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REDISCUSSION OF ECLIPSING BINARIES. PAPER 28: THE METALLIC-LINED SYSTEM DV BOÖTIS

By John Southworth

Astrophysics Group, Keele University, Staffordshire, ST5 5BG, UK

DV Boo is a detached eclipsing binary containing a metallic-lined A star and a chemically normal late-F star, in an orbit with a period of 3·783 d and a possible slight eccentricity. We use a light-curve from the *Transiting Exoplanet Survey Satellite* (*TESS*) and published spectroscopic results to determine the physical properties of the system to high precision. We find masses of $1{\cdot}617 \pm 0{\cdot}003\,M_\odot$ and $1{\cdot}207 \pm 0{\cdot}004\,M_\odot$, and radii of $1{\cdot}948 \pm 0{\cdot}008\,R_\odot$ and $1{\cdot}195 \pm 0{\cdot}022\,R_\odot$. The precision of the radius measurements is limited by the shallow partial eclipses and the unavailability of a spectroscopic light ratio due to the chemical peculiarity of the primary star. We measure a distance to the system of 125·0 ± 1·5 pc, in good agreement with the *Gaia* DR3 parallax, and an age of 1·3 Gyr. A comparison with theoretical models suggests the system has a modestly sub-solar metallicity, in conflict with the slightly super-solar photospheric abundances of the secondary star.

Introduction

Detached eclipsing binaries (dEBs) are a valuable source of direct measurements of the basic physical properties of normal stars.[1–3] From light- and radial-velocity (RV) curves it is possible to measure their masses and radii directly using geometry and celestial mechanics, and without reliance on theoretical stellar models. The current series of papers[4] is dedicated to using new space-based[5] light-curves of a significant number of dEBs to improve measurements of their physical properties.

In this work we present a study of DV Boötis (Table I), which consists of a metallic-lined (Am) primary component (hereafter star A) and a late-F secondary component (star B) which appears to be chemically normal. Such objects are well represented in the list of well studied dEBs[3] because a high fraction of Am stars are in short-period binaries[6–8] and because A-stars in dEBs are comparatively easy to study due to their quiet photospheres (no magnetic activity and usually no pulsations) and modest rotational velocities (allowing precise RV measurements).

DV Boötis

TABLE I

Basic information on DV Boötis. The BV magnitudes are each the mean of 92 individual measurements[9] *distributed approximately randomly in orbital phase. The JHKs magnitudes are from 2MASS*[10] *and were obtained at an orbital phase of* 0·13.

Property	*Value*	*Reference*
Right ascension (J2000)	$14^{h}22^{m}49^{s}\cdot698$	11
Declination (J2000)	$+14^{\circ}56'20''\cdot14$	11
Henry Draper designation	HD 126931	12
Hipparcos designation	HIP 70287	13
Tycho designation	TYC 915-464-1	9
Gaia DR3 designation	1228635253980613504	14
Gaia DR3 parallax (mas)	7·9495 ± 0·0274	14
TESS Input Catalog designation	TIC 450349567	15
B magnitude	7·945 ± 0·009	9
V magnitude	7·578 ± 0·009	9
J magnitude	6·836 ± 0·027	10
H magnitude	6·735 ± 0·029	10
Ks magnitude	6·704 ± 0·020	10
Spectral type	kA4hF1mF3(V) + F6/7V	16, 17

DV Boo was found to be eclipsing using photometry from the *Hipparcos* satellite[13], and was given its variable-star designation by Kazarovets *et al.*[18] Bidelman[19] specified it as an Am star; Grenier *et al.*[20] classified it as A3mA7F5, and McGahee *et al.*[16] updated that to kA4hF1mF3(V) following the standard approach of giving spectral classes for chemically peculiar stars based on their Ca I *K* line, hydrogen lines, and metal lines.

Carquillat *et al.*[17] obtained the first spectroscopic orbit of DV Boo, based on data from three spectrographs (*Élodie* plus two *Coravel* instruments) and comprising 48 radial-velocity measurements (RVs) for star A and 10 RVs for star B. They found a spectroscopic light ratio of 0·41 ± 0·05 from the ratio of the cross-correlation dips in their *Élodie* spectra, which corresponds to the ratio of the spectral-line strengths of the two components. That is not the same as a continuum light ratio due to the change in intrinsic line strength with temperature as well as the effect of the chemical peculiarity of star A. Carquillat *et al.* determined effective temperature ($T_{\rm eff}$) values of 7370 ± 80 K and 6410 ± 80 K, and a projected rotational velocity for star A of $V \sin i$ = 24·4 ± 2·4 km s^{-1}. Those authors also fitted the *Hipparcos* light-curve of the system to determine masses and approximate radii for the two components.

Kahraman Aliçavuş & Aliçavuş[21] presented an updated analysis of DV Boo based on the spectra from *Élodie*, additional archival spectra from the *FEROS* and *HARPS* échelle spectrographs, and three light-curves from small survey telescopes. They obtained mass and radius measurements to 0·25% and 2·5%, respectively, and $V \sin i$ values of 26 ± 2 and 17 ± 3 km s^{-1}. A detailed abundance analysis confirmed that star A is a typical Am star with underabundances of Ca and Sc and overabundances of iron-peak elements.

Catanzaro *et al.*[22] provided the most recent analysis of DV Boo, using a further 16 spectra from the *CAOS* échelle spectrograph at Catania Astrophysical Observatory. Those authors were the first to have access to a high-quality light-curve of the system, from the *Transiting Exoplanet Survey Satellite*[23] (*TESS*), which was modelled together with the RVs to determine the properties of the component stars. They (re)confirmed that star A is an Am star, found star B to have a normal photospheric chemical composition, and ruled out the existence of δ Scuti pulsations in the system.

Photometric observations

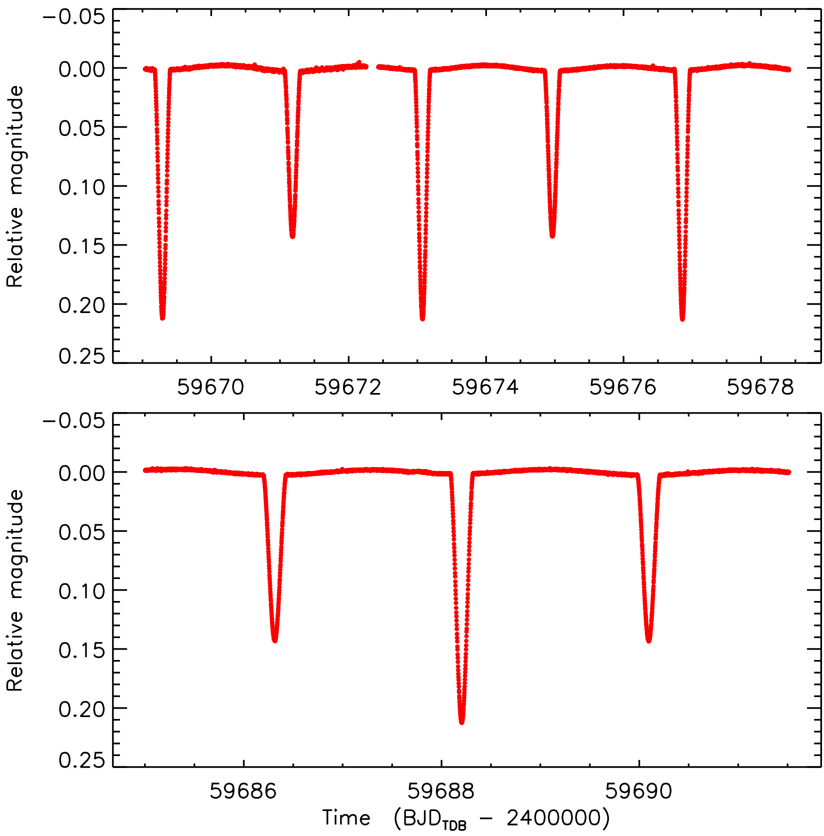

Fig. 1
TESS sector 50 photometry of DV Boo, including only the data analysed in the current work. The flux measurements have been converted to magnitude units and the median subtracted.

DV Boo has so far been observed by *TESS* in just one sector, 50, at a cadence of 120 s. We downloaded the SPOC (Science Processing Center[24]) light-curve from the NASA Mikulski Archive for Space Telescopes (MAST*) using the LIGHTKURVE package[25]. A significant portion of the light-curve is subject to quality flags, and specifying the 'hard' option returns a total of 12 948 data points. Those were converted into differential magnitudes and the median magnitude was subtracted for convenience. Isolated portions of the light-curve were then removed to leave two stretches of data containing five and three eclipses, respectively,

*https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html and totalling 11 273 data points. Fig. 1 shows the light-curve after that initial processing.

We queried the *Gaia* DR3 database* for all sources within 2 arcmin of DV Boo. Only 13 more objects were found, the brightest of which is fainter by G_{RP} = 9·3 mag, so we do not expect a significant amount of contaminating light in the *TESS* light-curves.

Light-curve analysis

TABLE II

Times of mid-eclipse for DV Boo and their residuals versus the fitted ephemeris. The ephemeris zeropoint was chosen to be during the TESS observations.

Orbital cycle	*Eclipse time (BJD_{TDB})*	*Uncertainty (d)*	*Residual (d)*	*Reference*
−3075·0	2448045·254	0·005	−0·00107	26
−3124·0	2447859·9071	0·0005	0·00112	17
−1839·0	2452720·5880	0·0010	−0·00343	27
−1153·0	2455315·4755	0·0036	−0·00325	28
−1066·0	2455644·56349	0·00098	−0·00447	29
−477·0	2457872·5360	0·0070	−0·00374	30
−476·5	2457874·4289	0·0025	−0·00228	31
−182·0	2458988·4224	0·0028	0·00546	32
0·0	2459676·856474	0·000006		This work[£]
103·0	2460066·4670	0·0080	−0·00080	33

[£]The eclipse time for the *TESS* observations was obtained from all data from sector 50. It was not included in the final JKTEBOP analysis to avoid double-use of data, but is given for reference.

The components of DV Boo are well-separated and suitable for analysis with the JKTEBOP† code[34,35], for which we used version 44. We fitted for the following 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 (J), third light (L_3), orbital inclination (i), orbital period (P), and a reference time of primary minimum (T_0). Limb darkening (LD) was accounted for using the power-2 law[36–38], the linear coefficients (c) were fitted, and the non-linear coefficients (α) were fixed at theoretical values[39,40]. The measurement errors were scaled to force a reduced χ^2 of χ^2_ν = 1·0. We additionally fitted for the coefficients of two first-order polynomials, one for each part of the light-curve, to account for any slow brightness trends.

We initially assumed a circular orbit, in line with previous analyses, but found that a better fit (χ^2_ν = 11 366 *versus* 11 473) could be obtained with a small amount of $e\cos\omega$, where e is the eccentricity and ω is the argument of periastron. We therefore added both $e\cos\omega$ and $e\sin\omega$ to the list of fitted parameters. The relatively shallow partial eclipses (0·22 and 0·15 mag) and non-zero orbital eccentricity made it likely that the results of the light-curve could be imprecise due to correlations between parameters. We therefore added some of the existing RVs to our analysis to provide more constraints on the shape and orientation of the orbit. After some experimentation we included the *Élodie* RVs from ref. 17 and the *CAOS* RVs from ref. 22. For the latter we rejected the RVs from a spectrum taken at phase 0·980 due to blending effects. The fitted parameters were augmented with the velocity amplitudes and systemic velocities for each star.

Simultaneous analysis of the *TESS* data, obtained in 2022 April, and RVs, taken in the years 2001–2002 and 2014–2022, is helped by having a precise orbital ephemeris. We

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

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

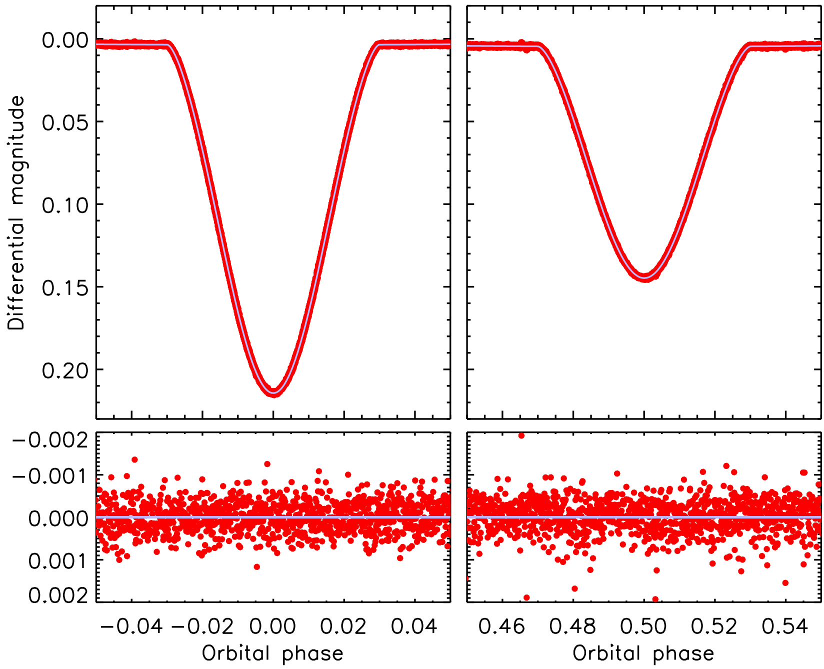

FIG. 2

JKTEBOP best fit to the light-curve of DV Boo from *TESS* sector 50 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.

therefore included in our JKTEBOP fit nine times of minimum taken from the literature[41] (Table II). Our fit therefore included the *TESS* light-curve, RVs for both stars, and times of minimum covering 32·4 years. The fit to the light-curve is shown in Fig. 2, and to the RVs in Fig. 3. Its parameters are given in Table III.

Uncertainties were calculated using the Monte Carlo (MC) and residual-permutation (RP) simulations implemented in JKTEBOP[42], after the data uncertainties for each of the three dataset (*TESS* light-curve and the RVs for each star) were scaled to give a reduced χ^2 of $\chi^2_\nu = 1$. We find results in agreement with previous studies but with smaller error bars relative to the most analogous work[22]. We could have decreased the error bars further by fixing the LD coefficients and/or setting third light to zero, but such assumptions are not justified. The RP error bars were generally similar to but slightly larger than those from the MC simulations so were adopted. However, we retained the MC error bars for the velocity amplitudes and systemic velocities because previous experience has shown that the RP error bars are affected by small-number statistics[43].

The amount of orbital eccentricity is questionable. Fig. 4 shows that eccentricity is clearly detected using the MC error algorithm, but not for the RP algorithm; the difference is likely due to the noise characteristics of the data. $e\cos\omega$ is convincingly non-zero for both the MC and RP algorithms, indicating that the secondary eclipse is slightly later than phase 0·5. However, $e\sin\omega$ is consistent with zero given the available data. The situation is reflected in the sizes of the error bars for the orbital-shape parameters in Table III. A clearer understanding of those points would benefit from new data, but unfortunately there

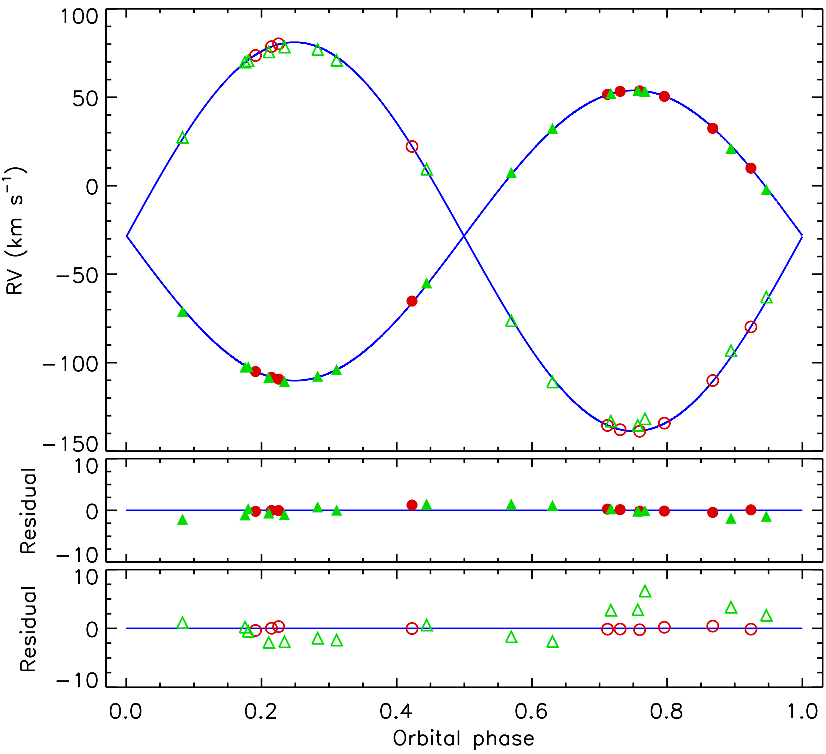

FIG. 3

RVs of DV Boo compared to the best fit from the JKTEBOP analysis (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 *Élodie*[17] are shown with red circles, and those from *CAOS*[22] with green triangles.

is currently no plan for *TESS* to revisit the field of DV Boo.

Physical properties and distance to DV Boo

Although the JKTEBOP best fit includes calculated physical properties of the components of the system, we recalculated them using the JKTABSDIM code[44] so we could use the RP error bars when they were larger than the MC equivalents, excepting the spectroscopic properties listed above. We took all relevant properties from Table III and give the results in Table IV.

Our measured properties of DV Boo agree well with those from previous works, with some caveats. The mass values are similar to those from refs. 21 and 22 but slightly smaller; roughly half the difference can be attributed to the larger orbital inclination found in this work, and half to differing velocity amplitudes. The radius values are also slightly smaller and significantly more precise. The comparison presented by ref. 22 between their properties and those of ref. 21 are erroneous because they compared their $M_{\rm A}$ and $M_{\rm B}$ with $M_{\rm A} \sin^3 i$ and $M_{\rm B} \sin^3 i$, which in the case of DV Boo is enough to cause significant disagreement, and because the comparison between the radii was based on a misreading or misinterpretation of the latter paper.

TABLE III

Photometric parameters of DV Boo measured using JKTEBOP *from TESS photometry and Élodie and CAOS RVs. The uncertainties are* 1σ *error bars.*

Parameter	*Value*
Fitted parameters:	
Orbital period (d)	3·7826346 ± 0·0000006
Time of primary eclipse (BJD_{TDB})	2459676·856434 ± 0·000012
Orbital inclination (°)	83·53 ± 0·17
Sum of the fractional radii	0·2177 ± 0·0015
Ratio of the radii	0·613 ± 0·011
Central-surface-brightness ratio	0·706 ± 0·036
Third light	0·025 ± 0·019
$e \cos \omega$	0·000051 ± 0·000012
$e \sin \omega$	0·0037 ± 0·0049
LD coefficient c_A	0·600 ± 0·064
LD coefficient c_B	0·680 ± 0·049
LD coefficient α_A	0·4030 (fixed)
LD coefficient α_B	0·4984 (fixed)
Velocity amplitude for star A ($\mathrm{km\,s^{-1}}$)	82·01 ± 0·12
Velocity amplitude for star B ($\mathrm{km\,s^{-1}}$)	109·91 ± 0·08
Systemic velocity for star A ($\mathrm{km\,s^{-1}}$)	−28·15 ± 0·10
Systemic velocity for star B ($\mathrm{km\,s^{-1}}$)	−28·82 ± 0·06
Derived parameters:	
Fractional radius of star A	0·13491 ± 0·00052
Fractional radius of star B	0·0828 ± 0·0015
Light ratio ℓ_B/ℓ_A	0·255 ± 0·010
Orbital eccentricity	0·0036 ± 0·0036
Argument of periastron (°)	89 ± 90

TABLE IV

Physical properties of DV Boo defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 45).

Parameter	*Star A*	*Star B*
Mass ratio M_B/M_A	0·7462 ± 0·012	
Semimajor axis of relative orbit ($\mathcal{R}^N_\odot$)	14·441 ± 0·011	
Mass ($\mathcal{M}^N_\odot$)	1·6174 ± 0·0034	1·2068 ± 0·0036
Radius ($\mathcal{R}^N_\odot$)	1·9482 ± 0·0077	1·195 ± 0·022
Surface gravity (log[cgs])	4·0676 ± 0·0034	4·365 ± 0·016
Density ($\rho_\odot$)	0·2187 ± 0·0025	0·707 ± 0·038
Synchronous rotational velocity ($\mathrm{km\,s^{-1}}$)	26·06 ± 0·10	15·99 ± 0·29
Effective temperature (K)	7370 ± 80	6410 ± 80
Luminosity $\log(L/\mathcal{L}^N_\odot)$	1·004 ± 0·019	0·337 ± 0·027
M_{bol} (mag)	2·230 ± 0·048	3·898 ± 0·067
Interstellar reddening $E(B-V)$ (mag)	0·04 ± 0·02	
Distance (pc)	125·0 ± 1·5	

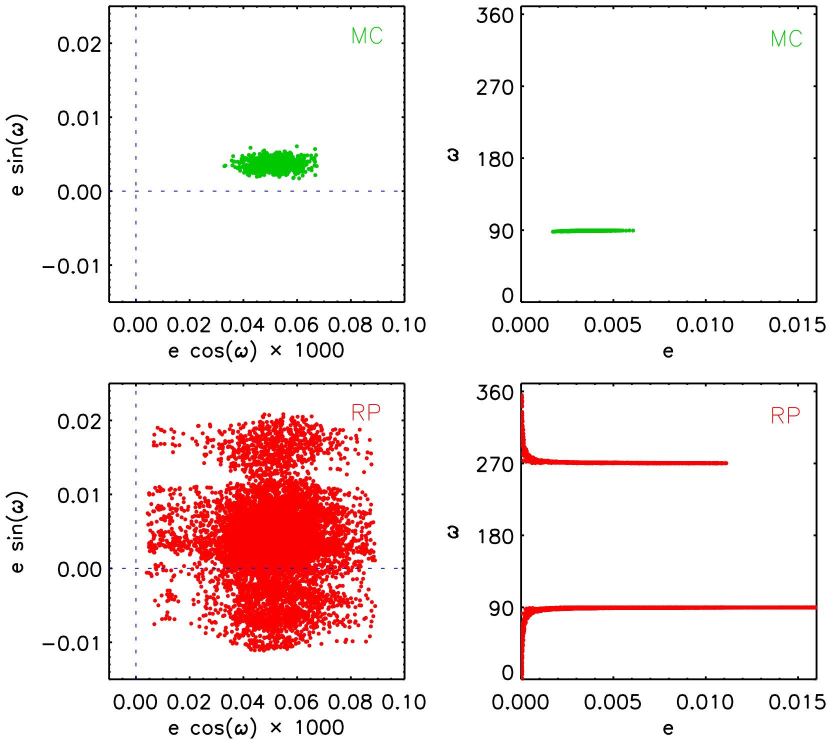

FIG. 4

Scatter plots of the MC (upper panels) and RP (lower panels) fits for the orbital-shape parameters. Blue dotted lines indicate where $e \cos \omega$ and $e \sin \omega$ are zero.

We estimated the distance to DV Boo using the $T_{\rm eff}$ values from Carquillat *et al.*[17], *BV* magnitudes from Tycho[9], and *JHKs* magnitudes from 2MASS[10] (see Table I). The *JHKs* magnitudes were obtained at orbital phase 0·17 so are well away from eclipse. Application of the surface brightness calibrations from Kervella *et al.*[46] to all five passbands showed that an interstellar reddening of $E(B-V) = 0{\cdot}04 \pm 0{\cdot}02$ mag was needed to equalize the optical distance measurements with the infrared ones. Our final distance estimate is $125{\cdot}0 \pm 1{\cdot}5$ pc, which is in unimpeachable agreement with the $125{\cdot}8 \pm 0{\cdot}4$ pc from the *Gaia* DR3 parallax[11].

Comparison with theoretical models

We compared the measured masses, radii, $T_{\rm eff}$ values, and luminosities of the two stars to the predictions of the PARSEC 1·2 theoretical stellar-evolutionary models[47]. The stars are significantly different, resulting in a situation where the radii of the stars constrain the age well and their temperatures constrain the metallicity well. For all metallicities tested (specifically fractional metal abundances by mass, Z, between 0·010 and 0·030) the system age must be in the region of 1280 ± 50 Myr to match the radius of star A for its mass. However, only the models for $Z = 0{\cdot}014$ can match the $T_{\rm eff}$ values, with a best age of 1300 Myr, indicating that the system has a mildly subsolar metallicity. A Hertzsprung–Russell diagram is shown in Fig. 5.

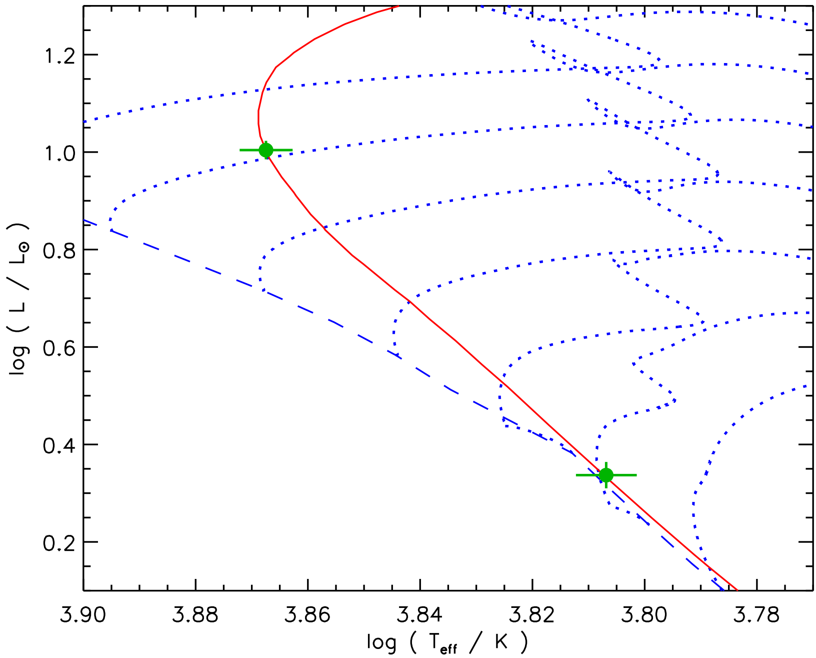

FIG. 5

Hertzsprung–Russell diagram for the components of DV Boo (filled green circles) and the predictions of the PARSEC 1·2 models[47]. The dashed blue line shows the zero-age main sequence for a metallicity of $Z = 0{\cdot}014$. The dotted blue lines show evolutionary tracks for that metallicity and masses of 1·1 $M_\odot$ to 1·7 $M_\odot$ in steps of 0·1 $M_\odot$ (from bottom-right to top-left). The solid red line shows an isochrone for that metallicity and an age of 1300 Myr.

The chances of using DV Boo to assess the reliability of the theoretical models are limited by the chemical peculiarity of star A, which makes its photospheric chemical abundances unrepresentative of its bulk metallicity. However, Catanzaro *et al.*[22] measured abundances for star B which could be used to indicate the metallicity of both stars. Those authors found abundances that are consistent with solar for 12 elements, and super-solar for five, which conflicts with our findings. The $T_{\rm eff}$ values presented by the three prior analyses of the system[17,21,22] also differ by more than their uncertainties and none lead to a completely consistent agreement with theoretical models. We therefore advocate a new spectral analysis of DV Boo to confirm or resolve that discrepancy.

Summary and conclusions

DV Boo is a dEB containing a slightly evolved Am star and a late-F star close to the zero-age main sequence. The 3·783-d orbit has a small but probably non-zero eccentricity, based on the orbital phase of secondary eclipse. Three studies of the system are available in the literature, all of which agree on the masses of the stars and the chemical peculiarity of the primary component, but none of which include precise measurements of the radii of the stars. We modelled the *TESS* sector 50 data to fill in that gap in knowledge of the system.

We determined the masses and radii to good precision — 0·2% and 0·3% for mass and

0·4% and 1·8% for radius. The comparatively shallow partial eclipses prevent more precise radius measurements, and the difficulty in obtaining a reliable spectroscopic light ratio means it will be hard to improve on the current results.

Our measurement of the distance of DV Boo is in excellent agreement with its *Gaia* DR3 parallax. The properties of the system match theoretical predictions for an age of 1300 Myr and a metallicity of $Z = 0{\cdot}014$; that sub-solar metallicity is discrepant with the measured photospheric chemical abundances of the secondary star. We searched for and found no evidence for pulsations in the system, in agreement with the suggestion that Am stars have a low fraction of pulsators [48,49].

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REVIEWS

Planetary Geology: An Introduction, 3rd Edition, by Dominic Fortes & Claudio Vita-Finzi (Liverpool University Press), 2025. Pp. 318, 26 × 20 cm. Price £31·99 (paperback; ISBN 978 1 78046 104 5).

Planetary Geology, by Fortes & Vita-Finzi, gives a thorough and up-to-date overview of this topical and rapidly advancing subject. It covers more or less all aspects of planetary geology, from the basic origin of the Solar System, orbital physics, and geophysical techniques, to crust-building processes, atmospheres and cryospheres and the possibility of volcanism, plate tectonics, and life on non-terrestrial planets.

The book is information-rich and must have been an enormous undertaking. The complementary specialties of the authors have enabled excellent integration of knowledge concerning Earth, about which we clearly have information gathered close-up that provides unique detail, and the other planets, most of which we can study only remotely. Integration of information on such disparate scales is challenging. However, the authors have effectively achieved what they set out to do.

It is a courageous undertaking to produce a book on this subject in the face of the almost monthly announcements of significant new findings. However, the content has been effectively designed to maintain relevance in the face of rapid advancements. A read of this