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.

References

(1) G. J. Toomer, *Ptolemy's Almagest* (Duckworth), 1984, p. 363.
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(3) R. H. Allen, *Star Names* (G. E. Stechert), 1899, p. 403.
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(6) J. E. Bode, *Allgemeine Beschreibung und Nachweisung der Gestirne* (self-published), 1801, p. 42.
(7) G. Piazzi, *Praecipuarum Stellarum Inerrantium* (Regia Typographia Militari), 1814, p. 23.

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 12·55 d^{-1} and 16·03 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 = $+68°45'28''{\cdot}78$; 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 ($V = 10{\cdot}46$, $B-V = 0{\cdot}374$) as the comparison star and TYC 4311-1276-1 ($V = 11{\cdot}29$, $B-V = 0{\cdot}321$) 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).

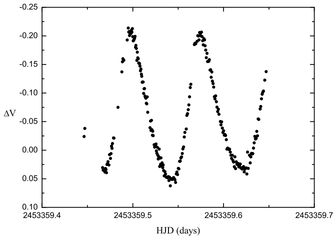
Fig. 8 displays the light-curves for the different filters used in this work on 2021 March 13 (the only night with measurements in the four filters). Clearly noticeable is the change in amplitude from the *Ic* (smaller) to the *B* (larger) filter.

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.

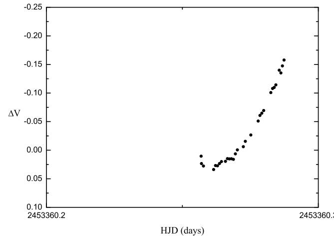
Frequency-analysis results

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.

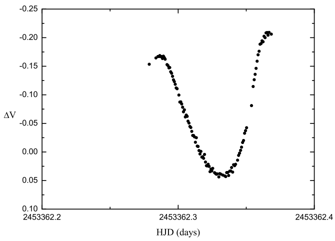
*https://www.period04.net



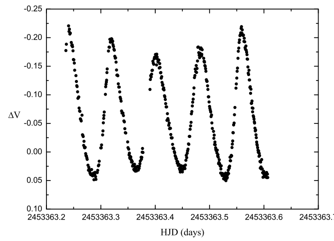
(a)
2004 Dec 19



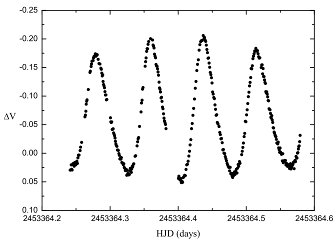
(b)
2004 Dec 20



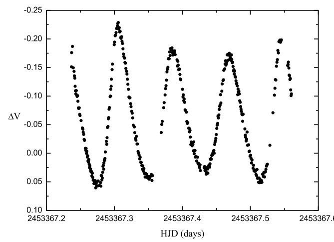
(c)
2004 Dec 22



(d)
2004 Dec 23

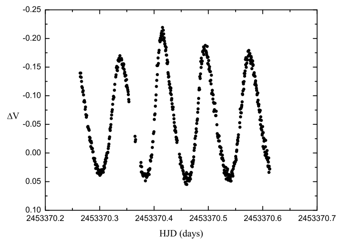


(e)
2004 Dec 24



(f)
2004 Dec 27

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



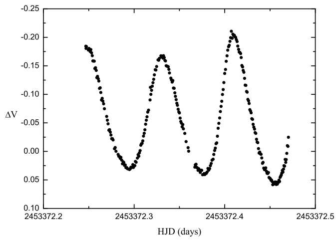
(g)
2004 Dec 30

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

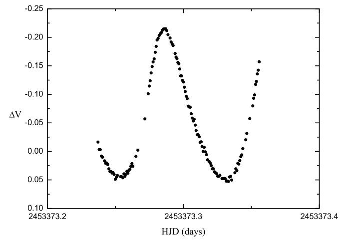
TABLE II

Results of the frequency analysis.

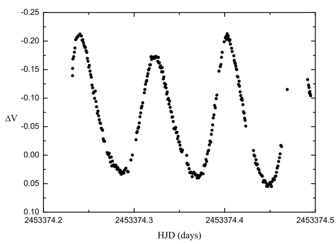
Filter	*Year*	*Frequency* (d^{-1})	*Amplitude (mag)*	*Phase (0–1)*	*Residuals (mag)*
		f_0 = 12·5455(1)	0·1497(8)	0·804(1)	
B	2021	$2f_0$ = 25·09(28)	0·027(4)	0·70(30)	0·008
		f_1 = 16·031(2)	0·0197(9)	0·14(2)	
		$f_0 + f_1$ = 28·57(2)	0·007(1)	0·65(11)	
		f_0 = 12·54569(3)	0·1106(2)	0·6945(2)	
V	2004	$2f_0$ = 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)	



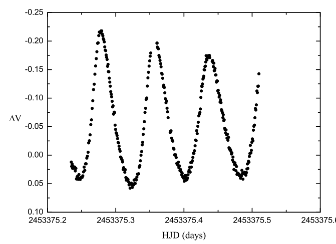
(a)
2005 Jan 1



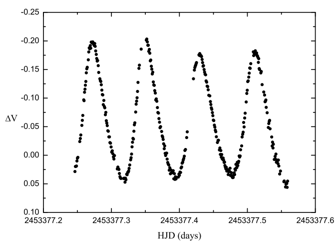
(b)
2005 Jan 2



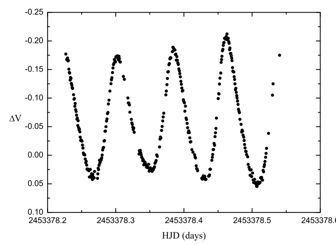
(c)
2005 Jan 3



(d)
2005 Jan 4

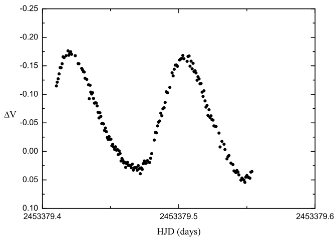


(e)
2005 Jan 6

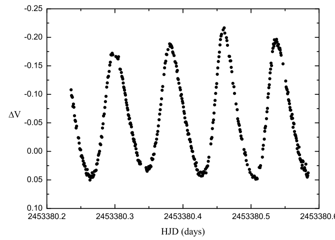


(f)
2005 Jan 7

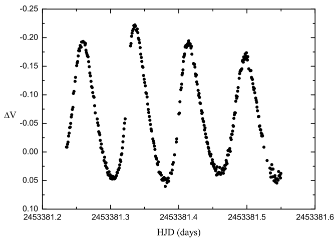
Fig. 2
2005 *V* light-curves of TYC 4311-825-1 (to be continued).



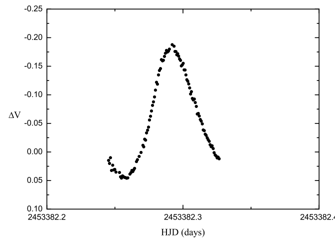
(g)
2005 Jan 8



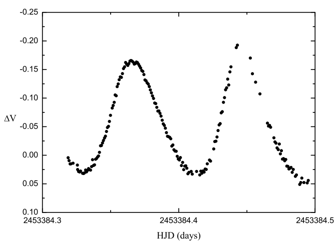
(h)
2005 Jan 9



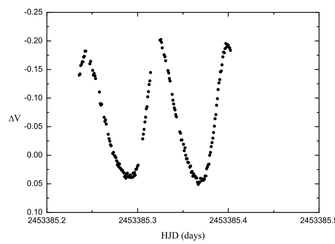
(i)
2005 Jan 10



(j)
2005 Jan 11

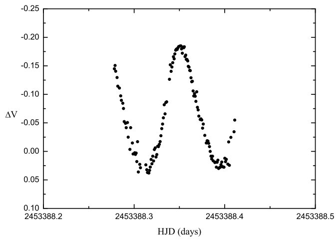


(k)
2005 Jan 13

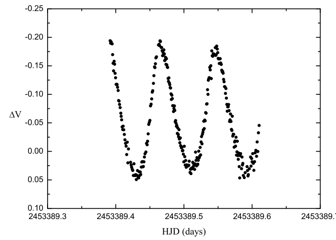


(l)
2005 Jan 14

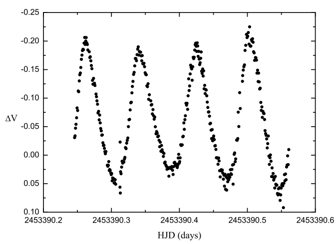
Fig. 2
2005 *V* light-curves of TYC 4311-825-1 (continued; to be continued).



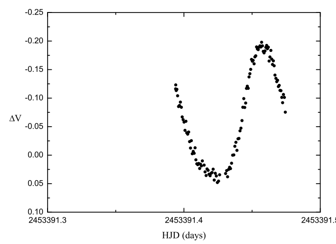
(m)
2005 Jan 17



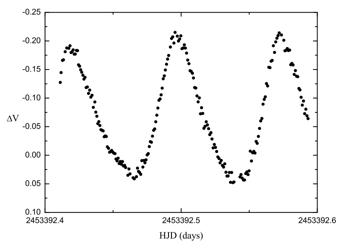
(n)
2005 Jan 18



(o)
2005 Jan 19

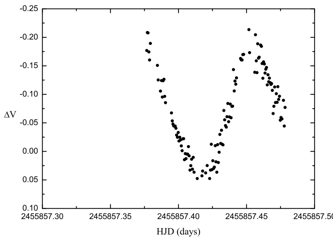


(p)
2005 Jan 20

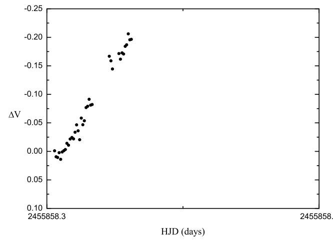


(q)
2005 Jan 21

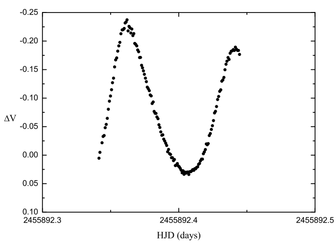
Fig. 2
2005 *V* light-curves of TYC 4311-825-1 (continued).



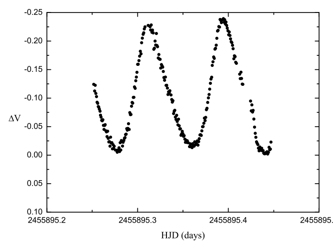
(a)
2011 Oct 22



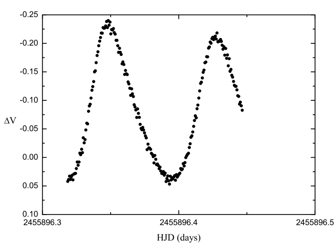
(b)
2011 Oct 23



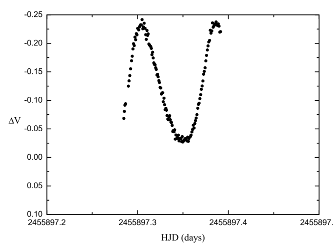
(c)
2011 Nov 26



(d)
2011 Nov 29

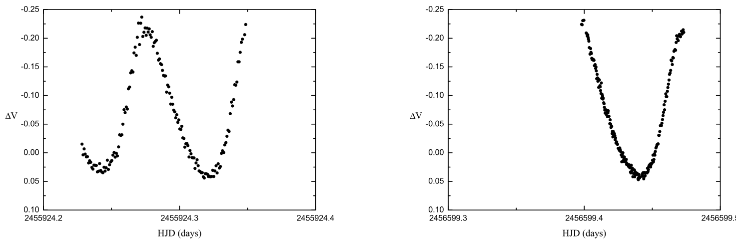


(e)
2011 Nov 30



(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).

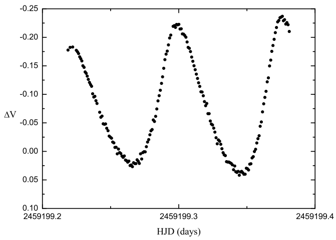
From Table II, there is evidence for the presence of two frequencies $f_0 = 12{\cdot}55\,\mathrm{d}^{-1}$ and $f_1 = 16{\cdot}03\,\mathrm{d}^{-1}$ but not the additional $12{\cdot}69\,\mathrm{d}^{-1}$ frequency indicated in the previous study. That confirms that the star has a double-pulsation mode. 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.

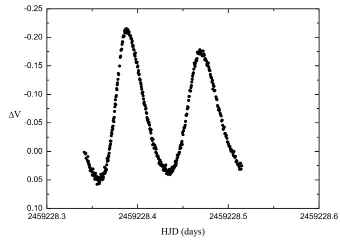
O – C *analysis*

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.

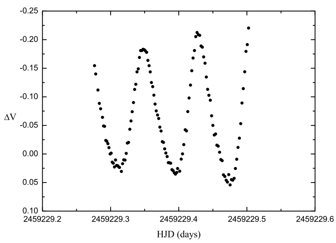
*The amplitudes listed in Table II are really semi-amplitudes according to the equation defining each Fourier term, $A_i \sin(2\pi(f_i t + \phi_i))$, where A_i is the amplitude, f_i, the frequency, and ϕ_i, the phase (between 0 and 1; the value in radians is obtained multiplying by 2π). Thus, the peak-to-peak 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.



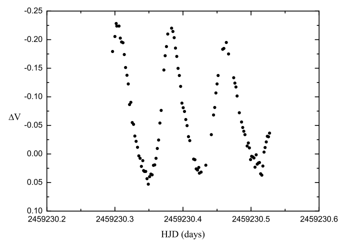
(a)
2020 Dec 15



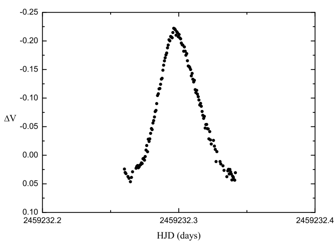
(b)
2021 Jan 13



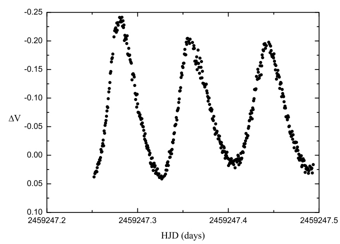
(c)
2021 Jan 14



(d)
2021 Jan 15

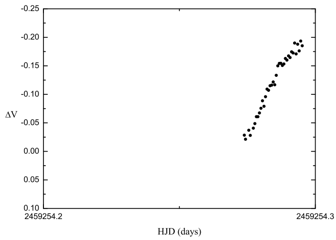


(e)
2021 Jan 17

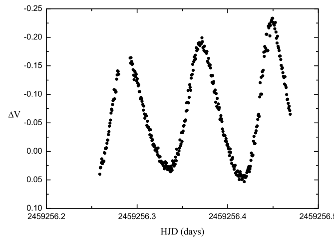


(f)
2021 Feb 1

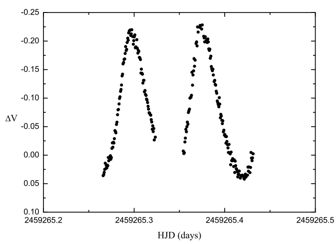
FIG. 4
2020–2021 *V* light-curves of TYC 4311-825-1 (to be continued).



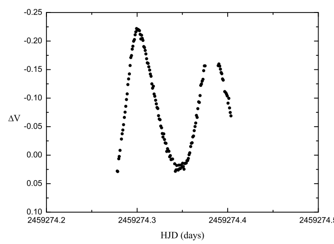
(g)
2021 Feb 8



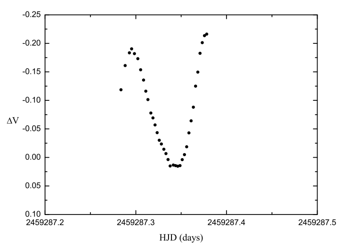
(h)
2021 Feb 10



(i)
2021 Feb 19

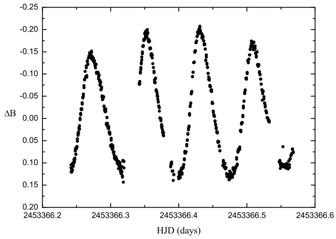


(j)
2021 Feb 28

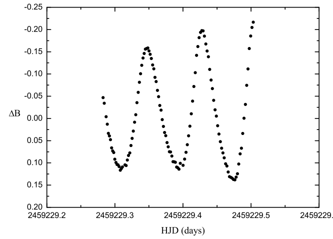


(k)
2021 Mar 13

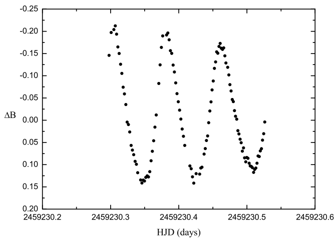
FIG. 4
2020–2021 *V* light-curves of TYC 4311-825-1 (continued).



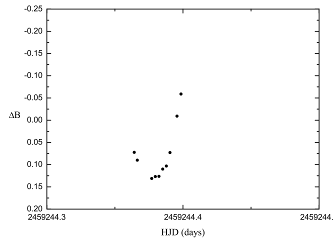
(a)
2004 Dec 26



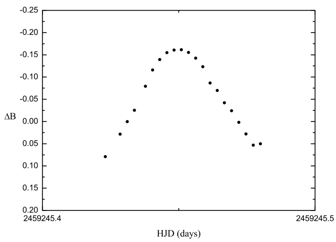
(b)
2021 Jan 14



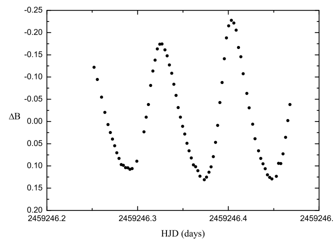
(c)
2021 Jan 15



(d)
2021 Jan 29

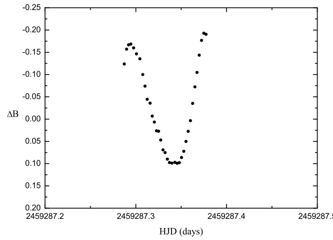


(e)
2021 Jan 30



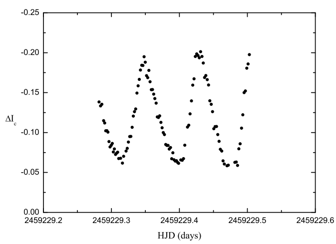
(f)
2021 Jan 31

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

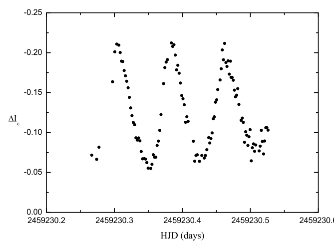


(g)
2021 Mar 13

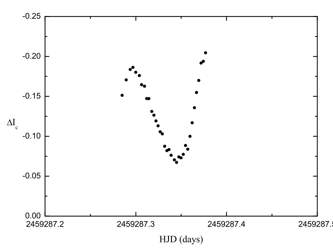
Fig. 5
2004 and 2021 *B* light-curves of TYC 4311-825-1 (continued).



(a)
2021 Jan 14

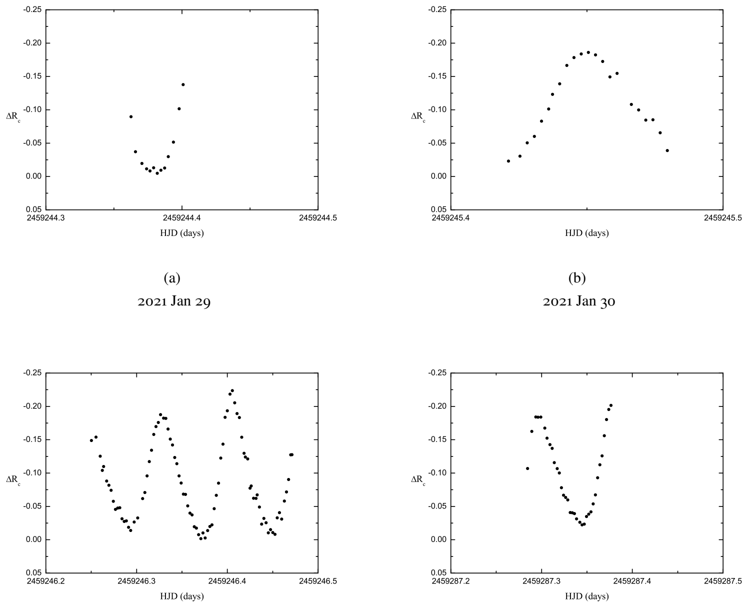


(b)
2021 Jan 15



(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.

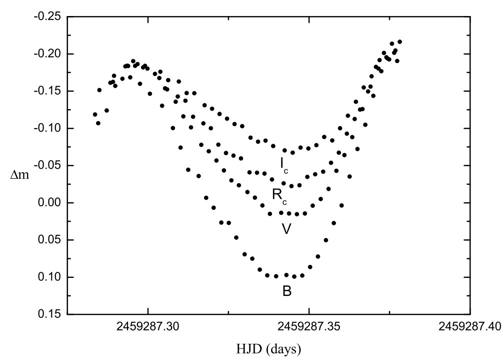


Fig. 8
Ic, *Rc*, *V* and *B* light-curves of TYC 4311-825-1 corresponding to the night of 2021 March 13.

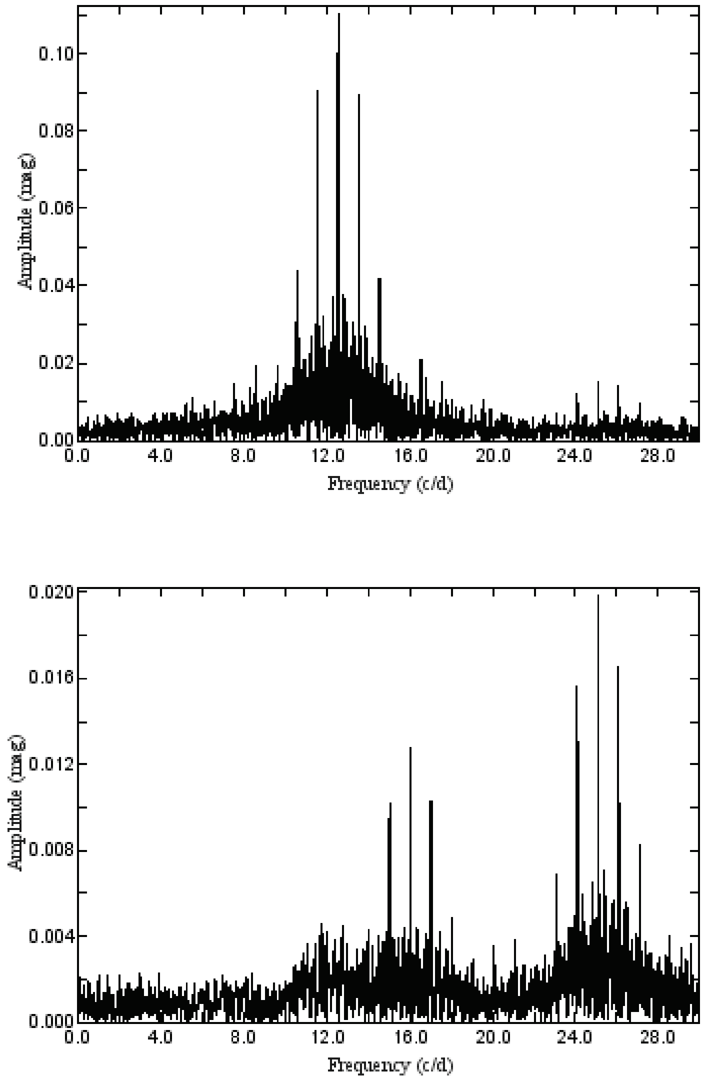


Fig. 9

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.

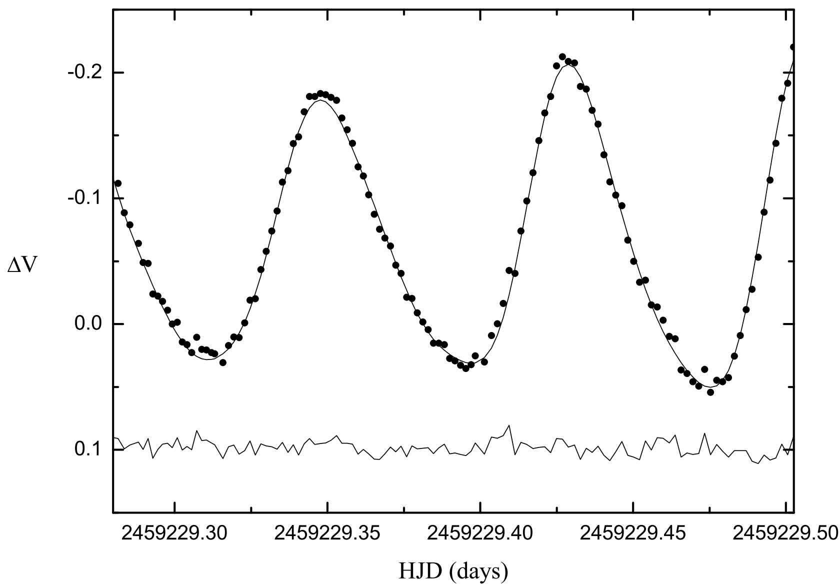


Fig. 10
V light-curve of TYC 4311-825-1 corresponding to the 2021 January 14 data. Overlaid on the data points is the best-fit model obtained from the frequency analysis (solid line) and (bottom) the O − C (observed minus calculated) plot, displaced by 0·1 mag in order to avoid confusion with the light-curve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

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

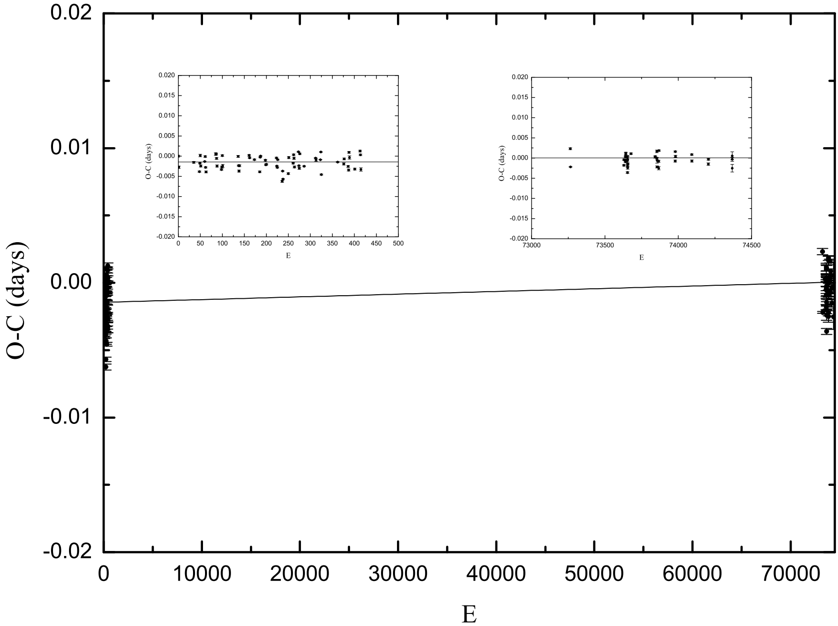


FIG. 11

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

$$M_V = m_V + 5 - 5\log r - A_V, \qquad (2)$$

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

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

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, $Q_0 = P_0(\rho/\rho_\odot)^{0.5}$. That parameter is $0.0287^{+0.0011}_{-0.0003}$ days. In regard to that, for the frequency f_1, the pulsation constant Q_1 is $0.0225^{+0.0008}_{-0.0003}$ days.

On the other hand, by using the global metallicity value $[Z/X] = -0.208^{+0.026}_{-0.033}$ (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 $[Z/X]_\odot = 0.0207$ and the relation $Y = 0.2485 + 1.78Z$ given by Bressan *et al.* [24], we obtain a value $Z = 0.0093 \pm 0.0007$. It must be noted that there are uncertainties associated with the solar metallicity value. For example, Bressan *et al.* assume $Z_\odot = 0.01524$ whereas Asplund *et al.* [25] obtain a value of $Z_\odot = 0.0139$, and others, such as Vagnozzi [26], an even higher value of $Z_\odot = 0.0196$. 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 $1.5M_\odot$ to $1.9M_\odot$ and $Z = 0.01$ 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 $\log t[\text{years}] = 8.8$ 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 $\log t = 9.1$ and $\log t = 9.2$ isochrones, although closer to the latter one. That translates to an age between 1.3×10^9 and 1.6×10^9 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 $M = 1.7M_\odot$, 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})	12.5457 ± 0.0003	This work
f_1 (d^{-1})	16.030 ± 0.002	This work
T_{eff} (K)	7135^{+23}_{-20}	*Gaia* DR3
$\log g$ (g in $\mathrm{cm\,s^{-2}}$)	$3.921^{+0.020}_{-0.006}$	*Gaia* DR3
R ($R_\odot$)	$2.35^{+0.02}_{-0.06}$	*Gaia* DR3
L ($L_\odot$)	$12.78^{+0.24}_{-0.60}$	Derived from *Gaia* DR3
M ($M_\odot$)	$1.68^{+0.01}_{-0.02}$	Derived from *Gaia* DR3
Q_0 (days)	$0.0287^{+0.0011}_{-0.0003}$	Derived from this work and *Gaia* DR3
Q_1 (days)	$0.0225^{+0.0008}_{-0.0003}$	Derived from this work and *Gaia* DR3
$[Z/X]$ (dex)	$-0.208^{+0.026}_{-0.033}$	*Gaia* DR3
Z	≈ 0.01	Derived from *Gaia* DR3 and other authors
t (Gyr)	≈ 1.3–1.6	Derived from PARSEC

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

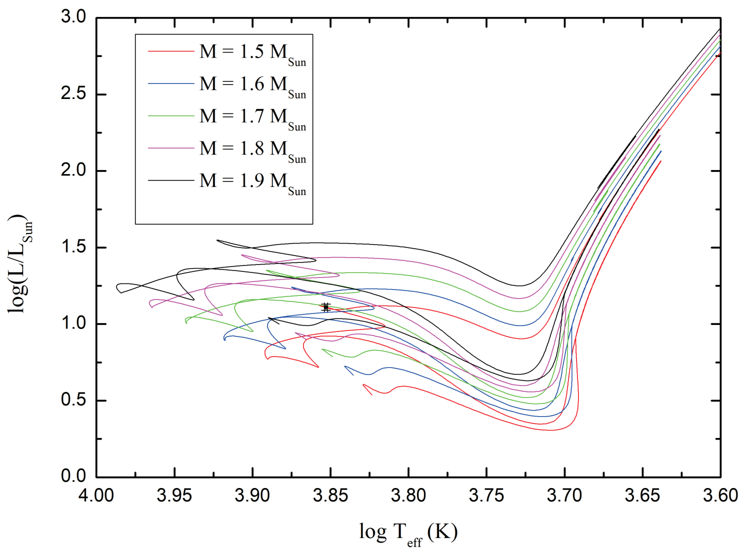


FIG. 12
Evolutionary tracks for masses from $1{\cdot}5M_\odot$ to $1{\cdot}9M_\odot$ and Z = 0·01 in the HR diagram, computed from PARSEC 2·0. The black point marks the position of TYC 4311-825-1.

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 = 0·01 (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 $M > 1{\cdot}5M_\odot$ 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]

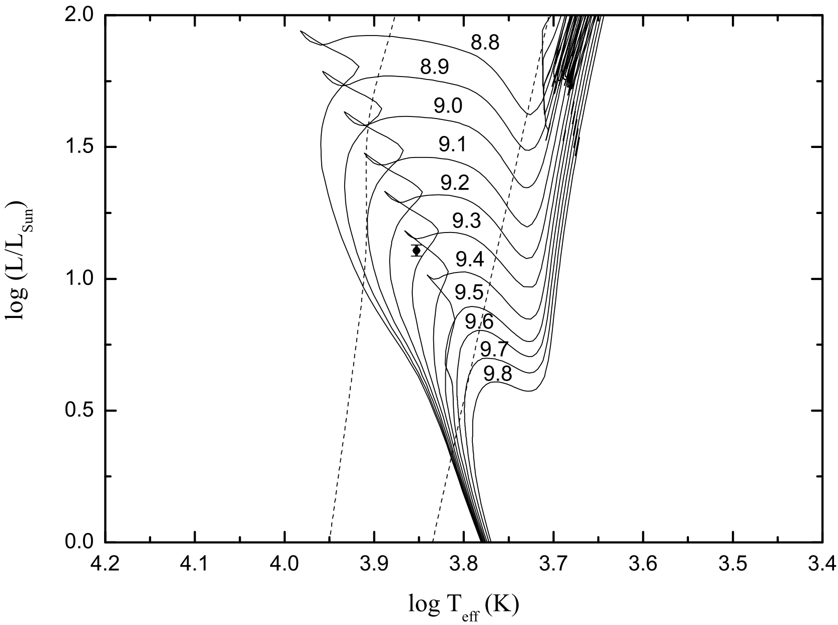


FIG. 13

Isochrones from $\log t$[years] = 8·8 to 9·8 and $Z = 0{\cdot}01$ 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 $M_V = 1{\cdot}5$ 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

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

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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 $1{\cdot}617 \pm 0{\cdot}003\, M_{\odot}$ and $1{\cdot}207 \pm 0{\cdot}004\, M_{\odot}$, and radii of $1{\cdot}948 \pm 0{\cdot}008\, R_{\odot}$ and $1{\cdot}195 \pm 0{\cdot}022\, R_{\odot}$. The precision of the radius measurements is limited by the shallow partial eclipses and the unavailability of a spectroscopic light ratio due to the chemical peculiarity of the primary star. We measure a distance to the system of 125·0 ± 1·5 pc, in good agreement with the *Gaia* DR3 parallax, and an age of 1·3 Gyr. A comparison with theoretical models suggests the system has a modestly sub-solar metallicity, in conflict with the slightly super-solar photospheric abundances of the secondary star.

Introduction

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

In this work we present a study of DV Boötes (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