THE OBSERVATORY

A REVIEW OF ASTRONOMY

EDITED BY

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Vol. 146 No. 1310

2026 FEBRUARY

THE OBSERVATORY

Vol. 146 2026 FEBRUARY No. 1310

THE 1946 OUTBURST OF T CRB OBSERVED FROM STOCKHOLM OBSERVATORY

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T CrB is a recurrent nova with two confirmed bright eruptions, in 1866 and 1946. This article presents the observations of the 1946 event made at the Stockholm Observatory and throws light on observational methods and instruments used at the time.

Introduction

T Coronae Borealis is a bright and well-known recurrent nova that has attracted many observers following its behaviour during and after its outburst in 1866 May, when it rose to magnitude 2. It was the first nova to be studied spectroscopically; William Huggins found several bright emission lines, among them Hα, Hβ, and Hγ.[1,2] After the 1866 outburst it settled at about magnitude 10, with minor variations with an amplitude of about 0·3 mag and a period of half the orbital period of the white dwarf and the red giant M4 III star of 227·6 days. It has ever since been keenly followed by amateurs as well as professional astronomers. In 1946, a second eruption occurred. A 'high state' of activity in that object was observed prior to that outburst, in 1935; since 2015, the object once again has exhibited such a 'high state' of activity by brightening substantially, leading to predictions of an upcoming outburst.[3]

The Stockholm Observatory

Stockholm has had an astronomical observatory since 1753, when the Royal Academy of Science's observatory was constructed. The observatory marks a major milestone for science in 18th-Century Sweden in general, and for the Academy in particular, with modern instruments and astronomers such as Pehr Wilhelm Wargentin, an expert on the movements of the Jovian satellites (and also a pioneer in Swedish population statistics through his involvement in *Tabellverket* and *Tabellkommissionen* [*the earliest Swedish population statistics, introduced in 1749, and the commission responsible for them, respectively. —Ed.*]).[4]

As the years went by, the observatory's location became a problem: what had been an acceptable site for nightly observations gradually became unsuitable as the expanding city of Stockholm surrounded the observatory with skies increasingly filled with dust from coal. Also, come the 20th Century, its instruments were outdated. Change happened when the

Knut and Alice Wallenberg Foundation made a large donation in order to construct a new observatory on the condition that it be placed in Saltsjöbaden; funding for and the idea behind that idyllic villa suburb and exclusive seaside resort project, constructed from 1890 onwards, had come from K. A. Wallenberg, and now the project was to be crowned by a magnificent and advanced observatory.[5,6]

With funding from the Wallenberg donation, the new Stockholm Observatory was constructed, situated on a hill, 'Karlsbaderberget', rising some 60 metres above sea level in Saltsjöbaden, 15 kilometres from the centre of Stockholm. The new Stockholm observatory was inaugurated in 1931 June, with modern telescopes: a 1-m reflector and a 50/60-cm double refractor, both made by Grubb Parsons, a 40-cm wide-field astrograph by Carl Zeiss, and auxiliary instrumentation such as spectrographs and microphotometers for measuring photographic plates. The staff expanded compared to the old observatory, working under the director, Professor Bertil Lindblad. Astronomers (and also mechanics working with instrument maintenance) lived with their families on the hill, thus having a short walk between home and dome. The logic behind having staff living on the premises of the Observatory, which was a not uncommon feature of large observatories situated in non-urban areas during the early 20th Century, was the essence of speed. Astronomers could get to work at short notice, which was doubly important should an urgent and unpredicted phenomenon occur. The Royal Swedish Academy of Sciences now ran one of the most modern astronomical observatories in Europe.[7]

1946 February 10

News of the 1946 outburst reached the Saltsjöbaden astronomers on the evening of February 10, by way of a telegram from the Central Bureau of the International Astronomical Union, then located in Copenhagen and tasked with rapidly disseminating information about astronomical objects such as newly discovered comets and novae. The telegram stated that Armin Deutsch of the Yerkes observatory had discovered an eruption of T CrB on February 9 at 08^h30^m UT. When the telegram arrived in Saltsjöbaden the sky was overcast, but it cleared on the morning of February 11: at 08^h30^m UT, Bertil Lindblad and Yngve Öhman managed to observe the object *in daylight*, some two hours after sunrise, with the visual 50-cm tube of the double refractor.[8]

Now, an intense scrutiny of the recurrent nova began at the Stockholm Observatory. Spectra were taken using the Zeiss spectrograph mounted on the 1-m Grubb Parsons reflector, and perhaps most important for future studies of that object, the object's brightness was observed, with both photographic and visual photometry done by Gunnar Larsson-Leander. The photographic magnitudes were measured on plates using the observatory's Schilt photometer, and visual observations were made by the Argelander method. Larsson-Leander had started out as an amateur astronomer doing observations of variable stars before becoming a professional astronomer and was thus trained in both visual and photographic photometric methods. Because of the nova's brightness, it was initially observed visually using a pair of binoculars, and as it faded Larsson-Leander shifted to 9·5- and 10-cm refractors.[8]

2025–2026?

As this is written, on 2026 January 8, T CrB has not erupted, but some astronomers have discussed the possibility of a coming eruption. A very thorough examination of the available photometry by Schaefer, using 213 730 magnitudes observed from 1842 to 2022, leads to a prediction of 2025·5 ± 1·3 as the time when a new eruption will occur.[3]

If, and when, the next eruption occurs, it will not be announced by a telegram, as in 1946; news will spread fast over various channels on the internet to observers distributed all over the world, most (or all) of them not having their private homes on the grounds of a professional astronomical observatory. Remote observing, with telescopes operated *via* computers, are abundant today. But given the brightness of T CrB in eruption, even an amateur astronomer using a pair of binoculars, just like Gunnar Larsson-Leander did, can contribute useful photometry in aid of unravelling the nature of T CrB.

Acknowledgements

I wish to acknowledge the on-going and rewarding discussions about the history of astronomy with my colleague Johan Kärnfelt, as well as the kind help provided by Eva Jurlander, librarian at the Lund Observatory, and the staff at the Center for the History of Science at the Royal Swedish Academy of Sciences, Stockholm. This work was supported by the Swedish Research Council, grant number 2022-01940.

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WHO NAMED THE STARS OF THE PLEIADES?

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The IAU recognizes official names for nine members of the Pleiades cluster. Those names come from ancient Greek mythology but were not allocated to specific stars until post-telescopic times when their positions could be accurately determined. Who first applied them?

Taurus is a grand constellation blessed with two of the finest naked-eye clusters in the sky, the Hyades [Ὑάδες in Greek] and Pleiades [Πλειάδες], named after two groups of nymphs from Greek mythology. The Hyades cluster is much the older of the pair, with an age of around 600 million years as against ≈ 100 million years for the Pleiades. Hence its stars have had longer to drift apart and are easier to see individually.

Ptolemy listed five individual members of the Hyades in his star catalogue in the *Almagest* compiled around AD 150, but in the case of the smaller and denser Pleiades he was less specific. Ptolemy's entry on the Pleiades referred to "the northern end of the advance side", "the southern end of the advance side", and "the rearmost and narrowest end", which suggests he was outlining the shape and extent of the cluster rather than attempting to list individual stars.[1]

Only with the invention of the telescope did it became possible to identify individual members of the Pleiades cluster with any certainty. Galileo published a sketch showing six naked-eye stars and 30 fainter ones in his book *Sidereus Nuncius* in 1610 (see Fig. 1), but he did not name them.[2]

FIG. 1

Galileo's sketch of the Pleiades from his book *Sidereus Nuncius* of 1610. The six brightest stars, depicted with larger symbols, are: Atlas (upper left), Alcyone (the brightest and hence the largest symbol of all), Merope (lower left), Maia (upper centre), Taygeta (upper right), and Electra (lower right). In Galileo's time, however, none of the individual stars had yet been named.

Nowadays we have names for nine stars of the Pleiades: the seven nymphs themselves and two other stars named after their parents, Atlas and Pleione. Although the names are taken from Greek mythology, their application to the individual members of the cluster dates from some time after Galileo. So who named them?

Riccioli, Langrenus, and Mutus

Even the great constellation historian R. H. Allen expressed uncertainty as to the answer in his classic book *Star Names*[3], but the available evidence suggests that the credit is jointly due to three men: the Italian astronomer Giovanni Battista Riccioli (1598–1671); the Mallorcan astronomer Vicente Mut (1614–87), aka Mutus; and the Dutch astronomer Michael van Langren (1598–1675), also known as Langrenus.

The first recorded use of names for any of the Pleiades is found in Riccioli's massive textbook *Almagestum Novum* ('New Almagest') of 1651. In that he wrote that Maia was "the most brilliant in the quadrilateral", *i.e.*, the shape formed by the four brightest members of the cluster.[4] The other three stars in the quadrilateral he named as Sterope, Taygeta, and

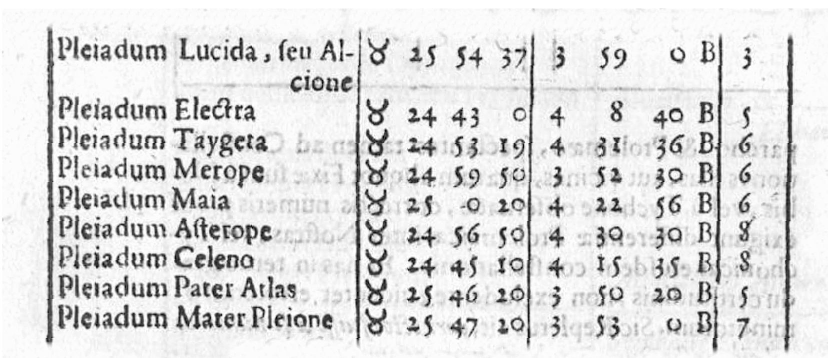
Celeno. Whether those attributions were his idea or someone else's he did not say, but either way they did not last. He renamed those stars in his next book, *Astronomia Reformata*, with the identifications we know today.

Names for two other related stars were also announced in *Almagestum Novum*, and in that case the names did stick. In 1647 July Langrenus had sent Riccioli a diagram of the Pleiades as seen through his telescope on which, Riccioli tells us, he added two stars "which he himself calls Atlas and Pleione".[4] That statement makes clear that it was Langrenus who named the stars representing the parents of the Pleiades. Unfortunately, Riccioli did not reproduce Langrenus's diagram so we cannot tell if he applied names to the other members of the cluster as well.

In 1650 March, just as Riccioli was finishing the *Almagestum Novum*, he received from Mutus a list of latitudes, longitudes, and magnitudes of the seven main members of the Pleiades, which he included in an appendix at the end of the book.* No names for those stars were given in that table; instead they are simply described by their position in the group, such as "Pleiadum occidentalis lucidior", "Media & Lucida Pleiadum", and so on (ref. 4, p. 747). A full set of names would have to await Riccioli's next book 14 years later, and that letter from Mutus turned out to play a significant role.

The final list

Riccioli's follow-up to *Almagestum Novum* was called *Astronomia Reformata* (*Astronomy Reformed*), published in 1665. It is there that we find the now-familiar names of the seven Pleiades, plus their parents, contained in a catalogue of star positions for the year 1700 (see Fig. 2). That star catalogue actually appears twice, once in Book IV and again in a set of tables at the end.[5]



Pleiadum Lucida, ſeu Alcione	♉	25	54	37	3	59	0	B	3
Pleiadum Electra	♉	24	43	0	4	8	40	B	5
Pleiadum Taygeta	♉	24	53	19	4	31	36	B	6
Pleiadum Merope	♉	24	59	50	3	52	30	B	6
Pleiadum Maia	♉	25	0	20	4	22	56	B	6
Pleiadum Aſterope	♉	24	56	50	4	39	30	B	8
Pleiadum Celeno	♉	24	45	10	4	15	35	B	8
Pleiadum Pater Atlas	♉	25	46	20	3	50	20	B	5
Pleiadum Mater Pleione	♉	25	47	20	3	53	0	B	7

FIG. 2

Names of the individual members of the Pleiades listed for the first time in G. B. Riccioli's *Astronomia Reformata* of 1665. Those names are still used today, with two minor changes of spelling: Alcione and Celeno are now written as Alcyone and Celaeno.

In *Astronomia Reformata* Riccioli quoted more extensively from Mutus's letter of 1650, and we discover that in that letter Mutus had referred to the individual stars of the Pleiades by name (ref. 5, pp. 243–4). For some reason Riccioli had not mentioned those names in the table published in *Almagestum Novum*, perhaps because they contradicted the ones he had

*Mutus and Riccioli were long-term collaborators, united by their anti-Copernicanism. Their original correspondence apparently no longer survives, but Riccioli quotes Mutus extensively in his books.

given earlier in the book. When Riccioli came to compile his star catalogue in *Astronomia Reformata* it seems that he adopted the names in Mutus's letter (abandoning his own early attempt), plus the two stars previously named by Langrenus.*

Although Riccioli was widely respected by other astronomers, the new names did not immediately catch on. Neither Johannes Hevelius nor John Flamsteed used them in their star catalogues of 1690 and 1725. But Johann Bode adopted all nine names in the catalogue that accompanied his *Uranographia* atlas of 1801[6], as did Giuseppe Piazzi in his *Palermo Catalogue* of 1814[7]. From then on they became firmly established, and were officially approved by the IAU Working Group on Star Names in 2016.

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LONG-TERM OBSERVATIONS AND COMPREHENSIVE STUDY OF THE NEW DELTA SCUTI STAR TYC 4311-825-1

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In this work, we present the results of a photometric study of the star TYC 4311-825-1. Differential photometry measurements (in the Johnson–Cousins — B, V, Rc, Ic — system) have been obtained from observations carried out in the years 2004–2005, 2011, and 2020–2021 by using a 0·51-m telescope. Analysis of those data shows that the star pulsates with two frequencies of $12{\cdot}55\,\mathrm{d}^{-1}$ and $16{\cdot}03\,\mathrm{d}^{-1}$. Those frequencies correspond to radial-pulsation fundamental and first-overtone modes in agreement with a model of adiabatic oscillations ($\gamma = 5/3$). Information derived from *Gaia* DR3 data indicates that TYC 4311-825-1 is a main-sequence Population I star with $\log T_{\rm eff} = 3{\cdot}85$, $\log L/L_{\odot} = 1{\cdot}11$, and $M = 1{\cdot}68\,M_{\odot}$. Those data place the star in the δ Scuti instability strip.

*Mutus published a summary of his positional measurements of the Pleiades in one brief paragraph in his *Observationes motuum caelestium* of 1666 (pp. 51–2), but without giving any names for the stars. Hence Riccioli's catalogue is the only published source for those names.

Introduction

δ Scuti stars have emerged in the last decades as an important stellar type from the point of view of asteroseismology.[1] Those stars are usually multi-periodic pulsating systems near or just after the end of the core-hydrogen-burning phase, located within the instability strip on the main sequence or moving from the main sequence to the giant branch.[2] Periods are around 0·02–0·25 days and masses range from about 1·5 to 2·5 $M_\odot$.[3] Although some δ Scuti stars show exclusively radial pulsations, many pulsate simultaneously with a large number of non-radial modes, being of low-degree and low-order *p* modes with the majority detected photometrically.[4] Those pulsation modes can shed light on the stellar interiors, providing clues even to the ages of intermediate-mass stars.[5] Thus, detailed studies about the structure and stellar evolution in the transition zone between lower-mass stars with thick convective envelopes and high-mass stars with thin convective shells can be carried out, by identifying the pulsation modes and comparing them with theoretical models.[6] Note that, from the photometric point of view, although the short periods of the δ Scuti stars allow complete light-curves to be obtained easily, long-term campaigns are useful to analyse possible period changes in the context of the evolutionary status of the star.

TYC 4311-825-1 (R.A. = $2^h4^m32^s{\cdot}22$; Dec = $+68^\circ45'28''{\cdot}78$; J2000·0) is listed as a suspected variable in the ASAS-SN catalogue of variable stars[7] with the name NSVS 366070. No information about the type of variability or period is indicated and only an estimation of the amplitude (ΔV = 0·41 mag) is provided, taking into account that images of stars with $V < 11$ mag could be saturated, according to that study. In the Tycho 2 catalogue[8], *V* and *B* magnitudes of 10·32 ± 0·04 and 10·73 ± 0·04, respectively, are assigned. NSVS 366070 is also listed in the VSX[9] as a high-amplitude δ Scuti star (HADS). The *Gaia* DR3 release[10] lists a parallax of 2·6357 ± 0·0132 mas, which places the star at a distance of about 380 pc. Note that the Bailer-Jones *et al.*[11] catalogue, based on a probabilistic analysis of the distances of *Gaia* sources, provides a distance of 377 pc, which coincides with the former value within the uncertainties.

In the years 2004–2005, 2011, and 2013 the star was observed (mostly in the *V* band) with the 0·51-m Newtonian telescope of the L'Ametlla del Vallès observatory (Barcelona, Spain), within the programme of searching for new variable stars of the Grup d'Estudis Astronòmics. A previous analysis of the 2004–2005 photometric data showed that the star could be a multi-periodic δ Scuti system with frequencies f_1 = 12·5454 d^{-1}, f_2 = 16·0300 d^{-1}, and f_3 = 12·6896 d^{-1} (ref. 12). In fact, the first frequency is recovered in a previous analysis of the ASAS-SN data of TYC 4311-825-1, and the *Gaia* DR3 data[10] provide, in the variability analysis of its upper-main-sequence (MS) oscillators catalogue, the same frequency with a semi-amplitude of 0·1 mag in the *G* band, and various harmonics. A similar value of f_1 is derived from the VSX data. From the former information, a similarity with V974 Oph, with possibly mixed radial and non-radial modes[13], was suggested. Stimulated by those results, new observations were performed in the years 2020–2021 in the bands *B*, *V*, *Rc*, and *Ic* of the Johnson–Cousins system. The derived differential photometry data were analysed together with the previous data (re-analysing the 2004–2005 campaign results) in order to elucidate the behaviour of the star.

In the following sections we present, firstly, the observational background of this work; secondly, the frequency analysis of the obtained data is displayed. In regard to that, an O − C analysis was performed with the aim of studying possible variations of the main period. Next, in order to establish the true nature of the star's variability, we estimated the unreddened colour index and temperature, comparing these results with those derived from the *Gaia* DR3 release. Other physical parameters, provided directly by *Gaia* and those indirectly determined from that, are also presented. Subsequently, from those results, we give an insight into the evolutionary status of the variable. Finally, the main results are discussed and the conclusions are presented.

Observations

The observations of TYC 4311-825-1 were performed by using a 0·51-m telescope at $f/4$. The former (years 2004–2005, 2011, and 2013) were carried out with a Starlight SX Xpress CCD camera whereas the later (years 2020–2021) were performed with an ST9XE CCD camera. Table I displays the details of the complete set of observations. Differential

TABLE I

Log of the observations.

Year	*Date*	*JD*	*Number*	*Filter*	*mean s.d. (mag)*
2004–2005	Dec 19–Jan 21 (24 nights)	2453359–2453392	6428	*V*	0·008
2004	Dec 26	2453366	637	*B*	0·012
2011	Oct 22–Dec 28 (7 nights)	2455857–2455924	1058	*V*	0·009
2013	Nov 2	2456599	216	*V*	0·007
2020–2021	Dec 15–Mar 13 (11 nights)	2459199–2459287	2167	*V*	0·007
2021	Jan 14–Mar 13 (6 nights)	2459229–2459287	380	*B*	0·008
2021	Jan 14–Mar 13 (3 nights)	2459229–2459287	263	*Ic*	0·007
2021	Jan 29–Mar 13 (4 nights)	2459244–2459287	158	*Rc*	0·006

photometry of TYC 4311-825-1 was carried out by using TYC 4311-989-1 (V = 10·46, $B-V$ = 0·374) as the comparison star and TYC 4311-1276-1 (V = 11·29, $B - V$ = 0·321) as the main reference star. Because of the similarity between the colour indices of the variable and reference, and the proximity of both stars (angular distance < 5 arcmin), we can consider that the difference between the instrumental magnitudes is very close to the difference between its Johnson–Cousins standard magnitudes.

Fig. 1 shows the differential V light-curves of TYC 4311-825-1 obtained from the observations in the year 2004, with a V amplitude peak-to-peak of about 0·20–0·25 mag. Note that the period associated with the 12·5 d^{-1} frequency (about 0·08 days) is clearly observed, along with a beat with a period of about 0·25–0·3 days, due to the presence of a secondary frequency. That behaviour is also displayed in the remaining V light-curves of the years 2005, 2011, 2013, and 2020–2021 (Figs. 2, 3, and 4, respectively) and in the B, Ic, and Rc light-curves (Figs. 5, 6, and 7, respectively).

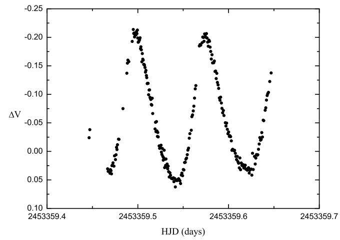
Fig. 8 displays the light-curves for the different filters used in this work on 2021 March 13 (the only night with measurements in the four filters). Clearly noticeable is the change in amplitude from the Ic (smaller) to the B (larger) filter.

Uncertainties of data (mean s. d. in Table I) were estimated from the standard deviation of the comparison minus check differential magnitudes for each night and filter, according to Koppelman[14]. The quoted values are the averages for each observation set.

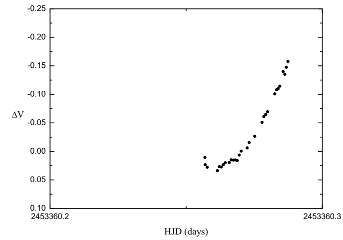
Frequency-analysis results

The program PERIOD04[*][15] has been used to perform the frequency analysis. The search for frequencies has been made iteratively, stopping when the residuals were comparable to the data dispersion. The main results are displayed in Table II. For this analysis, only the data corresponding to wide observational time ranges and including some complete light-curves were used (thus, for example, 2013 V values could not be used because the 216 data points correspond to only one night with an incomplete light-curve; the same decision was adopted for 2004 B and 2021 Rc data). In particular, Fig. 9 shows the amplitude spectrum for the 2004–2005 V data (the observational data set with the highest number of days and number of observations) and the residual amplitude spectrum of the pre-whitened original signal.

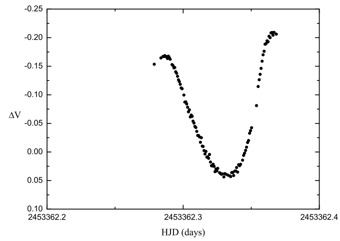
*https://www.period04.net



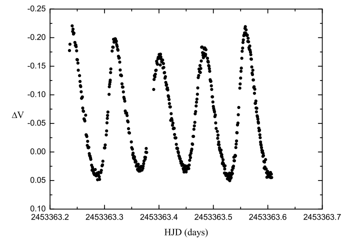
(a)
2004 Dec 19



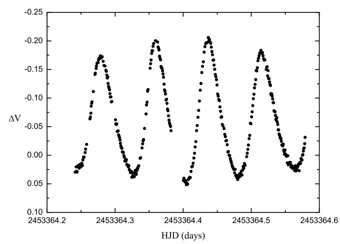
(b)
2004 Dec 20



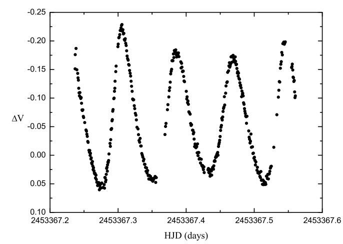
(c)
2004 Dec 22



(d)
2004 Dec 23

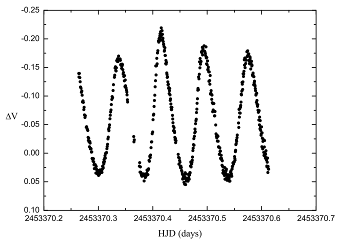


(e)
2004 Dec 24



(f)
2004 Dec 27

Fig. 1
2004 *V* light-curves of TYC 4311-825-1 (to be continued).



(g)
2004 Dec 30

FIG. 1
2004 *V* light-curves of TYC 4311-825-1 (continued).

TABLE II

Results of the frequency analysis.

Filter	*Year*	*Frequency* (d^{-1})	*Amplitude (mag)*	*Phase (0–1)*	*Residuals (mag)*
		f_0 = 12·5455(1)	0·1497(8)	0·804(1)	
B	2021	$2f_0$ = 25·09(28)	0·027(4)	0·70(30)	0·008
		f_1 = 16·031(2)	0·0197(9)	0·14(2)	
		$f_0 + f_1$ = 28·57(2)	0·007(1)	0·65(11)	
		f_0 = 12·54569(3)	0·1106(2)	0·6945(2)	
V	2004	$2f_0$ = 25·0914(1)	0·0201(2)	0·759(1)	0·009
	–2005	f_1 = 16·0302(2)	0·0131(2)	0·376(2)	
		$f_0 + f_1$ = 28·5759(6)	0·0050(2)	0·462(5)	
		$3f_0$ = 37·6356(7)	0·0042(2)	0·600(6)	
V	2011	f_0 = 12·5463(2)	0·108(1)	0·441(1)	0·025
		$2f_0$ = 25·0935(6)	0·023(1)	0·435(7)	
		f_0 = 12·54572(2)	0·1145(2)	0·9243(3)	
V	2020	$2f_0$ = 25·09152(9)	0·0212(2)	0·289(2)	0·007
	–2021	f_1 = 16·0306(1)	0·0157(2)	0·453(2)	
		$f_0 + f_1$ = 28·5772(3)	0·0062(2)	0·709(6)	
		$3f_0$ = 37·6370(5)	0·0039(2)	0·59(1)	
		f_0 = 12·5455(1)	0·0642(8)	0·523(2)	
Ic	2021	$2f_0$ = 25·09(3)	0·0125(8)	0·03(13)	0·008
		f_1 = 15·997(1)	0·0091(6)	0·10(1)	

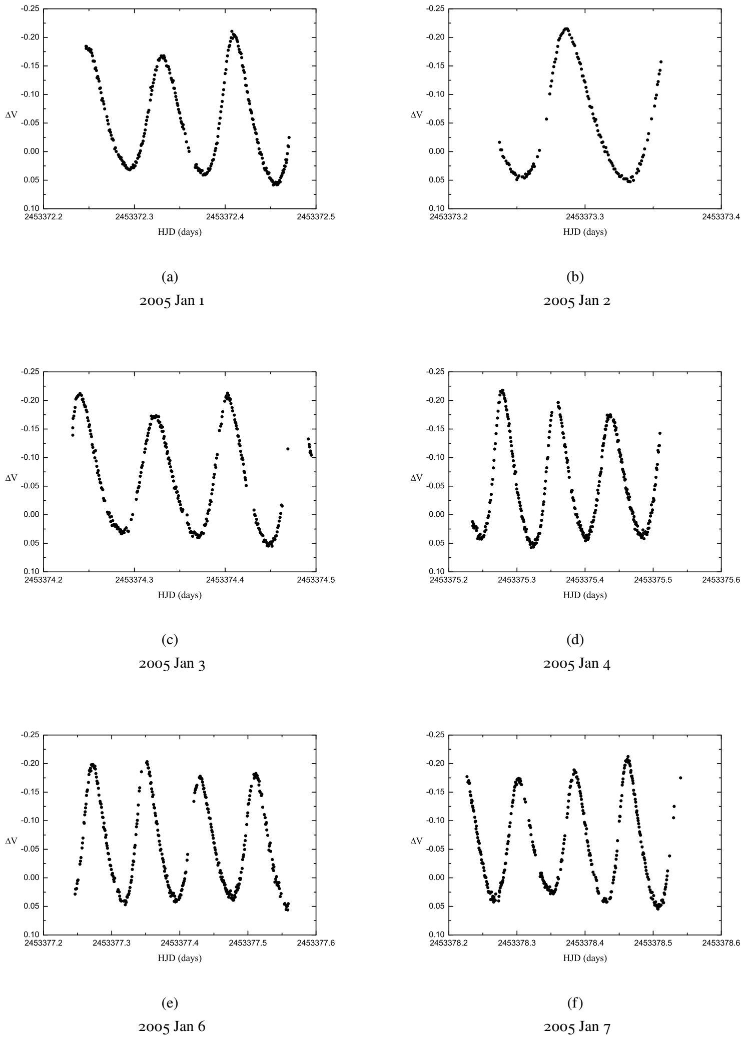
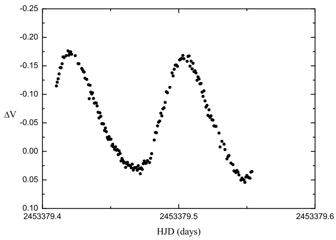
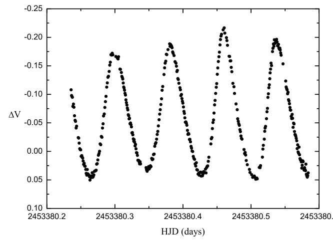


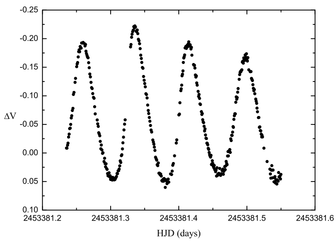
Fig. 2
2005 *V* light-curves of TYC 4311-825-1 (to be continued).



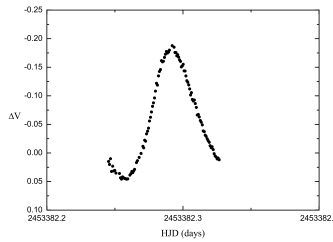
(g)
2005 Jan 8



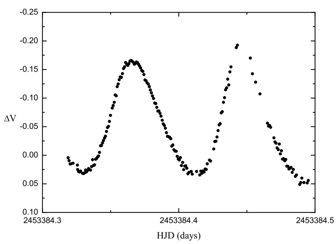
(h)
2005 Jan 9



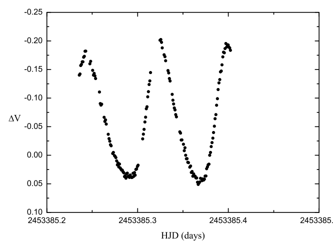
(i)
2005 Jan 10



(j)
2005 Jan 11

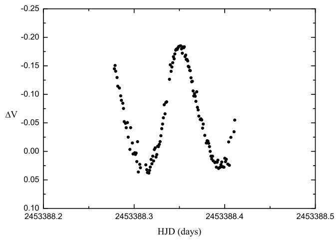


(k)
2005 Jan 13

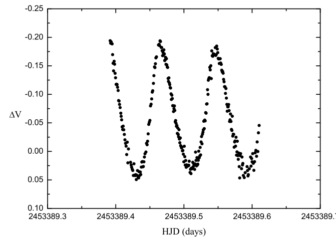


(l)
2005 Jan 14

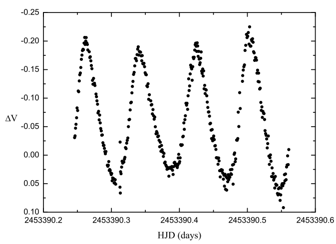
Fig. 2
2005 *V* light-curves of TYC 4311-825-1 (continued; to be continued).



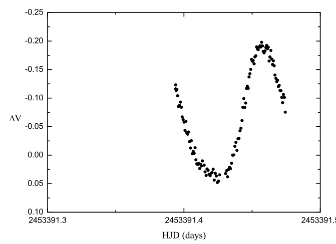
(m)
2005 Jan 17



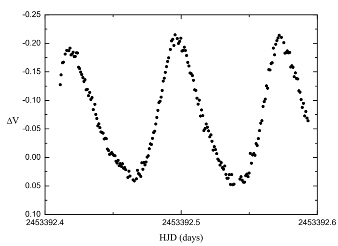
(n)
2005 Jan 18



(o)
2005 Jan 19

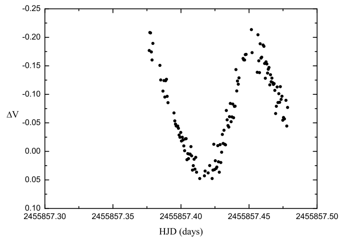


(p)
2005 Jan 20

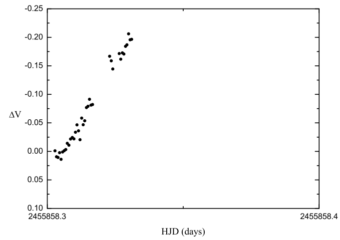


(q)
2005 Jan 21

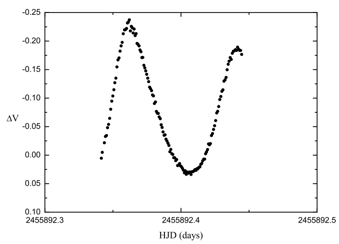
Fig. 2
2005 *V* light-curves of TYC 4311-825-1 (continued).



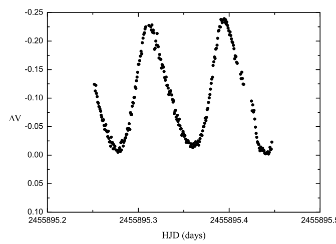
(a)
2011 Oct 22



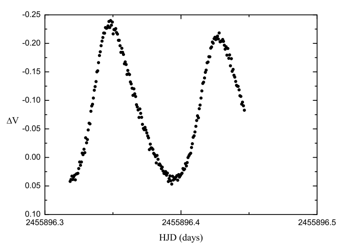
(b)
2011 Oct 23



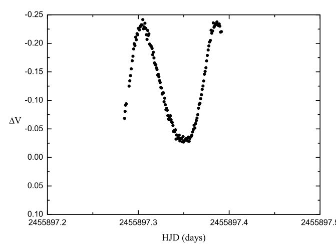
(c)
2011 Nov 26



(d)
2011 Nov 29

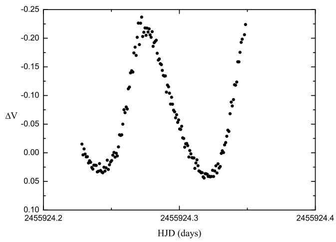


(e)
2011 Nov 30

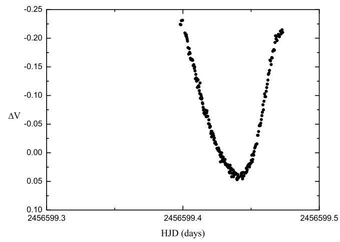


(f)
2011 Dec 1

Fig. 3
2011 and 2013 *V* light-curves of TYC 4311-825-1 (to be continued).



(g)
2011 Dec 28



(h)
2013 Nov 2

FIG. 3
2011 and 2013 *V* light-curves of TYC 4311-825-1 (continued).

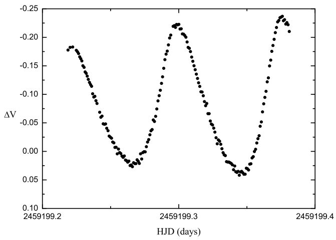
From Table II, there is evidence for the presence of two frequencies $f_0 = 12{\cdot}55\,\mathrm{d}^{-1}$ and $f_1 = 16{\cdot}03\,\mathrm{d}^{-1}$ but not the additional $12{\cdot}69\,\mathrm{d}^{-1}$ frequency indicated in the previous study. That confirms that the star has a double-pulsation mode. The beat derived from the former two frequencies has an associated period of $1/(f_1 - f_0) = 0{\cdot}286$ days, in agreement with the beat observed qualitatively in the light-curves. The observations provide frequency values in very close agreement between them, including some harmonics of f_0 and the sum of f_0 and f_1, irrespective of the observation dates. In that way, the upper panel of Fig. 9 displays a central peak corresponding to the main frequency of $12{\cdot}55\,\mathrm{d}^{-1}$ (the adjacent peaks are associated to the $1\,\mathrm{d}^{-1}$ aliasing). After the pre-whitening of the main frequency, the residual amplitude spectrum shows clearly the peaks of the first harmonic of that (around $25{\cdot}1\,\mathrm{d}^{-1}$) and the second frequency of about $16{\cdot}0\,\mathrm{d}^{-1}$, also with adjacent peaks also related to the $1\,\mathrm{d}^{-1}$ aliasing (Fig. 9, lower panel).

Note also that the amplitudes in the different bands decrease with the effective wavelength of the filter, from 0·15 mag (filter *B*) to about 0·064 mag (filter *Ic*), in agreement with the behaviour shown in Fig. 8.* Fig. 10 shows the differential *V* light-curve corresponding to the particular night of 2021 January 14 along with the best fit model as obtained from the frequency analysis.

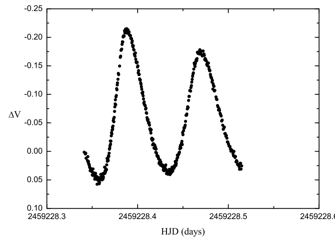
O – C *analysis*

An O – C analysis has been performed by using the light-maxima timings obtained from the observations in the different filters. In this analysis, a 2011 *V* observation was excluded because it provided an O – C value far from the usual data around 0·0, possibly due to an incorrect time baseline. The times of the light maxima were determined by means of the Kwee and Van Woerden procedure[16], as implemented in the program AVE 2·51[17]. Tables III and IV list those data.

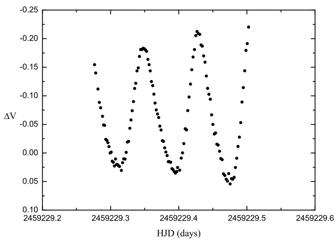
*The amplitudes listed in Table II are really semi-amplitudes according to the equation defining each Fourier term, $A_i \sin(2\pi(f_i t + \phi_i))$, where A_i is the amplitude, f_i, the frequency, and ϕ_i, the phase (between 0 and 1; the value in radians is obtained multiplying by 2π). Thus, the peak-to-peak amplitude for the fundamental mode using the *V* filter data is $2A_i \approx 0{\cdot}22$, close to the amplitude displayed in the light-curves. That amplitude is obviously variable due to the presence of the first overtone and harmonic terms.



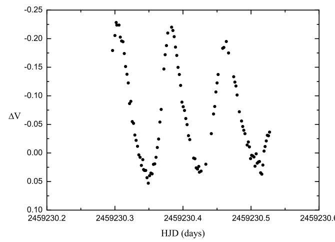
(a)
2020 Dec 15



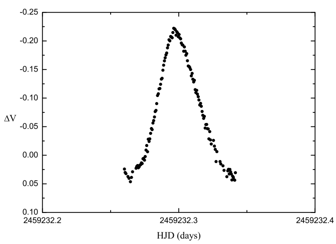
(b)
2021 Jan 13



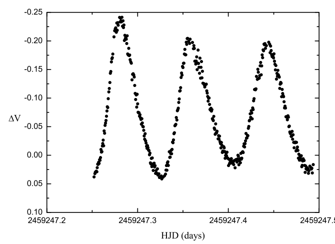
(c)
2021 Jan 14



(d)
2021 Jan 15

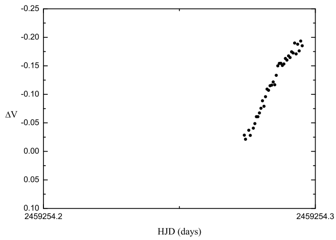


(e)
2021 Jan 17

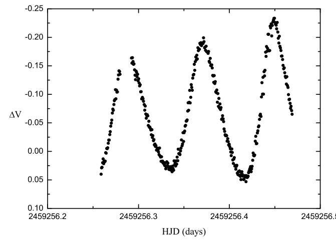


(f)
2021 Feb 1

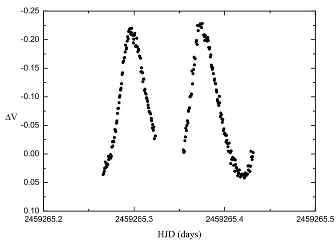
Fig. 4
2020–2021 *V* light-curves of TYC 4311-825-1 (to be continued).



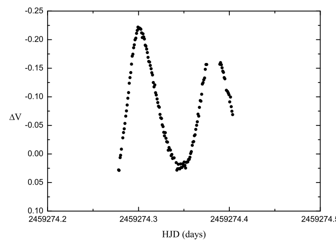
(g)
2021 Feb 8



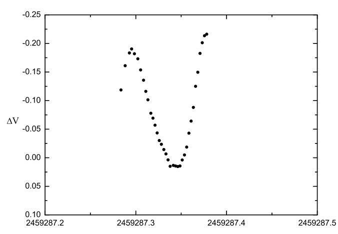
(h)
2021 Feb 10



(i)
2021 Feb 19

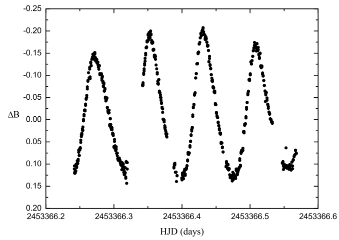


(j)
2021 Feb 28

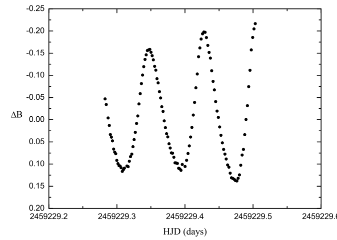


(k)
2021 Mar 13

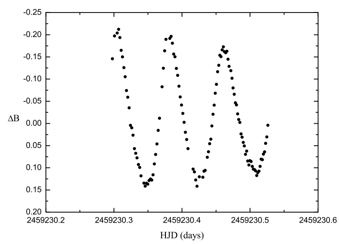
FIG. 4
2020–2021 *V* light-curves of TYC 4311-825-1 (continued).



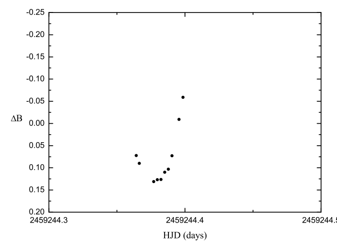
(a)
2004 Dec 26



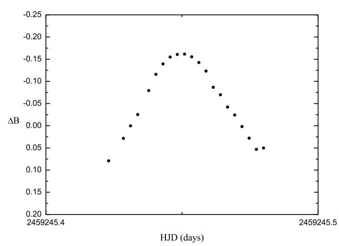
(b)
2021 Jan 14



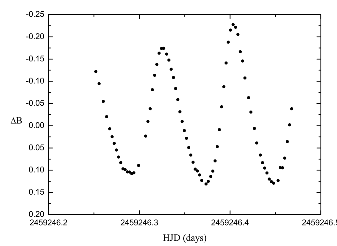
(c)
2021 Jan 15



(d)
2021 Jan 29

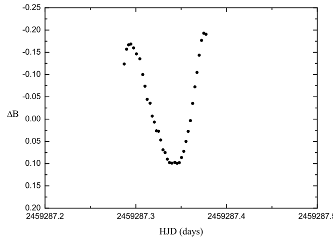


(e)
2021 Jan 30



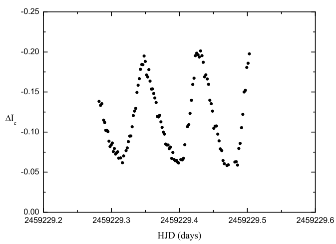
(f)
2021 Jan 31

Fig. 5
2004 and 2021 *B* light-curves of TYC 4311-825-1 (to be continued).

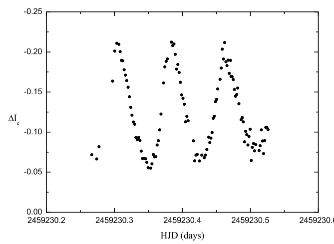


(g)
2021 Mar 13

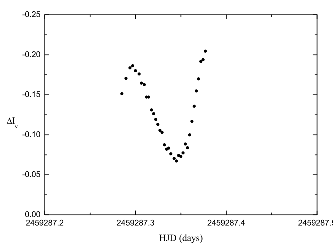
Fig. 5
2004 and 2021 *B* light-curves of TYC 4311-825-1 (continued).



(a)
2021 Jan 14

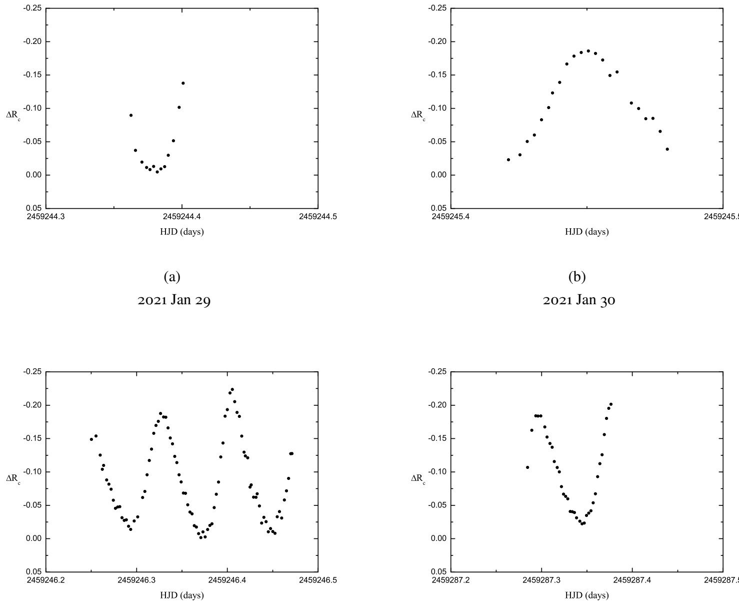


(b)
2021 Jan 15



(c)
2021 Mar 13

Fig. 6
2021 *Ic* light-curves of TYC 4311-825-1.



(a) 2021 Jan 29

(b) 2021 Jan 30

(c) 2021 Jan 31

(d) 2021 Mar 13

FIG. 7
2021 *Rc* light-curves of TYC 4311-825-1.

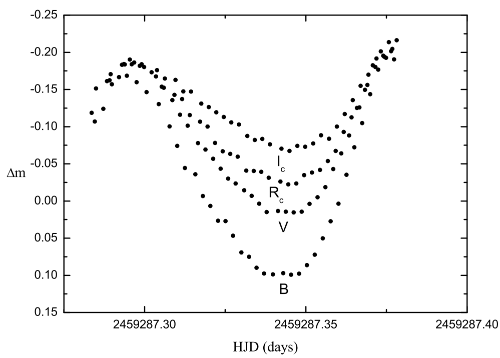


FIG. 8
Ic, *Rc*, *V* and *B* light-curves of TYC 4311-825-1 corresponding to the night of 2021 March 13.

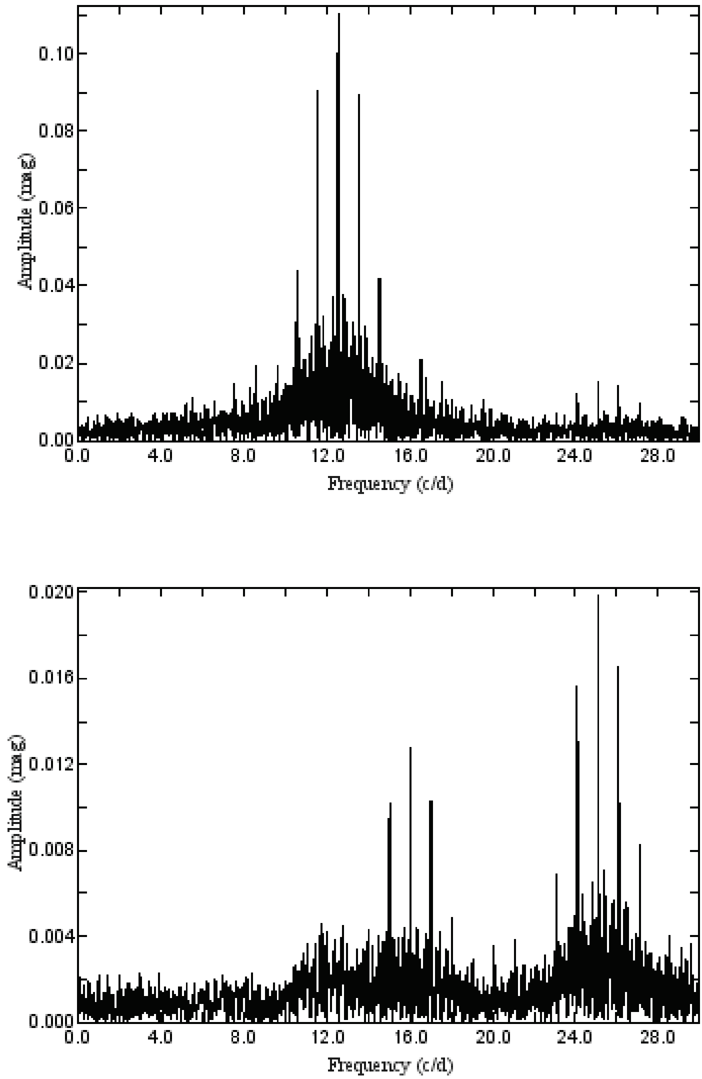


Fig. 9

Amplitude spectrum of the original data for the 2004–2005 V observations (upper panel) and residual amplitude spectrum for the same observation set (lower panel) after pre-whitening.

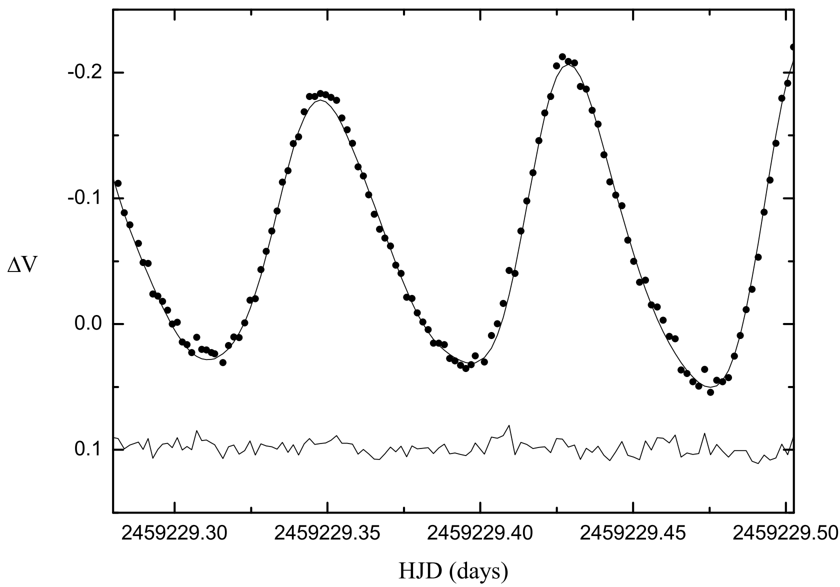


Fig. 10
V light-curve of TYC 4311-825-1 corresponding to the 2021 January 14 data. Overlaid on the data points is the best-fit model obtained from the frequency analysis (solid line) and (bottom) the O − C (observed minus calculated) plot, displaced by 0·1 mag in order to avoid confusion with the light-curve data.

Table III

Light-maxima timings obtained in this work (V data).

HJD (days)	*Uncertainty (days)*	*Filter*	*Year*
2453359·4979	0·0002	*V*	2004–2005
2453359·5748	0·0003	*V*	2004–2005
2453362·2861	0·0002	*V*	2004–2005
2453363·3201	0·0002	*V*	2004–2005
2453363·4018	0·0002	*V*	2004–2005
2453363·4835	0·0003	*V*	2004–2005
2453363·5606	0·0003	*V*	2004–2005
2453364·27906	0·00009	*V*	2004–2005
2453364·3600	0·0002	*V*	2004–2005
2453364·4370	0·0002	*V*	2004–2005
2453364·5156	0·0002	*V*	2004–2005
2453367·3060	0·0002	*V*	2004–2005
2453367·3864	0·0002	*V*	2004–2005
2453367·4689	0·0002	*V*	2004–2005
2453367·5460	0·0004	*V*	2004–2005
2453370·3382	0·0003	*V*	2004–2005
2453370·4157	0·0001	*V*	2004–2005
2453370·4940	0·0003	*V*	2004–2005
2453370·5750	0·0002	*V*	2004–2005

(continued on next page)

HJD (days)	*Uncertainty (days)*	*Filter*	*Year*
2453372·3312	0·0002	*V*	2004–2005
2453372·4103	0·0002	*V*	2004–2005
2453373·2867	0·0002	*V*	2004–2005
2453374·2402	0·0002	*V*	2004–2005
2453374·3235	0·0001	*V*	2004–2005
2453374·4035	0·0001	*V*	2004–2005
2453375·2792	0·0002	*V*	2004–2005
2453375·3578	0·0002	*V*	2004–2005
2453375·4376	0·0002	*V*	2004–2005
2453377·2725	0·0002	*V*	2004–2005
2453377·3502	0·0002	*V*	2004–2005
2453377·4296	0·0002	*V*	2004–2005
2453377·5112	0·0001	*V*	2004–2005
2453378·3029	0·0002	*V*	2004–2005
2453378·3852	0·0001	*V*	2004–2005
2453378·4629	0·0002	*V*	2004–2005
2453379·4208	0·0002	*V*	2004–2005
2453379·5045	0·0003	*V*	2004–2005
2453380·3002	0·0002	*V*	2004–2005
2453380·3820	0·0002	*V*	2004–2005
2453380·4608	0·0003	*V*	2004–2005
2453380·5384	0·0003	*V*	2004–2005
2453381·2595	0·0001	*V*	2004–2005
2453381·3358	0·0001	*V*	2004–2005
2453381·4148	0·0002	*V*	2004–2005
2453381·4981	0·0002	*V*	2004–2005
2453382·2921	0·0001	*V*	2004–2005
2453384·3666	0·0002	*V*	2004–2005
2453384·4458	0·0003	*V*	2004–2005
2453385·24298	0·00006	*V*	2004–2005
2453385·3246	0·0001	*V*	2004–2005
2453385·3987	0·0001	*V*	2004–2005
2453388·3511	0·0001	*V*	2004–2005
2453389·4665	0·0003	*V*	2004–2005
2453389·5475	0·0002	*V*	2004–2005
2453390·2630	0·0002	*V*	2004–2005
2453390·3418	0·0003	*V*	2004–2005
2453390·4259	0·0002	*V*	2004–2005
2453390·5043	0·0004	*V*	2004–2005
2453391·4580	0·0002	*V*	2004–2005
2453392·4189	0·0002	*V*	2004–2005
2453392·4977	0·0002	*V*	2004–2005
2453392·5738	0·0004	*V*	2004–2005
2455857·4544	0·0008	*V*	2011
2455892·3628	0·0002	*V*	2011
2455892·44173	0·00004	*V*	2011
2455895·3128	0·0003	*V*	2011
2455895·3953	0·0002	*V*	2011
2455896·3488	0·0002	*V*	2011
2455896·4280	0·0001	*V*	2011
2455897·3053	0·0002	*V*	2011
2455897·3864	0·0003	*V*	2011
2459199·3004	0·0002	*V*	2020–2021
2459199·37555	0·00007	*V*	2020–2021
2459228·3900	0·0002	*V*	2020–2021
2459228·4711	0·0002	*V*	2020–2021
2459229·3487	0·0001	*V*	2020–2021
2459229·4292	0·0003	*V*	2020–2021
2459230·3825	0·0003	*V*	2020–2021

(continued on next page)

HJD (days)	*Uncertainty (days)*	*Filter*	*Year*
2459230·4628	0·0002	*V*	2020–2021
2459232·2986	0·0002	*V*	2020–2021
2459247·2821	0·0003	*V*	2020–2021
2459247·3601	0·0004	*V*	2020–2021
2459247·4441	0·0002	*V*	2020–2021
2459256·2892	0·0003	*V*	2020–2021
2459256·3713	0·0001	*V*	2020–2021
2459256·4498	0·0003	*V*	2020–2021
2459265·2979	0·0002	*V*	2020–2021
2459265·3761	0·0003	*V*	2020–2021
2459274·3027	0·0003	*V*	2020–2021
2459274·3836	0·0002	*V*	2020–2021
2459287·2965	0·0005	*V*	2020–2021

(continued from previous page)

TABLE IV

Light-maxima timings obtained in this work (B, Ic, and R_c data).

HJD (days)	*Uncertainty (days)*	*Filter*	*Year*
2453366·2736	0·0004	*B*	2004
2453366·3534	0·0002	*B*	2004
2453366·4320	0·0002	*B*	2004
2453366·5098	0·0003	*B*	2004
2459230·3050	0·0005	*B*	2021
2459230·3809	0·0002	*B*	2021
2459230·4618	0·0004	*B*	2021
2459229·3474	0·0001	*B*	2021
2459229·4284	0·0002	*B*	2021
2459245·44985	0·00002	*B*	2021
2459246·3263	0·0002	*B*	2021
2459246·4039	0·0003	*B*	2021
2459287·294	0·001	*B*	2021
2459229·3478	0·0006	*Ic*	2021
2459229·4290	0·0003	*Ic*	2021
2459230·3843	0·0007	*Ic*	2021
2459230·4637	0·0009	*Ic*	2021
2459287·297	0·001	*Ic*	2021
2459245·4498	0·0003	*Rc*	2021
2459246·3280	0·0003	*Rc*	2021
2459246·4055	0·0007	*Rc*	2021

Using the listed first maximum as the initial HJD and $P_0 = 0{\cdot}07971$ d (corresponding approximately to $f_0 = 12{\cdot}5455\,\mathrm{d}^{-1}$), the O – C values derived from data of Tables III and IV are displayed in Fig. 11. The P_0 value was selected by examining the O – C values for different periods. Note that the *Gaia* DR3 and ASAS-SN data (obtained in the period 2014–2018, between the 2011 and 2020–2021 observations), although scarce, support the above f_0 value, excluding a large change in the period.

Data in Fig. 11 are clustered according to the observational windows analysed in this work (years 2004–2005, 2011, and 2020–2021). Although the observations are well separated, they are compatible with a linear trend. In that way, a linear fit to all data that provides the following ephemeris

$$\mathrm{HJD_{max}} = 2453359{\cdot}4959(2) + 0{\cdot}079710105(4)E. \quad (1)$$

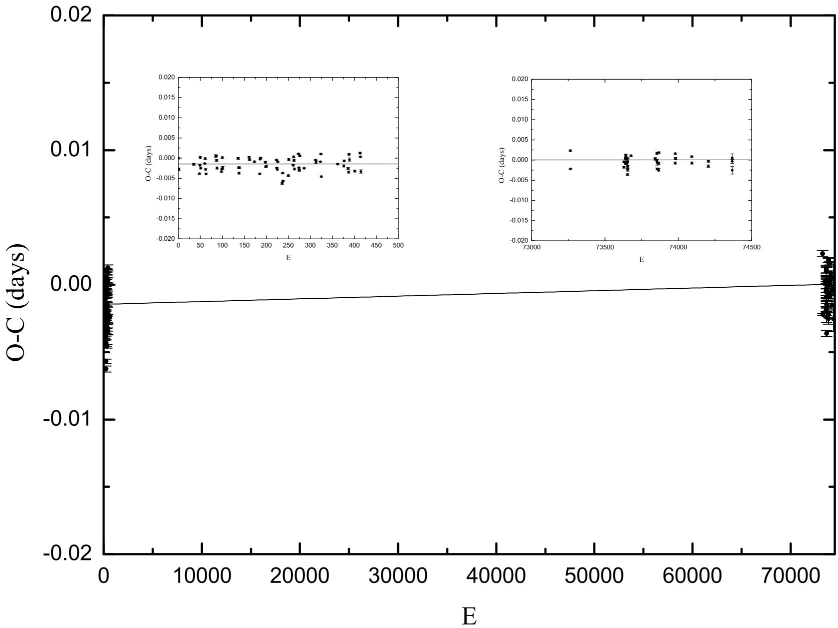


FIG. 11

O – C diagram obtained from data of Tables III and IV by using the reference ephemeris $HJD_{max} = 2453359{\cdot}497856 + 0{\cdot}07971E$. The line represents the best linear fit to the data.

That result seems to indicate that the main frequency (and the period associated with it) has remained stable between the date of the first and last observations.

Type of variability

Although the results presented in the previous section could indicate that TYC 4311-825-1 is a pulsating δ Scuti star, the sparse data of the system are insufficient to determine if that hypothesis is correct. Note that the Galactic coordinates of the star ($b = 6{\cdot}824°$, $l = 129{\cdot}502°$) place it very close to the Galactic equator and, consequently, noticeably affected by the interstellar extinction. In order to obtain a corrected colour index $B - V$, we have used 3D dust maps based in *Gaia* parallaxes of Green *et al.*[18], in the version known as Bayestar19, accessible through the web (http://argonaut.skymaps.info). In that way, for the aforementioned Galactic coordinates of TYC 4311-825-1, and taking into account the distance of 0·38 kpc provided by the *Gaia* DR3 parallax, a reddening $E(g-r) = 0{\cdot}23^{+0{\cdot}02}_{-0{\cdot}03}$ mag is obtained. In that way, by using the suggested transformation equation* $E(B-V) = 0{\cdot}884\,E(g-r)$ and assuming, as is usual for the Galactic interstellar extinction, $R_V = 3{\cdot}1$[19], we obtain $E(B-V) = 0{\cdot}20$ mag and $A_V = 0{\cdot}6$ mag.† Note that, using the former colour excess, now the corrected colour index (taking into account the uncorrected colour

*That equation is obtained from equation (29) of the Green *et al* paper by using the equation (1) in http://argonaut.skymaps.info/usage.

†In that way, A_0, the monochromatic extinction at 541·4 nm provided by *Gaia*, is 0·62 ± 0·01 mag, consistent with the above estimated A_V value, for a band with a mean wavelength of 553·8 nm[20].

index derived from Tycho 2 catalogue data, 0·41 ± 0·06) is $B - V = 0{\cdot}41 - 0{\cdot}2 = 0{\cdot}21$ mag, suggesting suggesting that the star could be a member of the δ Scuti-star class (with a late-A spectral type). Assuming an uncertainty of ±0·1 in the value of R_V, an estimate of the uncertainty of A_V is ±0·1, whereas the uncertainty in the value of $E(B - V)$ is about ±0·03. Therefore, the corresponding uncertainty in the corrected colour index is ±0·07. Note that those values should be considered as lower limits, because of the uncertainties involved in the analysis of the interstellar reddening.

With that value for the corrected $B - V$ index and using the calibration tables of Flower[21], a value of $\log T_{\rm eff} = 3{\cdot}89^{+0{\cdot}02}_{-0{\cdot}03}$ is obtained, being the corresponding bolometric correction $BC = 0{\cdot}033^{+0{\cdot}002}_{-0{\cdot}011}$. The absolute V magnitude can be obtained from

$$M_V = m_V + 5 - 5 \log r - A_V, \tag{2}$$

where r is the distance in pc. Using the m_V value reported by the Tycho 2 catalogue, an M_V value of 1·8 ± 0·1 is determined, and that value roughly agrees with similar values quoted for the δ Scuti stars[22]. Considering the aforementioned value for the bolometric correction, that translates to $M_{\rm bol} = 1{\cdot}8 \pm 0{\cdot}1$, and subsequently, to $\log(L/L_\odot) = 1{\cdot}17 \pm 0{\cdot}04$, assuming $M_{\rm bol,\odot} = 4{\cdot}74$ for the Sun.

In spite of the possible underestimation of the uncertainty values of the $\log T_{\rm eff}$ and $\log(L/L_\odot)$, the present results seem to indicate that TYC 4311-825-1 is a δ Scuti star, located in the area of the HR diagram corresponding to that pulsating-star class, according to figure 2.17 of Christensen-Dalsgaard[23].

Note that *Gaia* DR3 release provides more accurate astrophysical parameters for TYC 4311-825-1. Thus, an effective temperature of 7135^{+23}_{-20} K ($\log T_{\rm eff} \approx 3{\cdot}85$) is listed. It must be noted that that temperature value, although smaller than the rough estimate derived from the former photometric analysis, is close to its lower limit. The *Gaia* DR3 temperature, along with the calibration tables of Flower[21], provides a bolometric correction of about 0·034 and a colour index of 0·31. Whereas the bolometric correction coincides with the above estimated value, the colour index is greater than the previously calculated quantity, although only slightly larger than the upper statistical limit. In regard to that, note that, in spite of the discrepancies, the *Gaia* data also support the δ Scuti nature of TYC 4311-825-1.

Physical parameters and evolutionary status

Along with the temperature value, the *Gaia* archive*† also provides $\log g = 3{\cdot}921^{+0{\cdot}020}_{-0{\cdot}006}$ (g in cm s^{-2}) and $R = 2{\cdot}35^{+0{\cdot}02}_{-0{\cdot}06}\, R_\odot$. In that way, from the well-known equation linking luminosity, temperature, and radius

$$\frac{L}{L_\odot} = \left(\frac{R}{R_\odot}\right)^2 \left(\frac{T_{\rm eff}}{T_\odot}\right)^4, \tag{3}$$

and assuming $T_\odot = 5777$ K, the estimated luminosity is $L = 12{\cdot}78^{+0{\cdot}24}_{-0{\cdot}60}\, L_\odot$. That corresponds to $\log L/L_\odot = 1{\cdot}107^{+0{\cdot}008}_{-0{\cdot}021}$, close to the value estimated in the last section. That result leads to a bolometric magnitude of $1{\cdot}97^{+0{\cdot}05}_{-0{\cdot}02}$, slightly greater than the previous estimate. Finally, by using the values of $\log g$ and radius, an estimation of the star mass provides the value $M = 1{\cdot}68^{+0{\cdot}01}_{-0{\cdot}02}\, M_\odot$‡.

*Note that the *Gaia* parameters are referred to the median of MCMC (Monte Carlo Markov Chain) samples inferred from spectra, apparent magnitude in *G* band, and distance, taken from the best data library that achieves the highest goodness-of-fit value. The uncertainty upper and lower ranges are referred, respectively, to an upper confidence level of 84% and a lower confidence level of 16% that includes the usual 68% confidence interval.

†https://gea.esac.esa.int/archive/

‡In deriving those values we have considered the suggestions included in the *Gaia* DR3 documentation corresponding to the GSP-Phot data (https://gea.esac.esa.int/archive/documentation/)

In that way, the values estimated above can be used to determine the pulsation constant for the frequency f_0, $Q_0 = P_0(\rho/\rho_\odot)^{0\cdot5}$. That parameter is $0{\cdot}0287^{+0\cdot0011}_{-0\cdot0003}$ days. In regard to that, for the frequency f_1, the pulsation constant Q_1 is $0{\cdot}0225^{+0\cdot0008}_{-0\cdot0003}$ days.

On the other hand, by using the global metallicity value $[Z/X] = -0{\cdot}208^{+0\cdot026}_{-0\cdot033}$ (dex) provided from *Gaia*, the mass fraction of metals, Z, can be determined from

$$[Z/X] = \log\left[\frac{Z}{X}\right] - \log\left[\frac{Z}{X}\right]_\odot . \quad (4)$$

Thus, using the value $[Z/X]_\odot = 0{\cdot}0207$ and the relation $Y = 0{\cdot}2485 + 1{\cdot}78Z$ given by Bressan *et al.* [24], we obtain a value $Z = 0{\cdot}0093 \pm 0{\cdot}0007$. It must be noted that there are uncertainties associated with the solar metallicity value. For example, Bressan *et al.* assume $Z_\odot = 0{\cdot}01524$ whereas Asplund *et al.* [25] obtain a value of $Z_\odot = 0{\cdot}0139$, and others, such as Vagnozzi [26], an even higher value of $Z_\odot = 0{\cdot}0196$. Therefore, in order to use the evolutionary tracks [27,28] computed from PARSEC 2·0[*], we have rounded the Z value to the nearest hundredth (0·01). Thus, Fig. 12 displays the evolutionary tracks for masses from $1{\cdot}5M_\odot$ to $1{\cdot}9M_\odot$ and $Z = 0{\cdot}01$ in the $\log(L/L_\odot) - \log T$ (HR) diagram, along with the position of TYC 4311-825-1 herein, according to the physical parameters quoted in the preceding section. In that way, the PARSEC code (http://stev.oapd.inaf.it/cmd) has been used to compute the isochrones [29] corresponding to the above Z value. Those isochrones are displayed in Fig. 13, from $\log t$[years] = 8·8 to 9·8, along with the the boundaries defining the δ Scuti instability strip [30].

According to Fig. 13, TYC 4311-825-1 lies between the $\log t = 9{\cdot}1$ and $\log t = 9{\cdot}2$ isochrones, although closer to the latter one. That translates to an age between $1{\cdot}3 \times 10^9$ and $1{\cdot}6 \times 10^9$ years. Moreover, Fig. 12 shows that the position of TYC 4311-825-1 in the HR diagram is very close to the evolutionary track (green line) for $M = 1{\cdot}7M_\odot$, in agreement with the estimated star mass from *Gaia* data.

In summary, the main physical parameters of TYC 4311-825-1 are listed in Table V.

TABLE V

Main physical parameters of TYC 4311-825-1.

Parameter	*Value*	*Source*
d (pc)	379 ± 2	*Gaia* DR3
f_0 (d^{-1})	$12{\cdot}5457 \pm 0{\cdot}0003$	This work
f_1 (d^{-1})	$16{\cdot}030 \pm 0{\cdot}002$	This work
$T_{\rm eff}$ (K)	7135^{+23}_{-20}	*Gaia* DR3
$\log g$ (g in cm s^{-2})	$3{\cdot}921^{+0\cdot020}_{-0\cdot006}$	*Gaia* DR3
R ($R_\odot$)	$2{\cdot}35^{+0\cdot02}_{-0\cdot06}$	*Gaia* DR3
L ($L_\odot$)	$12{\cdot}78^{+0\cdot24}_{-0\cdot60}$	Derived from *Gaia* DR3
M ($M_\odot$)	$1{\cdot}68^{+0\cdot01}_{-0\cdot02}$	Derived from *Gaia* DR3
Q_0 (days)	$0{\cdot}0287^{+0\cdot0011}_{-0\cdot0003}$	Derived from this work and *Gaia* DR3
Q_1 (days)	$0{\cdot}0225^{+0\cdot0008}_{-0\cdot0003}$	Derived from this work and *Gaia* DR3
$[Z/X]$ (dex)	$-0{\cdot}208^{+0\cdot026}_{-0\cdot033}$	*Gaia* DR3
Z	$\approx 0{\cdot}01$	Derived from *Gaia* DR3 and other authors
t (Gyr)	$\approx 1{\cdot}3$–$1{\cdot}6$	Derived from PARSEC

[*] https://stev.oapd.inaf.it/PARSEC/tracks_database.html

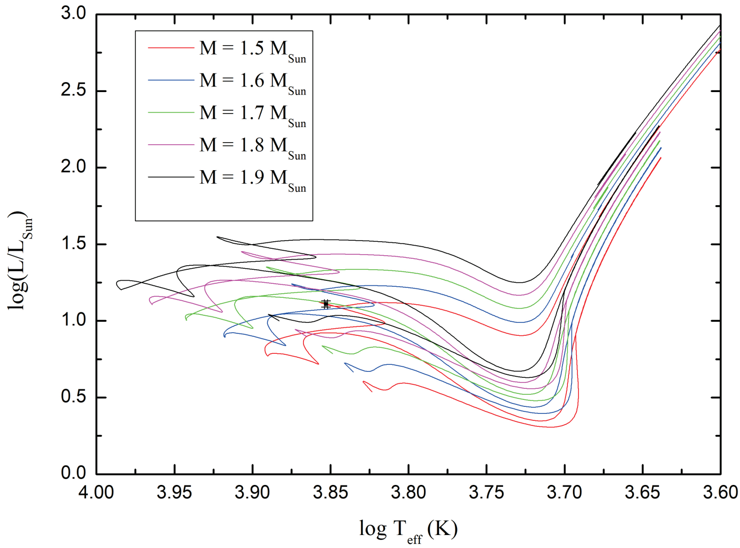


FIG. 12

Evolutionary tracks for masses from $1{\cdot}5 M_\odot$ to $1{\cdot}9 M_\odot$ and $Z = 0{\cdot}01$ in the HR diagram, computed from PARSEC 2·0. The black point marks the position of TYC 4311-825-1.

Discussion

Adopting for TYC 4311-825-1 the two frequencies found, $f_0 = 12{\cdot}546\,\mathrm{d}^{-1}$ and $f_1 = 16{\cdot}030\,\mathrm{d}^{-1}$, as corresponding to the fundamental and first-overtone modes of the radial pulsations, respectively, the ratio $P_1/P_0 = 0{\cdot}783$ is very close to the standard value of 0·779 associated to the double-mode radial pulsators*. Note that that value is well into the range of the first-overtone-to-fundamental-period ratios (0·756–0·787) obtained by Stellingwerf[32] for post-main-sequence Population I stars. In regard to that, TYC 4311-825-1 is located in the Petersen diagram[33] over the zone defined by mass–luminosity (M–L) relations for high-amplitude δ Scuti stars with $Z = 0{\cdot}01$ (figure 3 in that paper). In contrast, the mass, radius, and luminosity estimates for this star are in better agreement with the mass–luminosity, mass–radius and mass–temperature relations for $M > 1{\cdot}5 M_\odot$ main-sequence stars[34]. Note, in that sense, that the estimates for the parameters of TYC 4311-825-1 seem to correspond to low-amplitude main-sequence δ Scuti stars as suggested for the M–L relations presented by Petersen and Christensen-Dalsgaard[33]. In that way, the value obtained for the fundamental-mode pulsation constant Q_0 (0·0287 days) agrees, within the uncertainties, with the corresponding value for the linear adiabatic radial-oscillations model (0·0295 days). In fact, the first-overtone pulsation constant Q_1 obtained by us (0·0225 days) also agrees within

*for polytrope $n = 4$ and adiabatic exponent $\gamma = 5/3$, assuming adiabatic oscillations[31]

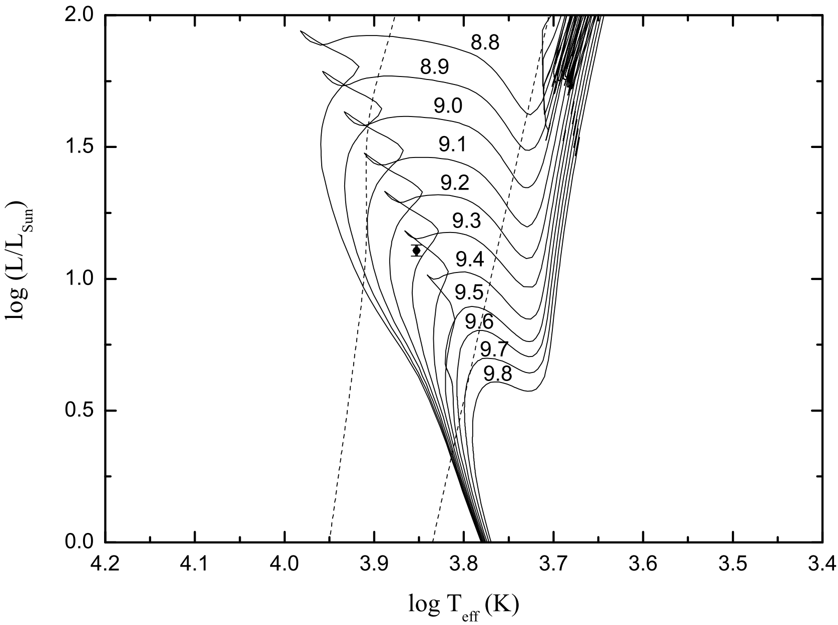


FIG. 13

Isochrones from log t [years] = 8·8 to 9·8 and Z = 0·01 in the HR diagram, computed from PARSEC 2·0. The black point marks the position of TYC 4311-825-1. Dashed lines define the δ Scuti instability strip, according to Xiong *et al.* [30].

the uncertainties, with the corresponding value of 0·0232 days given by that model [35].[*] In addition, if we use the empirical interpolation equation for the ratio P_1/P_0 [33] given by

$$\frac{P_1}{P_0} = (0{\cdot}7291 \pm 0{\cdot}0031) - (0{\cdot}0603 \pm 0{\cdot}0037)\log P_0 + (0{\cdot}008 \pm 0{\cdot}013)\log^2 P_0 + (0{\cdot}021 \pm 0{\cdot}010)\log^3 P_0, \quad (5)$$

we obtain (for $\log P_0 = \log f_0^{-1} = -1{\cdot}0985$) a predicted value of $P_1/P_0 = 0{\cdot}777$, very close to our empirical value of 0·783.

The Period–Luminosity (P–L) relation of Ziaali *et al.* [36], valid for the fundamental radial pulsation, provides an M_V value of about 1·9±0·1 mag, also close to the previously estimated value. That result corroborates the assumption of the dominant pulsation as the fundamental radial mode. A similar result can be obtained by means of the expressions of Poro *et al.* [37], although, in that case, the P–L relation for the first-overtone pulsation leads to a smaller value of M_V = 1·5 mag. However, an inspection of figure. 4 in that paper shows several first-overtone pulsators at the right of the line corresponding to P–L equation, where TYC 4311-825-1 is located. For that reason, we cannot exclude that that first-overtone P–L relation is underestimating M_V compared with the P–L relation for the fundamental mode.

On the other hand, it is well known that δ Scuti stars can be divided into two groups, one belonging to Population I stars (including high- and low-amplitude pulsators) and the other

*Note that the fundamental-mode pulsation constant of Fitch [35] is slightly different from the Cox value [31], but that does not modify the present discussion.

belonging to old disc Population II stars, collectively denoted as SX Phe variables [38]. In that way, the information provided by *Gaia* can be useful to elucidate the character of TYC 4311-825-1. From the values for the distance and Galactic latitude of the star, a distance to the Galactic plane of about 45 pc is obtained. Moreover, using the parallax, the proper motion (μ_α = 0·2323 ± 0·0108 and μ_δ = −4·1214 ± 0·0127 mas/year), and the radial-velocity (v_r = −21·07 ± 2·20 km/s) values obtained from *Gaia*, kinematical properties of the star can be derived.[39] For that calculation, we have used the North Galactic Pole coordinates $\alpha_{NGP} = 12^h49^m$ and $\delta_{NGP} = 27°24'$ (B1950) and the Galactic longitude of the North Celestial Pole, $\theta_o = 123°$ [40]. Thus, the Galactic velocity components, corrected for the solar motion using the data of Schönrich *et al.* [41], are U = 22 km/s, V = −5 km/s, and W = −2 km/s. Those values provide a total space velocity of about 23 km/s. Those results support the hypothesis that TYC 4311-825-1 is a Population I star belonging to the thin Galactic disc. In addition, the *Gaia* DR3 release gives a metallicity factor [Fe/H] = −0·208. Considering the metallicity distributions for thick- and thin-disc stars (see Lee *et al.* [42]) that [Fe/H] value suggests that TYC 4311-825-1 is really a thin-disc star.

It must be noted that the maximum peak-to-peak V amplitude of about 0·25 mag is close to the usual amplitude limit for high-amplitude δ Scuti (HADS) stars, established around 0·25–0·3 mag. Therefore, TYC 4311-825-1 could be preliminarily classified as a limiting case of an HADS star. In that sense, the amplitude of the fundamental mode of about 0·11 magnitudes (in the V band), although small, can be comparable to the values of examples of HADS stars, such as V974 Oph, with a fundamental-mode amplitude of about 0·16 magnitudes. However, it has been suggested [43] that the amplitude criterion is not relevant to define if a δ Scuti star belongs to the HADS class or not. In fact, Balona [44] points out that the term HADS should be dropped, according to the study of δ Scuti stars observed by the *Kepler* observatory. Note that, irrespective of the classification of TYC 4311-825-1 as an HADS star, its properties are similar to some of the 132 double-mode (radial fundamental + first overtone) HADS stars listed in the work of Yang *et al.* (https://arxiv.org/pdf/2110.13594). In particular, in the corresponding Petersen diagram for that catalogue, the period ratio of the star agrees with the period ratio of HADS stars with similar fundamental periods. In addition, amplitudes in the B and V bands are roughly stable comparing the data of 2004–2005 and 2020–2021, taking into consideration the possible effects of minor systematic errors due to the changes on equipment between both dates.* Moreover, according to the O − C analysis, the period associated to the fundamental mode appears also to be stable. Note, however, that the data are concentrated in the years 2004–2005, 2011, and 2020–2021, without useful maxima-timing measurements between those dates.

Regarding the evolutionary status, the PARSEC data of the evolutionary tracks seem to indicate that TYC 4311-825-1 is a MS star. The location of the star in the Petersen diagram built by Xue *et al.* [45] using double-mode pulsators observed by *TESS*, agrees with that hypothesis. Although TYC 4311-825-1 is clearly located within the instability-strip limits defined by Xiong *et al.* [30], approximately halfway between the blue and red edges, it appears somewhat displaced towards the red edge according to the instability strip defined by other authors, such as Dupret *et al.* [46]. Note also that the models developed by those last authors predict the stabilization of radial p-modes at the red edge.

Conclusions

From the analysis of differential-photometry data obtained in this work, we conclude that TYC 4311-825-1 is a double-mode pulsating star with fundamental and first-overtone periods of 0·080 days (≈ 1·9 h) and 0·062 days (≈ 1·5 h), respectively. Periods and amplitudes seem to be relatively stable in the analysed interval time, from 2004 to 2021.

*Note that uncertainties in Table II are statistical.

Data derived from the *Gaia* DR3 release indicate that TYC 4311-825-1 is a Population I star. Pulsation constants derived from the aforementioned periods are in agreement with a model of radial adiabatic oscillations ($\gamma = 5/3$). Physical parameters provided by *Gaia* data (or calculated from them) suggest that TYC 4311-825-1 is a low-mass MS star (core-hydrogen burning), with $M = 1{\cdot}68 M_{\odot}$ located in the δ Scuti instability strip, with $L/L_{\odot} = 1{\cdot}11$ and $\log T_{\rm eff} = 3{\cdot}85$. New photometric and, especially, accurate spectroscopic data can shed light in order to improve the knowledge of this system.

Acknowledgments

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium*. Funding for DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. F. S-B. acknowledges the support of the Junta de Extremadura and the European Regional Development Fund under projects GR18081, GR12021, and GR24101.

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

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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 1·617 ± 0·003 $M_\odot$ and 1·207 ± 0·004 $M_\odot$, and radii of 1·948 ± 0·008 $R_\odot$ and 1·195 ± 0·022 $R_\odot$. 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)	$14^h22^m49^s.698$	11
Declination (J2000)	$+14°56'20''.14$	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

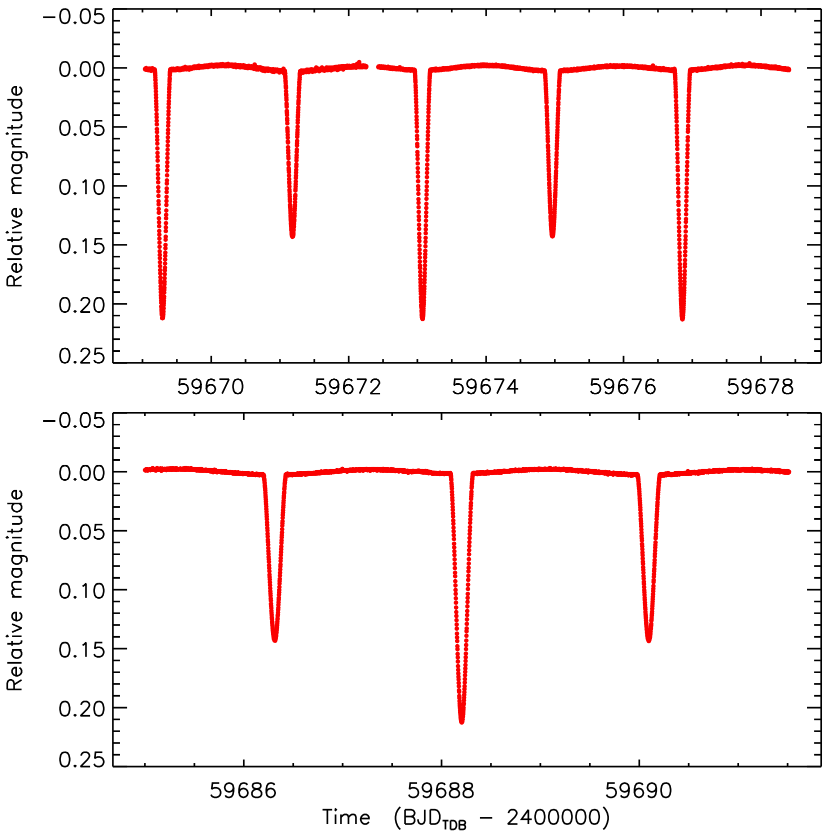

FIG. 1
TESS sector 50 photometry of DV Boo, including only the data analysed in the current work. The flux measurements have been converted to magnitude units and the median subtracted.

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 $G_{\rm RP}$ = 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 ($r_{\rm A}$ and $r_{\rm B}$) taken as the 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), 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

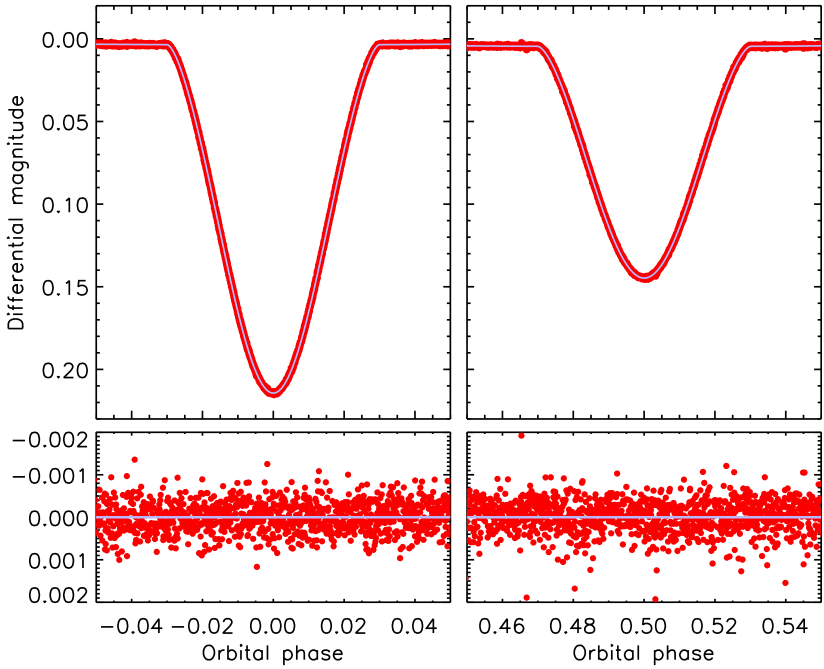

FIG. 2

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

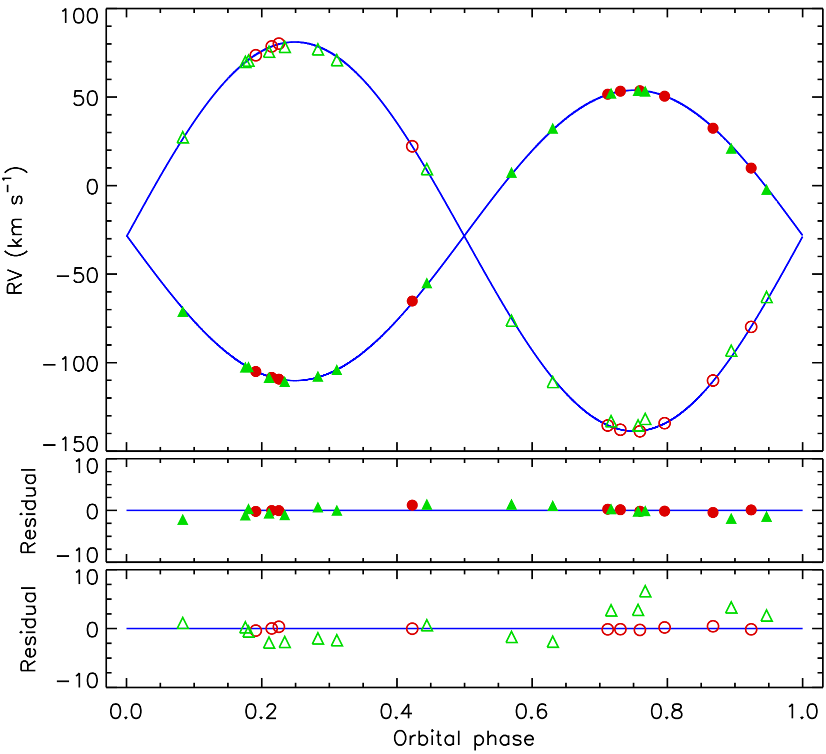

FIG. 3

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 (km s^{-1})	82·01	±	0·12
Velocity amplitude for star B (km s^{-1})	109·91	±	0·08
Systemic velocity for star A (km s^{-1})	−28·15	±	0·10
Systemic velocity for star B (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 (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	

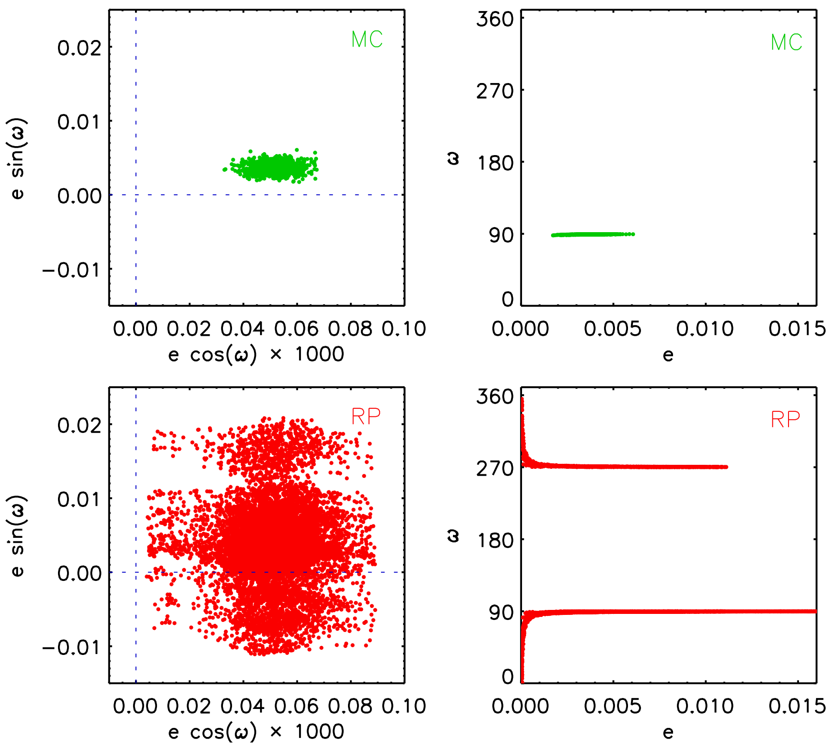

FIG. 4

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 $E(B-V)$ = 0·04 ± 0·02 mag was needed to equalize the optical distance measurements with the infrared ones. Our final distance estimate is 125·0 ± 1·5 pc, which is in unimpeachable agreement with the 125·8 ± 0·4 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 = 0·014 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.

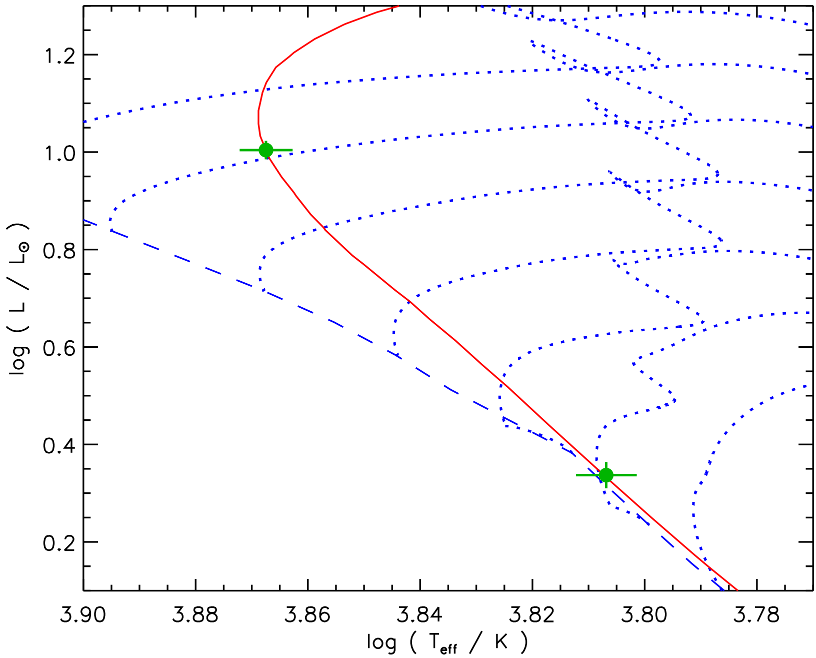

FIG. 5

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].

Acknowledgements

We thank the anonymous referee for a prompt report which led to much more discussion of the possible eccentricity of the system. We thank Jerzy Kreiner and Waldemar Ogłoza for providing a list of times of minimum for DV Boo. This paper includes data collected by the *TESS* mission and obtained from the MAST data archive at the Space Telescope Science Institute (STScI). Funding for the *TESS* mission is provided by the NASA's Science Mission Directorate. STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

This work has made use of data from the European 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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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 book equips the reader with an excellent overview and basic understanding of most aspects of the subject on which to build as new advances are made.

The book is beautifully produced and a pleasure to read. It is scholarly, and assumes a readership with a good general scientific grounding. At the same time, it is well readable and attractively and abundantly illustrated in beautiful colour. It also provides a good level of detailed data in the form of tables and charts. Given that, it will have wide utility for students, teachers, scholars, and interested lay persons. It provides an excellent supporting text for courses and can function as a basic reference volume on the bookshelves (for those of us who still have such things) of all Earth scientists. I recommend it highly as a supporting text to courses on planetary geology. — Gillian R. Foulger.

From the Laboratory to the Moon: The Quiet Genius of George R. Carruthers, by David H. DeVorkin (MIT Press), 2025. Pp. 434, 23 × 15 cm. Price $75 (about £55) (paperback; ISBN 978 0 262 55139 7).

I had never heard of George Carruthers, and I suspect most astronomers not involved in instrument development may share my ignorance. And yet he played a vital role in the Apollo programme and in earlier attempts to discover what happens above the Earth's atmosphere. This book explains how and why.

Born in 1939, Carruthers's family were part of the professional middle class, unlike the vast majority of other African Americans at the time (his Uncle Ben taught at Howard University in DC). He was brought up on a farm, where his father had worked hard to make the farm buildings useable and liveable, setting an example of hard work that his son followed throughout his career. He helped his father, who had a background in civil and general engineering, to fix things around the farm. The farm was run for just themselves, and his father worked during the week at an Air Corps base in Dayton, Ohio, and told young Carruthers many tales of what he saw there. His school grades were excellent, and his private reading mostly involved how to build flying machines in air and space. He also made designs for spacecraft and wrote "quite corny" stories about space flight. With his father's help and encouragement, he made himself a small refractor and loved looking at the Moon, planets, and stars, so he became very excited when people like von Braun started talking seriously about space rockets being possible and useable for astronomy.

His father died young, when Carruthers was about six, and the family moved to Chicago to live with his grandmother and great aunt. At his new school, several science teachers guided him through experimental work, at which he excelled. He also built himself a better telescope, a reflector for which he ground the mirror, with the help of the Adler Planetarium, which ran programmes for young people. After school, he went to the Champaign/Urbana campus of the University of Illinois to pursue a degree in engineering, where he found himself for the first time in a mostly White environment. However, he encountered little direct racism — mostly the White students simply ignored him. That didn't bother him, because he had always been a loner and just continued his goal of learning enough to get involved in space flight. He was particularly keen on working in the laboratories, and it was practical work with a special interest in cameras and in the engineering of rocketry that became his life's work. He even set up his own laboratory in his mother's basement while he was still a student. He was always trying risky things and had plenty of mishaps as a result. Much later, he had a sign on his office wall saying, "If it ain't broke, let's see if we can break it."

After graduation, he obtained a summer job at the Aerojet Corporation in California, his first introduction "to what engineers actually do" and discovered that he didn't like being one cog in much larger wheel — he wanted to see the whole picture. After that, he pursued graduate study, studying aeronautical and astronautical engineering combined with a minor in physics and astronomy, which introduced him to some of the astronomy faculty. He chose a thesis topic that was very precise but which he knew would give him insight into how rockets would interact with the Earth's atmosphere. He built all his own laboratory equipment, which involved becoming a competent glassblower and learning about photoelectronic detectors. During that time, he gave a very-well-received talk about his work, at the Naval Research Laboratory (NRL), which much impressed Herbert Friedman and led to Carruthers joining Friedman's group at NRL in Washington, DC, where he moved in 1964. He began working on sounding rockets (Aerobees, built at the Aerojet Corporation) and designing and building instruments to fly on them, with special concentration on the UV radiation expected to be produced by nebulae around hot stars. He first designed and built a low-resolution spectrophotometric camera of a new design that was a hybrid of a camera introduced in the 1930s by Lallemand and modern (1960s) electronography and would be sensitive in the far-UV. It would present the results as two-dimensional images. However, his desire (and ability) to do everything himself annoyed the NRL technical staff and created some difficulties, which he ignored. They got used to it.

By that time, his skill and dedication had won him support and admiration from the science community and he began to be in demand for a variety of projects. Despite his first love being his camera, which he kept tweaking and improving (he patented one version), he did accept other work, such as developing a night-vision programme of interest to the navy. Friedman arranged for him to become a full-time staff member at NRL. One of his first achievements there (in 1971) was the first detection of molecular hydrogen in space in the UV, from a sounding rocket, which added to his growing reputation amongst astronomers. In his first cameras, the images were recorded on film, which needed to be returned to the ground for processing, but later technology enabled him to use electronic recording (CCDs by the 1990s) which could be returned to Earth digitally. He started to publish regular articles reviewing the technology.

He had also started, as early as the 1960s, to write NASA proposals for instruments to be used in the Apollo programme. He made many such proposals, but they kept being turned down by committees. The main aim of Apollo was to put men on the Moon and use them to explore its properties, and it was difficult to persuade anyone that astronomy was a priority. Carruthers's case was that his camera could record the whole geocorona and its auroral patterns for the first time, as well as providing a stable platform for many other astronomical observations. He began to get support from Thornton Page (described as a "consummate networker"), who had made his own more elaborate proposal for a 20-inch telescope on the Moon. After much politics in high places, a combined proposal was accepted for Carruthers's small camera to be taken on *Apollo 16*. Unfortunately, the camera design was too large to fit into the Lunar Module (LM), even folded up — so a new design was called for, still retaining both imaging and spectroscopic modes. The launch date was fixed, so there was great pressure on all parties to meet tight deadlines. Finally, the flight took off and landed safely, but six hours later than planned, requiring both Carruthers and Page rapidly to recalculate the altitudes and azimuths of the objects they wanted to observe from the alt-az mount. It was then up to John Young to set up the telescope in the shadow of the LM. He did that successfully and many images were recorded on the film roll, which was brought safely back to Earth. There followed many months of anxious waiting before the results were known. They were able to present a few unique and impressive images and spectra at the AAS meeting in 1972 August, but it was years before all the data had been fully processed.

The *Apollo 16* images led to a flurry of public interest, particularly among the local Black Caribbean community, and he began to be invited to visit schools and talk about his work. He turned out to be an excellent speaker and good with children, so those invitations kept coming. Some of those talks were arranged by Francis Redhead, a prominent member of the Caribbean community, and he had a daughter, Sandra, so those public events led indirectly to his marriage to Sandra, who helped her father to coordinate the speaking events.

The *Apollo 16* success spurred him on to new projects, the first of which was *Skylab*, where his Apollo package was used on *Skylab 4* in 1973 November to observe the close approach of Comet Kohoutek to the Sun. Although many useful results were obtained by Carruthers and others, to the public the comet was a disappointment because it did not brighten as expected. He applied for every new project (the Shuttle, *IUE*, *LST/Hubble*, *etc*.) on which he could use his camera to record images and spectra. He even applied to become an astronaut but was not accepted. He stuck with his original electronographic camera design but was constantly improving it and updating the recording device as new detectors became available, such as CCDs in the late 1980s onwards. His enthusiastic mentor, Friedman, retired in 1981 and was replaced by Gursky, who was equally supportive. However, funding became scarce as NASA's support dwindled after the *Challenger* disaster in 1986, which stopped all manned space flights for three years, and Carruthers's far-UV group was especially badly damaged, losing staff to other areas. Gradually, Carruthers's role as leader became more that of consultant and mentor of students.

Carruthers never threw anything away, and gradually took over new laboratory space, the cost of which had to be borne by NRL. His success rate for new projects also started to decrease, because new members of staff were tending to avoid using his camera, regarding it as now out of date, even though its spectral range stretched as far as Lyman-alpha. He had been promoted to a very senior rank, but had too few grants to cover his space costs, which was causing management problems, and he was eventually moved out into a 40-foot trailer attached to the main building. That move coincided with (and perhaps prompted) his increased activity in outreach, where he was one of the originators of an apprenticeship scheme and supervised many summer students and year-long co-op students. By the 2000s, his outreach activities were becoming increasingly visible. That was not a new interest — he had given a motivational talk in 1960, when he was still in college, to a conference of mainly minority schoolchildren. That was not his only outside interest. He also felt strongly about encouraging more minorities and women into science, and he joined the NTA[*] and became very active within it, even spending several years as editor of its journal and making the NTA itself better organized. He also got involved in S.M.A.R.T. Inc.[†] which quickly became a way of making direct contact with students, their parents, and teachers to advise them on what school subjects were needed to succeed in those areas. NRL was happy to support those outreach activities because they were a good advertisement for the lab. By that time, he was well known nationally and had received many awards for his work, including the AAS's Helen B. Warner Prize for his discovery of molecular hydrogen. The most prestigious award was The President's National Medal of Technology and Innovation, presented to him by President Obama in the White House in 2013. The citation specifically mentions his "invention of the Far-UV Electrographic Camera".

In 2002, Carruthers took retirement, aged 63, under a scheme devised by Gursky by which he was rehired for another ten years with full access to his lab, where he appeared almost every day and which he used as a base for his increasing work with students. On retirement, he also became an adjunct professor at Howard University in DC, the students of which he had already been in contact with for many years. Carruthers had been promoted early in his career in recognition of his work, and continued to be paid well, so he and Sandra were comfortably off and he was able and willing to help close family members with loans and gifts, as his brother Gerald gratefully acknowledged. The final chapter of the book gives more details of his family life, including his wife's death in 2009 and his subsequent second marriage in 2011 to a colleague and helper whom he had met in 2004, Debra Thomas. But even by the time he received the Presidential Medal in 2013, his physical health was getting

[*]The National Technical Association, founded in the 1920s by 'Black technical, scientific and professional engineers'. It encouraged African Americans to enter jobs in science, engineering and technology. By the late 1980s, its membership had risen to some 500,000.

[†]S.M.A.R.T. stands for Science, Mathematics, Aerospace, Research and Technology, founded in 1985 as a group 'to advise on science and technology issues of importance to the Black community'.

worse, and he was less alert mentally. Those changes continued, with visits to hospital with heart problems, and he died peacefully of heart failure in George Washington University Hospital on Boxing Day 2020. His 1972 camera still sits on the Moon's surface and serves as a suitable memorial for this remarkable man.

I must now comment on the writing style. DeVorkin gives a lot more detail than I have included here and makes a digression every time he introduces a new person with a significant effect on Carruthers's career. That makes it quite difficult to discern a clear path through Carruthers's development and progress. That is true of the whole book, which makes it hard to see the wood for the trees. I think this would have been a better book if he had restructured it so that the digressions were separated off into separate coherent chapters and didn't interrupt the flow of Carruthers's story. However, it is easy to follow each individual paragraph, and I found myself reading easily and, in the end, reading every word. So — would I recommend this book? It is certainly a comprehensive account of the life and work of the man DeVorkin calls a "Quiet Genius", but there is so much detail that it is hard to remember it all, which perhaps makes it more of a reference book. It is useful therefore that there is a 20-page index. There are also 61 pages of notes — mostly just references to sources but including occasional comments — as well as a 21-page bibliography of the books the author has consulted. There is a useful list at the beginning of the meaning of many acronyms, such as NRL, and at the end there is a brief glossary of scientific terms. He also lists all the oral-history interviews by himself and others (six with Carruthers himself) and his archival resources. Unusually, he also includes brief profiles of four of Carruthers's students and mentees, including quotations from them of their opinion of Carruthers (all favourable!).

If you want all that detail, then this book can be recommended. But if you just want to find out quickly who the man was and what he achieved you may be better to consult his entry on Wikipedia (https://en.wikipedia.org/wiki/George_Robert_Carruthers). — Robert Connon Smith.

Reading the Mind of God: Johannes Kepler and the Reform of Astronomy, edited by A. E. L. Davis, J. V. Field & T. J. Mahoney (Springer and the RAS), 2024. Pp. 405, 24 × 16 cm. Price £79·99 (hardbound; ISBN 978 94 024 2248 1).

The very first word in the first chapter of this book is "Surprising." In that case the surprise is Kepler's very deep religious conviction. It is true that in most history-of-science primers Kepler's faith is rarely mentioned except as causing him annoying logistical difficulties by occasionally having to move home from one city to a more tolerant one. The editors' comment that in a book organized according to what was most important to Kepler, his theology takes first place. Thus, the initial chapter, subtitled a 'Theological Biography', on Kepler's religion and his commitment to Lutheranism, written by the theologian Charlotte Methuen, reveals his uncompromising approach on matters of theology, to the extent that may have made life very difficult for a less talented, and thus less socially tolerated individual. The second chapter, by J. V. Field, considers his religion in relation to his belief that the heliocentric cosmogony shows the nature of the creator. Kepler's deep belief in God as the creator and geometer of the Universe was the central driving force to his scientific efforts and that is persuasively argued in those first two chapters. Field takes us through Kepler's published works, including *Mysterium Cosmographicum* and *Harmonice Mundi*, the two books which link the geometry of the orbits of the then-known six planets. Kepler placed the five Platonic solids to nestle between their orbits, which they fit astonishingly well; in fact the inscribed and circumscribed spheres (at the faces and at the vertices) of each polyhedron create spherical shells the thicknesses of which accurately bound the eccentricities of the planetary orbits — surely unequivocal proof of God's geometry. It is not surprising then, that religion underpins the unlikely looking title of this collection of essays. However, the surprises do not stop with religion: Kepler had described the concepts, and indeed designed the optics for astronomical telescopes before Galileo; he also developed the beginnings of using infinitesimals to calculate the area of difficult shapes — perhaps sowing the seeds of calculus. In his study of volumes constructed from regular polygons he discovered two new Archimedean solids; his description of how the Universe would look from the surface of the Moon resulted in the first science-fiction story; and he came up with the concept of a force emanating from the Sun as being responsible for the planetary orbits. Despite all that he was not a modern physicist; he still believed in astrology, but in his semi-rational physical version, believing that just as the Moon causes the tides it would not be surprising if, through similar action at a distance, the position of the planets could affect the environment of a person's birth. He was a traditionalist to the extent that he did not make use of algebra, believing it untrustworthy as it allowed for "non-constructable" phenomena, thus his calculations of planetary orbits were carried out using Euclidian geometry, based on straight-edge-and-compass diagrams and page after page of tedious arithmetic. Although he had advanced from the ancient medieval alchemists, he was certainly a scientist of his time, but a key, perhaps *the* key, scientist leading to the 17th-Century scientific revolution.

This book has had a seemingly long gestation period of 15 years. Although published in 2024, it grew out of special session on the life and work of Kepler at the General Assembly of IAU held in Rio de Janeiro in 2009. That session was organized to mark the four-hundredth anniversary of the publication of Kepler's *Astronomia Nova*, which introduced his first two laws of planetary motion. The session organizers had gathered the leading Kepler experts in all branches of his work, and their meeting was regarded as a huge success. (T. J. Mahoney's minutes of the meeting are available on-line.*) Because the conference and its proceedings were deemed to be rather too technical for general appreciation, a working group was formed to develop a programme to promote Kepler and ensure that his huge contribution to science was more widely known. One proposal was to make the conference contents available in book form, but in a version aimed at a sophisticated readership but one not necessarily as familiar with all the details of Kepler's life as the conference attendees. What was needed was a good, serious, detailed book about most things Kepler (there are too many for all), and this volume is the result.

The 13 chapters are written by experts as diverse as theologians, astronomers, mathematicians, space scientists, teachers, and linguists. In addition to religion and its influence on Kepler's cosmology — mentioned in the first two chapters — subsequent essays cover: T. J. Mahoney's account of the astonishing accuracy of Tycho Brahe's astronomical instruments, which provided the data that led Kepler to his first two planetary laws; A. E. L. Davis's description of the mathematics — by geometry — that led to those laws; Andrew Gregory's analysis of the single word in Greek in the full title of the otherwise Latin *Astronomia Nova*, and the difficulties in decoding the word which can be interpreted to mean both explanation and cause and therefore presents problems to later Kepler scholars. Kepler's unconventional approach and reform of astrology are covered by Shiela Rabin in a chapter in which Kepler is said to dismiss the signs of the zodiac as the products of a peasant's imagination, and rejects astrology's predictive power, stating that the stars instruct they do not compel. But he also describes astrology as financially necessary for him, and that it benefits his study of astronomy. On optics Kepler is on modern ground and W. H. Donahue describes, with contemporaneous drawings, Kepler's leading role in that science and his use of ray diagrams, a technique seemingly borrowed from the artist Dürer. The design of lenses for telescopes led to a correspondence with Galileo and their relationship is examined in Chapter 8 by J. V. Field, simply titled 'Kepler and Galileo'. That relationship was initiated almost by accident, as an acquaintance of Kepler's travelling to Italy had been instructed to pass on a copy of *Mysterium Cosmographicum* to professors of mathematics, which in

*https://www.researchgate.net/publication/231990068_Marking_the_400th_Anniversary_of_Kepler's_Astronomia_nova

Padua just happened to be Galileo. Galileo's friendly letter of thanks and Kepler's enthusiastic response are reproduced here in English translation. The next chapter, also by J. V. Field, considers the *Rudolphine Tables*, which enabled accurate calculation of the future positions of the Sun, Moon, and planets from an initial observed position. That work started by Tycho based on his observations was completed more than 20 years after Tycho's death by Kepler using his own model of planetary motion, including elliptical orbits, and makes use of his third law. Jay Pasachoff in the next chapter on observing planetary transits notes that the 3rd law is the key to uncovering the planetary content of the Universe by means of the *Kepler*, *TESS*, and *CHEOPS* spacecraft. He discusses some of the difficulties of observing transits as exemplified by the 1761 transit of Venus which had the aim of establishing the scale of the Solar System. He makes the point that centuries after his death, Kepler's work has led directly to a flourishing branch of astronomy today in the study of extrasolar planets. Chapter 11 by Eberhard Knobloch outlines some of Kepler's contributions to mathematics which include his philosophical belief that in geometry existence is equivalent to constructability and thus non-constructable items cannot be known to the human mind or by God. Thus, Kepler rejected algebra, despite which he made huge mathematical contributions, some of obviously geometric concern, like polygons and polyhedra, but also conic sections, logarithms (the tables of logarithms in the *Rudolphine Tables* were from Kepler's own calculations), the precursor of infinitesimal mathematics and calculus, and strangely the ideal shape for wine barrels. The penultimate chapter by Jarosław Włodarcyk tells us of Kepler's science-fiction story *Somnium* ('Dream') which he had been writing for most of his adult life, although it was not published until after his death. Kepler's *Dream* describes a journey to the surface of the Moon and the conditions that might be experienced there, with an accurate description of the cosmos as seen from the lunar surface. There had been numerous earlier authors of such journeys but because they had used wild imagination and were from a geocentric, stationary-Earth perspective they are regarded as fantasy. Kepler's view of the lunar skyscape is based on his thorough, accurate calculation from a heliocentric viewpoint which gives it a factual basis and makes it science fiction.

This range of authors, and subjects assembled from such individual skill, knowledge, and enthusiasms, might need firm editorial control to achieve a coherent whole with a consistent level of intellectual demand of the reader. However, the editors have, quite rightly in my opinion, decided not to impose a unified version of Kepler, but have allowed the distinguished experts to express their own views by their own methods. That necessarily results in variation of styles. A one-time colleague of mine describes as 'viscous' passages and book chapters that require repeated rereading or simply cause an 'er what!' response. The sticky viscosity of some chapters in this book is understandable from the editors' light-touch approach. For the reader, enthused by the introductory passages, some of the chapters' technicalities can be overwhelming. That becomes particularly troublesome when an author makes repeated references to Kepler's or other published works in order to describe an exchange of view. Those other works may well be on the bookshelf of the expert, but however copiously footnoted and referenced in the essay, those writings are not within reach, or even a simple mouse click away from the general reader. The true enthusiast will persevere and follow the link to the on-line sources* in Latin and German, and will doubtless be rewarded *via* the arcane paths of mathematics, theology, Latin, Greek, and post-medieval German to a richer understanding. However, if you are accepting of being occasionally baffled, and being just carried along with the expert enthusiasm, then this book works as an enjoyable read for the non-specialist who will be awed by Kepler as an amazing scientist, one who led the way to our rational understanding of the Universe. He lit the path to modern data-driven physics and in so many instances built the ladder for others, such as Galileo and Newton, to climb to greatness.

*https://kepler.badw.de/en/kepler-digital.html

The last chapter, written by W. H. Donahue, an author and translator of Kepler into English, describes the careful nuance required in revealing the intention and meaning in translating writing, diagrams, and even print layout of work from a different time and culture. He hopes for more of Kepler's work to made accessible in the form of readable, well-annotated selections, in translation, for the general reader. In that last chapter, on the last page and in the last paragraph, we find this: "Kepler is too good to be constrained within the province of experts". Amen to that. This book is a serious work and not a light-weight popularizing book for public understanding, but it does a very good job in making the astonishing range and achievement of Kepler's work more widely accessible — so much of which is presented in English translation of Kepler's own words. As befits its expert scholarly origins this book is thoroughly referenced at the end of each, well-footnoted, chapter. Additionally, there is a very useful chronology covering the relevant period, from the birth of Martin Luther in 1483 to the end of the thirty years war in 1648, plus a glossary of terms including those that are now obsolete or have changed meaning over time, and finally there is a 28-page index.

This book is an absolute joy; there is not one chapter that does not delight or surprise. It is detailed enough for the serious scholar who might want a jumping-off point to research a particular aspect of Kepler's work, but enough enthusiastic description for the amateur who simply wants to get into the mind of Kepler, to try to understand just how he arrived at his understanding of the cosmos. It should be made available in all libraries wherever science is studied. — Barry Kent.

The Universe: A Biography, by Paul Murdin (Thames & Hudson), 2022. Pp. 288, 24 × 15·5 cm. Price £31·99 (hardbound; ISBN 978 0 500 02464 5).

Not to be confused with *Secrets of the Universe*, *Mapping the Universe*, *Universe*, *Discovering the Universe*, or *Catalogue of the Universe* (all (sub)titles of books (co-)authored by Murdin, who has about a score altogether), this book offers a chronological overview of the history of the Universe (with the time since the Big Bang on the upper right of the rectos), starting off with discussions of Olbers's paradox and the expansion of the Universe, the "questions that revealed the universe was born". Murdin is well known for his work with Louise Webster identifying Cygnus X-1 as the first convincing black-hole candidate; that story is told in more detail in a book[1] recently reviewed[2] in these pages than in this book. The following chapters cover the early Universe, galaxy formation, the dark ages, the Milky Way, the Sun, end phases of stellar evolution, the origin of the Solar System and Earth's Moon, the structure and history of Earth, the future of the Universe, and a discussion of the cause of the expansion. (Note that the last two chapters, though numbered as expected, are referred to as 'sequel' and 'prequel', perhaps reflecting their somewhat more speculative status.) What differentiates this book somewhat from similar books is more emphasis on the people involved (though of course much less than in books on the history of astronomy) and integrating related topics into the appropriate chapters, covering such subjects as big-bang nucleosynthesis, the cosmic microwave background, dark matter, primordial fluctuations, expansion, surveys, gravitational lensing, Messier objects, active galactic nuclei, radio astronomy, gravitational waves, the Lyman-α forest, H I intensity mapping, galaxy mergers, *Gaia*, Sgr A*, meteorites, the faint-young-Sun problem, the Carrington Event, X-ray binaries, chaos in the Solar System, Milanković cycles, life, plate tectonics, planetary magnetic fields, mass extinctions, and *eLisa* — thus fleshing out a more or less standard qualitative history with a bit more astrophysics, in many cases in somewhat more detail than in similar books.

As with many authors, Murdin's discussion of the relationship between the geometry and destiny of the Universe is that of a universe with no cosmological constant, though Murdin, of course, notes elsewhere that that is not our Universe. The ultimate conclusion, that our Universe is (almost) flat and will expand forever, is technically correct, but obscures the important point that the latter (assuming a Friedmann model the parameters of which we have correctly determined) is certain whether or not the Universe is exactly flat or has a slight positive or negative curvature (whereas in the case without a cosmological constant the flat case is a boundary not only with regard to geometry but also with regard to destiny); also, our Universe will not "slow its expansion but never completely stop" — that is the Einstein–de Sitter Universe with no cosmological constant and the critical density — but rather is now accelerating and will asymptotically approach the exponential acceleration of the empty de Sitter model. (See ref. 3 for more details on that common mistake.) A few other common misconceptions are repeated, *e.g.*, the first indications of dark matter came in 1933 through the work of Zwicky (see ref. 4 for references to earlier work). That the Big Bang resulted in 96 per cent hydrogen and 4 per cent helium is incorrect; closer to the truth are 92 per cent and 8 per cent, respectively (in addition, it is not stated that the values are by number of atoms, rather than by mass, in which case the (correct) values are 75 per cent and 25 per cent, respectively). His discussion of the expansion of the Universe being the outcome of an "explosion in which various fragments are thrown out at different speeds" is more reminiscent of Milne's Kinematic Relativity than standard cosmology. While the former also results in a velocity–distance law of the form $v = HD$ (where v is the recession velocity, H the Hubble constant, and D the proper distance), in standard cosmology the recession velocity is (in general, and in our Universe) not constant. In such a universe (and in the 'equivalent' Friedmann model with neither matter nor a cosmological constant) the reciprocal of the Hubble constant is always the age of the Universe; in our Universe, it is so near the present time; that appears to be a coincidence which holds only near the present time[5] (rather like the coincidence in the angular sizes of the Sun and Moon). Sometimes statements depend on a context which, however, is not always clear; I'm sure that the clustering of galaxies was noted before a 2001 paper by Peacock and Cole. Like his use of Λ-CDM rather than ΛCDM, Henry for Heber Curtis, and Ralph for Rudolph Minkowski (nephew of Hermann who, like Walter Baade, moved from Hamburg to Mt. Wilson), such issues demonstrate an unfamiliarity with cosmology. While no-one can be an expert on everything, either the publisher or the author should get enough experts to read the manuscript so that all areas are covered (including the very confusing last paragraph of the main text). However, those goofs are made up for by Murdin not only avoiding the common misconception that John Wheeler coined the term 'black hole' (though, as Murdin correctly notes, he did popularize it), but (very probably correctly) also attributing it to "Robert Dicke about 1961"[6,7*]. A non-cosmological mistake is mentioning the supernova of 1054 in connection with the Bayeux tapestry; the latter probably shows what was later known as Halley's comet, not a supernova, which was visible in 1066. While I suppose it is conceivable that "*Homo sapiens* took to living in caves about that time, perhaps motivated to shelter because of the risk of severe sunburn", I don't see any causal connection with "that time", which refers to the last major reversal of the Earth's magnetic field about 800 000 years ago.

The book is a bit hard to pigeonhole. Like a book[10] reviewed here a year ago[11] it is a long narrative, though that book is told as a history of astronomy and this one as a history of the Universe; both, however, contain details not always found in similar books. It is mostly up to date (though my former employer was never known as the Nuffield Radio Astronomy Observatory and hasn't been known as the Nuffield Radio Astronomy Laboratories for a long time) and there are many references to other sections of the book. Maryland (mentioned in connection with Gamow, Alpher, and Herman) is not a suburb of Washington, DC, but maybe that is just a typo and an 'in' is missing. Another typo is the depth of the CfA survey at 400 million light years; 400 Mpc is correct (though the caption on the corresponding illustration correctly has 1·3 billion light years).

Note that in addition to the 288 numbered pages (the front matter is also roman-numbered)

*Note that the author of ref. 7 is the same as that of ref. 8, a book, reviewed in these pages[9], which I very highly recommend.

there are 16 pages of colour plates, half of which are near the beginning and half near the end of the book. I probably would have chosen similar illustrations, but not devoted a quarter of the plates' pages to simulated images of the future merger of the Milky Way and Andromeda galaxies. The only other figures are line drawings at the beginning of each chapter, illustrating the corresponding main topic. There are neither footnotes nor endnotes. The main text is followed by a seven-page glossary then, in small print, picture credits and an eight-page index. The book comes with a dust jacket, but beneath that the binding is covered by a CMB map from *Planck* and its mirror image, joined at the spine.

On the whole, this book is a good broad overview of the history of the Universe, but one sufficiently different that most readers will probably run across something which they haven't read before. Despite the qualms mentioned above it could be a good first book on the topic. (I mentioned more qualms than usual as I'm sure that the author will appreciate the curmudgeonly attention to detail and the exacting standards of this *Magazine*[12].) — Phillip Helbig.

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THESIS ABSTRACT

Planetesimal Belts in Misaligned Wide Stellar Binaries

By Steven Young

Some main-sequence and post-main-sequence stars show signatures of close-in hot dust which cannot have formed there or been produced *in situ* as the collisional time-scales at these locations are much smaller than the ages of the systems. Hence, there must exist some dynamical mechanism to deliver rocky bodies to small distances on time-scales of 10–10^4 Myrs. This thesis examines the feasibility and detectability of one of these potential mechanisms: the eccentric Kozai–Lidov effect (Eccentric Kozai Mechanism, EKM) whereby a stellar companion on a misaligned wide orbit perturbs planetesimals to high eccentricities. First, in order to explain the mysterious light-curve of KIC 8462852, one component of a wide binary-star system in the *Kepler* field with deep, irregular, and aperiodic dips in its light-curve, a Monte Carlo model of planetesimal belts in wide stellar binaries was created. It found that the occurrence rate of KIC 8462852-like observations in the *Kepler* field is 10^{-8} and hence that the probability of the *Kepler* telescope observing such phenomena to be 10^{-3}. It also found that the systems most likely to be observed have planetesimal belts at 10^2–10^3 AU, stellar companions at 10^2–10^4 AU, stellar masses of $\geq 1M_\odot$ and ages of 10^2–10^3 Myrs. Therefore, despite being in the right age range and with a companion at the right distance, it is unlikely that the EKM caused by the companion star is the cause of these observations.

This thesis then followed the surface-density evolution of three narrow debris discs, as well as one wide disc, with a stellar companion at $a_{\rm comp}$ = 878 AU and an inclination of 88°. It found that the EKM imprinted a petal-shaped structure on the narrow discs due to the disc particles librating between a fixed set of values for the longitude of pericentre which depend only on the initial inclination. As the evolution of the wide disc is the superposition of the evolution of the three narrow discs, these petal structures combined to produce an X-shaped structure. 'Thermal emission' images were then produced for the wide disc to see if the X-shaped structure would be observable. It was found that, as the tips of the structure corresponding to the apocentres of eccentric orbits were more dense, they dominate the thermal emission and the structure appears as four 'clumps'. The time evolution of the fractional luminosity and flux at 5 and 12 µm for these discs was then calculated. The fractional luminosity did not vary by more than an order of magnitude as it was dominated by distant cold dust and hence this mechanism cannot explain the high values of fractional luminosity associated with extreme debris discs. Likewise, whilst the infrared flux at 5 and 12 µm does increase by orders of magnitude to $\approx 10^{-4}$, it is not high enough to explain the brightest exozodi like η Corvi or β Leo, though it could explain fainter exozodi. — *University of Cambridge*; *accepted 2024 June*.

Here and There

THE OLDEST CITIES?

. . . mega-flood from the North Sea when the land bridge from Dover in England to Calais in France collapsed. —Paul Murdin, *The Universe: A Biography* (Thames & Hudson), p. 230.

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(1) G. H. Darwin, *The Observatory*, **1**, 13, 1877.
(2) D. Mihalas, *Stellar Atmospheres (2nd Edn.)* (Freeman, San Francisco), 1978.
(3) R. Kudritzki *et al.*, in C. Leitherer *et al.* (eds.), *Massive Stars in Starbursts* (Cambridge University Press), 1991, p. 59.

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submissions@obsmag.org (submissions)

Publication date is nominally the first day of the month and the issue will normally include contributions accepted three months before that date.

Publishers: The Editors of 'THE OBSERVATORY'
Typeset in LaTeX by Phillip Helbig

ISSN 0029-7704