculated) diagram which showed a parabolic trend of the residuals of a linear fit to the times of mid-eclipse. Zverko *et al.*[40] suggested this was due to the light-time-travel effect caused by a third star in a wider orbit. Chochol *et al.*[41] found the period of this third body, P_3, to be between 24·75 and 27·09 yr. NJ94 fitted the times of minimum light to obtain $P_3 = 24{\cdot}18 \pm 0{\cdot}21$ yr, with an amplitude of 0·0094 d and a probable small eccentricity of $e_3 = 0{\cdot}17$. Albayrak *et al.*[42] and Zasche[43] have progressively refined the orbital properties of the third body.

Wilson & Van Hamme[44] presented a detailed reanalysis of the AR Aur system. Aside from measuring masses to (a questionable) 0·2% and radii to 0·5%, they obtained $P_3 = 23{\cdot}452 \pm 0{\cdot}096$ yr and $e_3 = 0{\cdot}262 \pm 0{\cdot}023$. They also found the minimum mass of the third body to be $0{\cdot}5122 \pm 0{\cdot}0087\ M_\odot$ — a single main-sequence star of this mass would be much fainter than either of the eclipsing stars, and if it were a binary or a white dwarf it would be fainter still.

Photometric observations

AR Aur was observed in eight sectors (19, 43, 44, 45, 59, 71, 73, and 86) by the NASA *Transiting Exoplanet Survey Satellite*[45] (*TESS*). In all cases data are available at 120-s cadence and were used for our analysis below. Lower-cadence observations (200, 600, and/or 1800 s) are also available for all sectors but were not used due to their lower time resolution. The data were downloaded from the NASA Mikulski Archive for Space Telescopes (MAST*) using the LIGHTKURVE package[46].

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

We adopted the simple aperture photometry (SAP) light-curves from the SPOC data-reduction pipeline[47] for our analysis, and rejected low-quality data using the quality flag "hard". Additional data points from sectors 73 and 86 were rejected manually due to gaps and increased scatter. The remaining 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 19; the remaining sectors are similar but for clarity are not plotted.

We queried the *Gaia* DR3 database* for all sources within 2 arcmin of AR Aur. A lot of sources were returned — 147 — due to the proximity of the Galactic plane. All are fainter by at least 4·2 mag in the *Gaia* G_{RP} band, so the contamination of the *TESS* light-curve should be small. This is backed up by the CROWDSAP parameter from *TESS*, which depends on the sector but is typically in the region of 0·98.

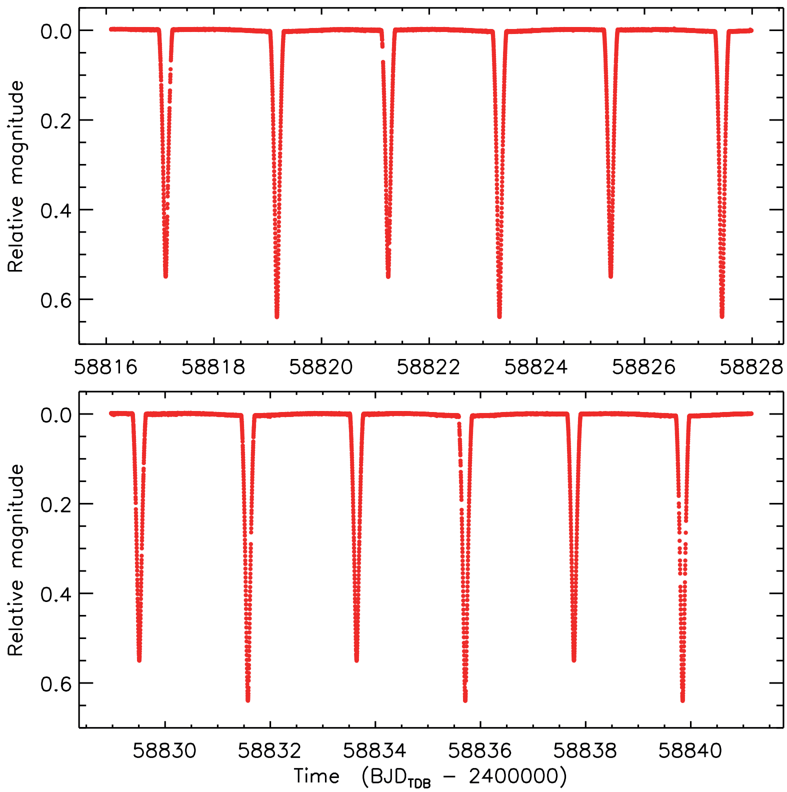

FIG. 1

TESS sector-19 photometry of AR Aur. The flux measurements have been converted to magnitude units after which the median was subtracted. The other seven sectors used in this work are similar but are not plotted for reasons of space.

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

Light-curve analysis

The components of AR Aur are well-detached and almost spherical, so the light-curve is suitable for analysis using the JKTEBOP* code[48,49]. We modelled the light-curves from each sector individually to check for consistency and to guard against small changes in the amount of contaminating light between sectors. We defined star A to be the star eclipsed at the primary (deeper) eclipse, and star B to be its companion. These identities are consistent with the literature discussed above.

The fitted parameters were the fractional radii of the stars (r_A and r_B), expressed as their 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 was assumed as there is no evidence for orbital eccentricity. Limb darkening (LD) was accounted for using the power-2 law[50–52] and we required both stars to have the same LD coefficients. The linear coefficient (c) was fitted and the non-linear coefficient (α) fixed at a theoretical value[53,54]. The observational uncertainties supplied with the *TESS* flux measurements were scaled to force a reduced χ^2 of $\chi^2_\nu = 1{\cdot}0$.

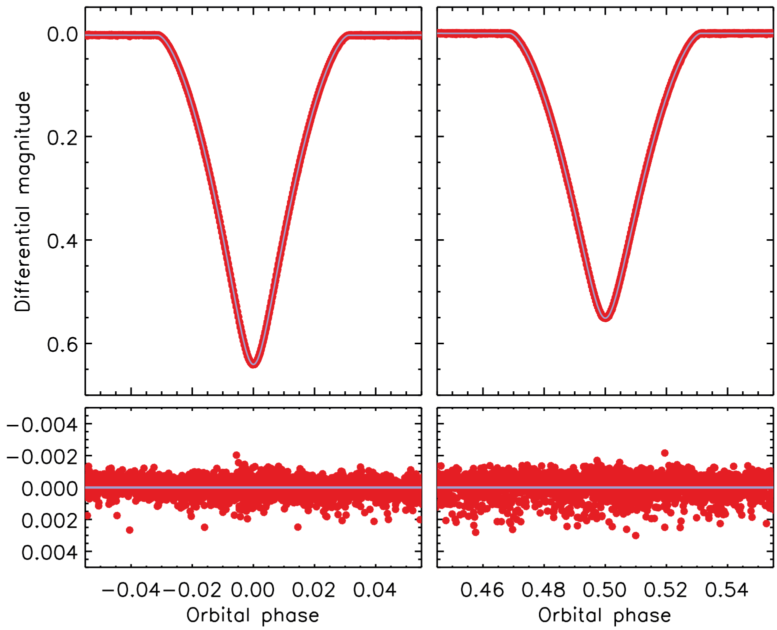

FIG. 2

JKTEBOP best fit to the light-curves of AR Aur 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.

*http://www.astro.keele.ac.uk/jkt/codes/jktebop.html

TABLE II

Photometric parameters of AR Aur measured using JKTEBOP *from the light-curves from all eight TESS sectors. The error bars are 1σ and were obtained from the scatter of the results for individual sectors.*

Parameter	*Value*
Fitted parameters:	
Orbital inclination (°)	88·6000 ± 0·0072
Sum of the fractional radii	0·19596 ± 0·00007
Ratio of the radii	0·9578 ± 0·0013
Central-surface-brightness ratio	0·89939 ± 0·00032
Third light	0·0152 ± 0·0027
LD coefficient c	0·553 ± 0·014
LD coefficient α	0·4318 (fixed)
Derived parameters:	
Fractional radius of star A	0·100089 ± 0·000052
Fractional radius of star B	0·095870 ± 0·000092
Light ratio ℓ_B/ℓ_A	0·8249 ± 0·0023

We found that the fits to all sectors were excellent; an example for sector 19 is shown in Fig. 2. The parameters were also highly consistent between sectors, inspiring confidence in the results. In Table II we report the adopted values of the photometric parameters and their uncertainties. We calculated these by taking the unweighted mean and standard deviation of the values for the eight sectors. We did not divide by $\sqrt{8}$ to convert the latter to the standard error as the standard deviations are already very small. We also calculated uncertainties using Monte Carlo and residual-permutation algorithms (tasks 8 and 9 in JKTEBOP) and found that their mean values were similar to each other and to the standard deviation.

Our results differ significantly compared to previous analyses in that we find star B to be definitively fainter and smaller than star A. The radius ratio we find, 0·9578 ± 0·0013, is very different to published spectroscopic values (1·020 ± 0·015 from NJ94 and 1·033 ± 0·005 from ref. 35), and supports the assertion of Takeda[1] that SLRs are not reliable if one or both stars is chemically peculiar. The implications of this result are discussed below.

TABLE III

Times of minimum light measured for AR Aur. Each time is calculated from the data for a whole sector and corresponds to a midpoint of primary eclipse. The final two columns give the uncertainties calculated via the Monte Carlo and residual-permutation analyses, respectively.

Sector	T_0 (BJD_{TDB})	*MC error* (d)	*RP error* (d)
19	2458827·440864	0·000003	0·000004
43	2459484·849830	0·000002	0·000003
44	2459513·792354	0·000002	0·000004
45	2459534·465589	0·000002	0·000003
59	2459923·122341	0·000002	0·000004
71	2460245·624785	0·000003	0·000006
73	2460299·375195	0·000003	0·000007
86	2460650·820263	0·000004	0·000008

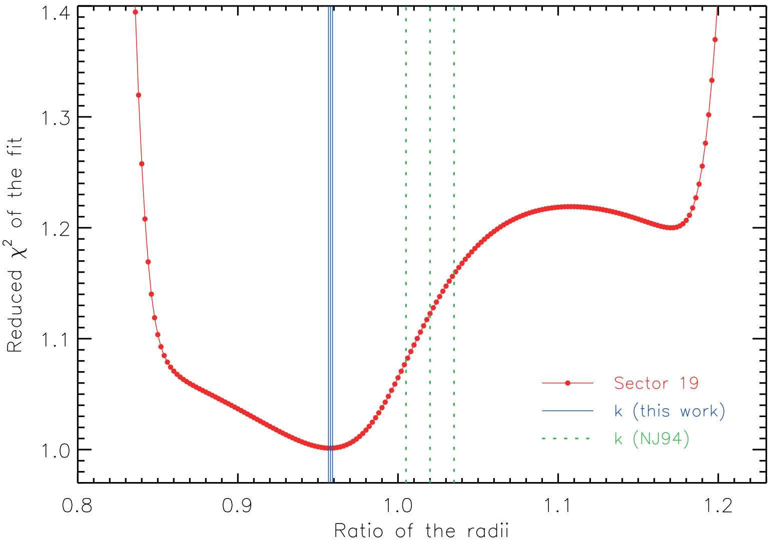

FIG. 3

Variation of χ^2_ν of the JKTEBOP fit to the light-curve from *TESS* sector 19 as a function of the ratio of the radii k (red line with points). Our overall best value and its uncertainty are shown with blue vertical lines, which are very close together. The k from NJ94 is shown with vertical green dotted lines.

To visualize this further we refitted the light-curve from sector 19 in the same way as above, but with k fixed at values from 0·8 and 1·2 at intervals of 0·002. The data uncertainties were scaled to give $\chi^2_\nu = 1{\cdot}0$ for the overall best fit. The result is shown in Fig. 3, where there is a clear minimum χ^2_ν corresponding to the adopted value of k in Table II. This k is significantly different to that found by NJ94 and supports our approach of not including an SLR in our light-curve fit.

It is beyond the scope of the current work to perform an analysis of the times of minimum light. In Table III we report the times of primary mid-eclipse we obtained — one per sector — for use by anyone who wishes to do so.

Physical properties and distance to AR Aur

We calculated the physical properties of AR Aur using the JKTABSDIM code[56] with the photometric properties from Table II and the P_{orb} from ref. 44. We adopted $K_A = 108{\cdot}36 \pm 0{\cdot}18$ km s^{-1} and $K_B = 116{\cdot}92 \pm 0{\cdot}17$ km s^{-1} from Hubrig *et al.*[33], and the T_{eff} values from Folsom *et al.*[35]. The resulting physical properties are given in Table IV. The synchronous rotational velocities are consistent with the measured values[31].

Fig. 4 shows measurements of the masses and radii of the components of AR Aur from this work (squares) and from the literature (triangles and circles). Our use of the new *TESS* data and precise velocity amplitudes from ref. 33 allows us to reach a new level of precision in our measurements. Not using an SLR to constrain the ratio of the radii causes us to find a steeper mass–radius relation than previous measurements.

TABLE IV

Physical properties of AR Aur defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 55).

Parameter	*Star A*	*Star B*
Mass ratio M_B/M_A	0·9268 ± 0·0020	
Semi-major axis of relative orbit ($R^N_\odot$)	18·416 ± 0·020	
Mass ($M^N_\odot$)	2·5444 ± 0·0086	2·3658 ± 0·0085
Radius ($R^N_\odot$)	1·8433 ± 0·0022	1·7658 ± 0·0026
Surface gravity (log[cgs])	4·3125 ± 0·0008	4·3169 ± 0·0011
Density ($\rho_\odot$)	0·4063 ± 0·0007	0·4285 ± 0·0013
Synchronous rotational velocity (km s^{-1})	22·555 ± 0·027	21·604 ± 0·031
Effective temperature (K)	10950 ± 150	10350 ± 150
Luminosity log($L/L^N_\odot$)	1·644 ± 0·024	1·508 ± 0·025
M_{bol} (mag)	0·631 ± 0·060	0·969 ± 0·063
Interstellar reddening $E(B-V)$ (mag)	0·01 ± 0·01	
Distance (pc)	136·4 ± 1·7	

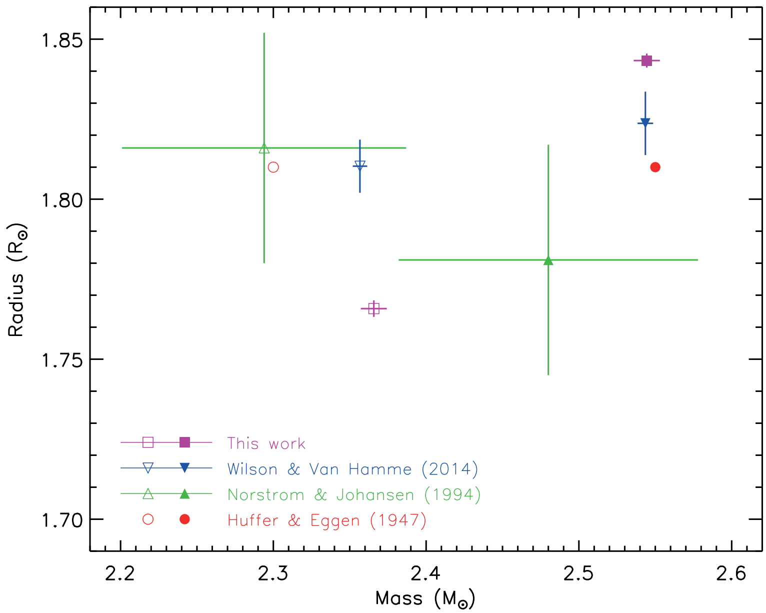

FIG. 4

Mass–radius plot for the components of AR Aur showing the results from the current work and from the literature. Star A is shown with filled symbols and star B with open symbols. No uncertainties were given by Huffer & Eggen[21].

We determined the distance to the system using the *BV* magnitudes from *Tycho*[8], *JHK*$_s$ magnitudes from 2MASS[9], and bolometric corrections from Girardi *et al.*[57]. An interstellar reddening of $E(B-V) = 0{\cdot}01 \pm 0{\cdot}01$ satisfactorily equalizes the distance measurements in the optical and infrared. The resulting distance to the system in the K_s band is $136{\cdot}4 \pm 1{\cdot}7$ pc, which is $2{\cdot}6\sigma$ shorter than the *Gaia* DR3[10] value of $141{\cdot}4 \pm 0{\cdot}9$ pc.

A comparison with the theoretical predictions of the PARSEC 1·2 theoretical stellar evolutionary models[58] finds a good agreement for a metal abundance of $Z = 0{\cdot}020$ and an age of 33 ± 3 Myr after the zero-age main sequence. A lower Z of 0·017 and an age of 59 Myr predicts a mass–radius relation steeper than observed so is disfavoured. A higher Z of 0·030 can be ruled out as its zero-age main sequence predicts radii over 20σ larger than we have measured. The $T_{\rm eff}$ values proposed by Takeda[1] are higher by 200 K for star A and 300 K for star B, and do not match the theoretical predictions as well as the $T_{\rm eff}$ values we have adopted. This analysis confirms that the system contains two young main-sequence stars, and disproves earlier claims that star B is pre-main-sequence.

Summary and conclusions

AR Aur is a system containing a dEB of two late-B stars in an orbit of period 4·135 d, and a lower-mass outer component with a period of 23·5 yr around the inner binary. Star A is established as a HgMn star and star B has been found to show abundances characteristic of a weak Am star. These chemical peculiarities appear to have led to erroneous radius measurements in the past, caused by the use of a spectroscopic light ratio to help specify the ratio of the radii of the stars.

We have modelled eight sectors of data from the *TESS* mission using the JKTEBOP code, and found that the radii of the stars are very well-determined by these exceptionally good data. Combined with published spectroscopic velocity amplitudes we have determined the stars' masses to 0·35% and their radii to 0·15%. The properties of the system match theoretical predictions for a metallicity of $Z = 0{\cdot}020$ and an age of 33 ± 3 Myr, indicating that both components are young main-sequence stars. The distance we determine to the system is $2{\cdot}6\sigma$ shorter than the *Gaia* DR3 value; this moderate discrepancy may be due to the photospheric chemical peculiarity of the system.

We searched for pulsations by feeding the residuals of the fits to the light-curves from *TESS* sectors 43, 44, and 45 to the PERIOD04 code[59]. We found two significant frequencies, corresponding to once and twice the orbital frequency and thus explicable by slight imperfections in the light-curve model. No other significant frequencies were detected up to the Nyquist limit of 359 d^{-1}. Brightness variations on the surface caused by chemical peculiarity are a plausible reason for the signals at once and twice the orbital frequency, but if so are very weak.

Our work on AR Aur therefore yields extremely precise parameter measurements which are consistent with theoretical predictions. The measured values are inconsistent with the hypothesis that star B is a pre-main-sequence star, but do support the assertion by Takeda[1] that spectroscopic light ratios of this system are not reliable due to the chemical peculiarity of both stars. We are left in the unusual and encouraging position of stating that no further work is needed on this system, perhaps save for a refined third-body orbit and a systematic monitoring of the photospheric abundances of the stars to search for temporal changes.

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References

(1) Y. Takeda, *Research in Astronomy and Astrophysics*, **25**, 025016, 2025.
(2) B. Nordstrom & K. T. Johansen, *A&A*, **282**, 787, 1994.
(3) J. Southworth, *The Observatory*, **140**, 247, 2020.
(4) J. Southworth, *Universe*, **7**, 369, 2021.
(5) J. Andersen, *A&ARv*, **3**, 91, 1991.
(6) G. Torres, J. Andersen & A. Giménez, *A&ARv*, **18**, 67, 2010.
(7) J. Southworth, in *Living Together: Planets, Host Stars and Binaries* (S. M. Rucinski, G. Torres & M. Zejda, eds.), 2015, *Astronomical Society of the Pacific Conference Series,* vol. 496, p. 321.
(8) E. Høg *et al.*, *A&A*, **355**, L27, 2000.
(9) R. M. Cutri *et al.*, *2MASS All Sky Catalogue of Point Sources* (NASA/IPAC Infrared Science Archive, Caltech, US), 2003.
(10) Gaia Collaboration, *A&A*, **674**, A1, 2023.
(11) D. Hoffleit & C. Jaschek, *The Bright Star Catalogue* (Yale University Observatory, 5th ed.), 1991.
(12) A. J. Cannon & E. C. Pickering, *Annals of Harvard College Observatory*, **92**, 1, 1918.
(13) ESA (ed.), *The Hipparcos and Tycho Catalogues, ESA Special Publication*, vol. 1200, 1997.
(14) Gaia Collaboration, *A&A*, **649**, A1, 2021.
(15) K. G. Stassun *et al.*, *AJ*, **158**, 138, 2019.
(16) H. N. Pedersen & J. C. Steengaard, *Beobachtungs-Zirkulare der Astronomischen Nachrichten*, **13**, 70, 1931.
(17) H. N. Pedersen & J. C. Steengaard, *Beobachtungs-Zirkulare der Astronomischen Nachrichten*, **13**, 72, 1931.
(18) W. E. Harper *et al.*, *Journal of the Royal Astronomical Society of Canada*, **29**, 411, 1935.
(19) A. B. Wyse, *PASP*, **48**, 24, 1936.
(20) J. J. Nassau, *AJ*, **45**, 137, 1936.
(21) C. M. Huffer & O. J. Eggen, *ApJ*, **106**, 106, 1947.
(22) K. T. Johansen, *A&A*, **4**, 1, 1970.
(23) B. Cester *et al.*, *A&A*, **33**, 91, 1978.
(24) D. J. K. O'Connell, *Ricerche Astronomiche*, **8**, 563, 1979.
(25) S. J. Adelman, *A&AS*, **128**, 245, 1998.
(26) S. C. Wolff & R. J. Wolff, in *IAU Colloq. 32: Physics of Ap Stars* (W. W. Weiss, H. Jenkner & H. J. Wood, eds.), 1976, p. 503.
(27) Y. Takeda, M. Takada & M. Kitamura, *PASJ*, **31**, 821, 1979.
(28) D. J. Stickland & J. Weatherby, *A&AS*, **57**, 55, 1984.
(29) V. L. Khokhlova *et al.*, *Astronomy Letters*, **21**, 818, 1995.
(30) J. Zverko, J. Ziznovsky & V. L. Khokhlova, *Contributions of the Astronomical Observatory Skalnate Pleso*, **27**, 41, 1997.

★https://www.cosmos.esa.int/gaia

†https://www.cosmos.esa.int/web/gaia/dpac/consortium

(31) S. Hubrig *et al.*, *MNRAS*, **371**, 1953, 2006.
(32) S. Hubrig *et al.*, *MNRAS*, **408**, L61, 2010.
(33) S. Hubrig *et al.*, *A&A*, **547**, A90, 2012.
(34) S. Hubrig *et al.*, *MNRAS*, **495**, L97, 2020.
(35) C. P. Folsom *et al.*, *MNRAS*, **407**, 2383, 2010.
(36) Y. Takeda *et al.*, *MNRAS*, **485**, 1067, 2019.
(37) D. Hoffleit, *Catalogue of Bright Stars*, 1964.
(38) W. L. W. Sargent & O. J. Eggen, *PASP*, **77**, 461, 1965.
(39) A. Guarnieri, A. Bonifazi & P. Battistini, *A&AS*, **20**, 199, 1975.
(40) J. Zverko *et al.*, *IBVS*, **1997**, 1, 1981.
(41) D. Chochol *et al.*, *Bulletin of the Astronomical Institutes of Czechoslovakia*, **39**, 69, 1988.
(42) B. Albayrak, T. Ak & A. Elmasli, *AN*, **324**, 523, 2003.
(43) P. Zasche, *Ap&SS*, **296**, 127, 2005.
(44) R. E. Wilson & W. Van Hamme, *ApJ*, **780**, 151, 2014.
(45) G. R. Ricker *et al.*, *Journal of Astronomical Telescopes, Instruments, and Systems*, **1**, 014003, 2015.
(46) Lightkurve Collaboration, 'Lightkurve: Kepler and TESS time series analysis in Python', Astrophysics Source Code Library, 2018.
(47) J. M. Jenkins *et al.*, in *Proc. SPIE*, 2016, *Society of Photo-Optical Instrumentation Engineers* (*SPIE*) *Conference Series*, vol. 9913, p. 99133E.
(48) J. Southworth, P. F. L. Maxted & B. Smalley, *MNRAS*, **351**, 1277, 2004.
(49) J. Southworth, *A&A*, **557**, A119, 2013.
(50) D. Hestroffer, *A&A*, **327**, 199, 1997.
(51) P. F. L. Maxted, *A&A*, **616**, A39, 2018.
(52) J. Southworth, *The Observatory*, **143**, 71, 2023.
(53) A. Claret & J. Southworth, *A&A*, **664**, A128, 2022.
(54) A. Claret & J. Southworth, *A&A*, **674**, A63, 2023.
(55) A. Prša *et al.*, *AJ*, **152**, 41, 2016.
(56) J. Southworth, P. F. L. Maxted & B. Smalley, *A&A*, **429**, 645, 2005.
(57) L. Girardi *et al.*, *A&A*, **391**, 195, 2002.
(58) A. Bressan *et al.*, *MNRAS*, **427**, 127, 2012.
(59) P. Lenz & M. Breger, *Communications in Asteroseismology*, **146**, 53, 2005.

REVIEWS

General Post-Newtonian Orbital Effects. From Earth's Satellites to the Galactic Centre, by Lorenzo Iorio (Cambridge University Press), 2025. Pp. 282, 25 × 17·5 cm. Price £125/$160 (hardbound; ISBN 978 1 009 56287 4).

The title of this book neatly summarizes both it and many of the author's numerous papers, which have made his name well known. The book deals with many subtle issues which can, in principle, be examined by careful perturbative analysis of two-body motions in the Universe. Thus it is packed with formulae providing the effects on orbital elements (mainly) of perturbations from a wide variety of sources. Actually, while 'post-Newtonian' might to many readers mean 'relativistic' or, more widely, non-classical, the book actually also includes quite classical topics, such as the J2 perturbation of an oblate body, though these are often included as nuisance terms which, if omitted, might mimic the non-Newtonian effects of interest. Little is said of the effects of gravitational waves.

The kinds of effects under discussion are divided into about eight chapters, dealing separately with first- and second-order effects, gravitoelectric and gravitomagnetic relativistic effects, perturbations in non-standard dynamical theories, and so on. Each one of these chapters begins with a short introduction