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δ Scuti pulsations in the bright Pleiades eclipsing binary HD 23642

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ABSTRACT

We announce the discovery of pulsations in HD 23642, the only bright eclipsing system in the Pleiades, based on light curves from the *Transiting Exoplanet Survey Satellite* (*TESS*). We measure 46 pulsation frequencies and attribute them to δ Scuti pulsations in the secondary component. We find four $\ell = 1$ doublets, three of which have frequency splittings consistent with the rotation rate of the star. The dipole mode amplitude ratios are consistent with a high stellar inclination angle and the stellar rotation period agrees with the orbital period. Together, these suggest that the spin axis of the secondary is aligned with the orbital axis. We also determine precise effective temperatures and a spectroscopic light ratio, and use the latter to determine the physical properties of the system alongside the *TESS* data and published radial velocities. We measure a distance to the system in agreement with the *Gaia* parallax, and an age of 170 ± 20 Myr based on a comparison to theoretical stellar evolutionary models.

Key words: binaries: eclipsing – stars: fundamental parameters – stars: oscillations.

1 INTRODUCTION

The Pleiades is one of the closest and most extensively studied star clusters, containing ∼1300 stars at a distance of 136 pc (Melis et al. 2014; Heyl, Caiazzo & Richer 2022). It is a benchmark for studying theoretical modelling (e.g. Vandenberg & Bridges 1984), the kinematics of star clusters (Lodieu et al. 2019), binarity (Torres, Latham & Quinn 2021), pulsations (Murphy et al. 2022), rotation (Rebull et al. 2016), and the connection between rotation, lithium depletion, and stellar inflation (Somers & Pinsonneault 2015; Bouvier et al. 2018).

Eclipsing binary stars (EBs) are another crucial research area for improving our understanding of stellar evolution (Torres, Andersen & Giménez 2010). The masses, radii, and effective temperatures ($T_{\rm eff}$s) of stars can be determined to precisions approaching 0.2 per cent (Maxted et al. 2020; Miller, Maxted & Smalley 2020), allowing their use as checks and calibrators of theoretical models (e.g. Claret & Torres 2018; Tkachenko et al. 2020). In particular, EBs in open clusters are enticing targets for multiple scientific goals (e.g. Southworth, Maxted & Smalley 2004a; Brogaard et al. 2011; Torres et al. 2018).

A third phenomenon well suited to extending our understanding of stellar physics is that of pulsations. δ Scuti stars pulsate in pressure modes of low radial order ($n \sim 1 \ldots 10$) that are mostly sensitive to the stellar envelope (Aerts, Christensen-Dalsgaard & Kurtz 2010; Kurtz 2022). These modes probe the stellar density, making them good indicators of age (Aerts 2015), especially when mass and/or metallicity are already constrained. Recently, the discovery that δ Scuti stars pulsate in regular patterns (Bedding et al. 2020) has allowed pulsation modes to be identified in many stars (e.g. Currie et al. 2022; Kerr et al. 2022), including five members of the Pleiades (Murphy et al. 2022), facilitating detailed asteroseismic modelling. In some cases, this confers an age precision better than 10 per cent (Murphy et al. 2021).

HD 23642 (V1229 Tau, HII 1431) was found to be a double-lined spectroscopic binary by Pearce (1957) and Abt (1958). Its eclipsing nature was announced independently by Miles (1999) and Torres (2003) using data from the *Hipparcos* satellite. Detailed analyses of the system using ground-based data have been presented by Griffin (1995), Torres (2003), Munari et al. (2004), Southworth, Maxted & Smalley (2005), and Groenewegen et al. (2007). HD 23642 was observed in long cadence mode by the K2 satellite (Howell et al. 2014) in Campaign 4.[1] An analysis of these data was presented by David et al. (2016).

In this work, we present the discovery of δ Scuti pulsations in this important EB and determine the physical properties of the system to high precision for the first time. We note that independent detections are presented by Chen et al. (2022) without detailed analysis, and by Bedding et al. (2023). Section 2 in the current work outlines the observations used, Sections 3 and 4 present our spectroscopic and photometric analyses, Section 5 is dedicated to the pulsation analysis, and our work is concluded in Section 6.

2 OBSERVATIONS

HD 23642 was observed using the Transiting Exoplanet Survey Satellite (*TESS*) mission (Ricker et al. 2015) in three consecutive sectors (42–44) covering 76 d (2021 August 20 to 2021 November 6), at a cadence of 120 s. We downloaded the data from the *Mikulski*

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[1] HD 23642 was requested as a target by nine Guest Observer proposals including GO4028 (PI Southworth) and GO4035 (PI Murphy).

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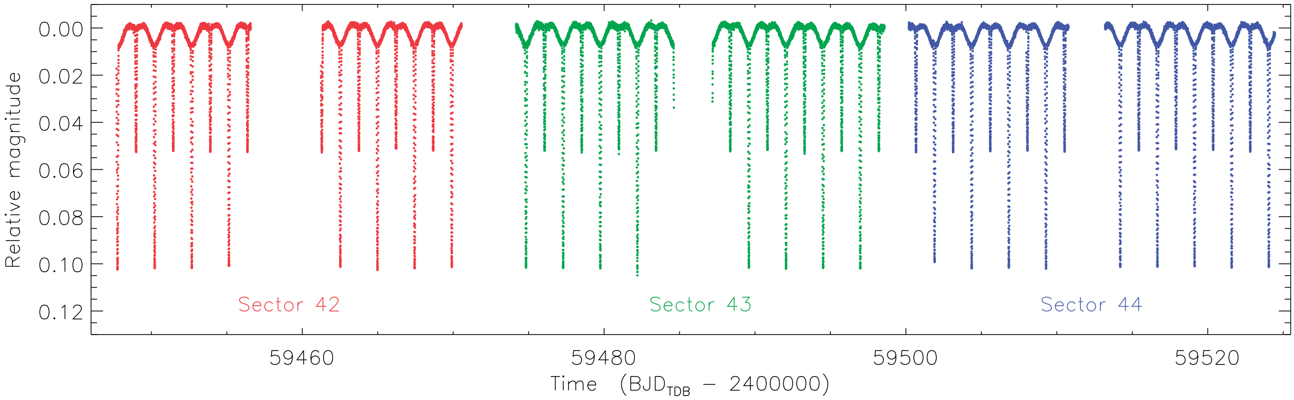

Figure 1. *TESS* SAP light curve of HD 23642. The sectors are labelled.

Table 1. Properties of the HD 23642 system. The velocity amplitudes K are from Torres et al. (2021).

Quantity and unit	Star A	Star B
Spectroscopic parameters:		
K (km s^{-1})	100.07 ± 0.23	142.60 ± 0.28
$T_{\rm eff}$ (K)	$10\,200 \pm 90$	7670 ± 85
Light ratio at H α	0.313 ± 0.010	
Light ratio in *TESS* passband	0.328 ± 0.011	
JKTEBOP *analysis:*		
$r_{\rm A} + r_{\rm B}$	0.2664 ± 0.0011	
k	0.784 ± 0.012	
i (°)	78.63 ± 0.09	
J	0.5561 ± 0.0011	
ℓ_3	0.029 ± 0.014	
c	0.52 fixed	0.63 fixed
α	0.45 fixed	0.42 fixed
P (d)	$2.461\,132\,23 \pm 0.000\,000\,60$	
T_0 (BJD$_{\rm TDB}$)	$2459\,509.282\,357 \pm 0.000\,007$	
Fractional radii	0.1494 ± 0.0016	0.1171 ± 0.0017
Physical properties:		
Mass ($\mathcal{M}^{\rm N}_{\odot}$)	2.273 ± 0.011	1.595 ± 0.008
Radius ($\mathcal{M}^{\rm N}_{\odot}$)	1.799 ± 0.019	1.410 ± 0.021
log g (c.g.s.)	4.285 ± 0.009	4.342 ± 0.13
$V_{\rm synch}$ (km s^{-1})	36.98 ± 0.40	28.99 ± 0.42
Luminosity $\log(L/\mathcal{L}^{\rm N}_{\odot})$	1.499 ± 0.018	0.792 ± 0.023
Reddening $E_{B\,-\,V}$ (mag)	0.040 ± 0.010	
K-band distance (pc)	134.7 ± 2.0	

Archive for Space Telescopes (*MAST*) archive and extracted the simple aperture photometry (SAP) from the FITS files (Jenkins et al. 2016); the PDCSAP data are practically identical. We included only the data with a QUALITY flag of zero, totalling 44 438 points, and converted them into differential magnitude. The data errors were not used as they were much smaller than the scatter of the measurements. The full *TESS* data are shown in Fig. 1 and an except is shown in Fig. 2.

We observed HD 23642 during two observing runs in November 2006 using the Nordic Optical Telescope (NOT) and its FIbre Échelle Spectrograph (FIES). A total of 27 échelle spectra were obtained using the medium-resolution fibre in bundle A, which covered 364–736 nm with a resolving power of $R \approx 47\,000$. Exposure times of 600 s yielded a signal-to-noise ratio (S/N) of approximately 200, although some spectra had a lower S/N due to cloudy conditions. The data were reduced using IRAF échelle package routines, with particular care taken in the normalization and merging of the échelle orders (Kolbas et al. 2015).

3 SPECTROSCOPIC ANALYSIS

We first sought to measure the spectroscopic parameters of the two stars, in particular their $T_{\rm eff}$s and light ratio. To do this we applied the method of spectral disentangling (Simon & Sturm 1994) using the Fourier approach (Hadrava 1995) and concentrating on the 650–670 nm spectral range that includes the H α line. This wavelength interval is contaminated by telluric lines, which we removed before the disentangling process. We used the FDBINARY code (Ilijić et al. 2004) and our standard methods (Pavlovski & Hensberge 2010; Pavlovski, Southworth & Tamajo 2018). We also fixed the velocity amplitudes of the stars to the values measured by Torres et al. (2021), so effectively ran in spectral separation mode.

The H α profiles of the two stars were then modelled to determine the $T_{\rm eff}$s and light ratio. We fixed the surface gravities and rotational velocities of the stars to the values determined in Section 4, thus avoiding the degeneracy between $T_{\rm eff}$ and log g present in the Balmer lines of hot stars. This approach required us to iterate our analysis with that described in Section 4 to ensure internal consistency; the iteration converged within one step. Optimal fitting was performed with the STARFIT code (Kolbas et al. 2015), which uses a genetic algorithm to search for the best fit within a grid of synthetic spectra pre-calculated using the UCLSYN code (Smalley, Smith & Dworetsky 2001). The fractional light contributions of the two components were forced to sum to unity (Tamajo, Pavlovski & Southworth 2011) and only the wings of the H α line were fitted (with metallic lines masked). The uncertainties were calculated using the MCMC approach described in Pavlovski et al. (2018).

We found $T_{\rm eff}$s of $10\,200 \pm 90$ and 7670 ± 85 K for the two stars, and a light ratio of $\ell_{\rm B}/\ell_{\rm A}({\rm H}\,\alpha) = 0.313 \pm 0.010$. HD 23642 A is known to be chemically peculiar: Abt & Levato (1978) classified its spectrum as A0Vp(Si) + Am. Our light ratio should not be affected by this because it was obtained from only the H α line. We propagated it to the *TESS* passband using BT-Settl theoretical spectra (Allard, Homeier & Freytag 2012) to obtain $\ell_{\rm B}/\ell_{\rm A}(TESS) = 0.328 \pm 0.011$ where the errorbar includes the contributions from $\ell_{\rm B}/\ell_{\rm A}({\rm H}\,\alpha)$ and both $T_{\rm eff}$s.

4 LIGHT CURVE AND PHYSICAL PROPERTIES

The light curve of HD 23642 shows shallow partial eclipses and clear reflection and ellipsoidal effects. The stars are well separated and the

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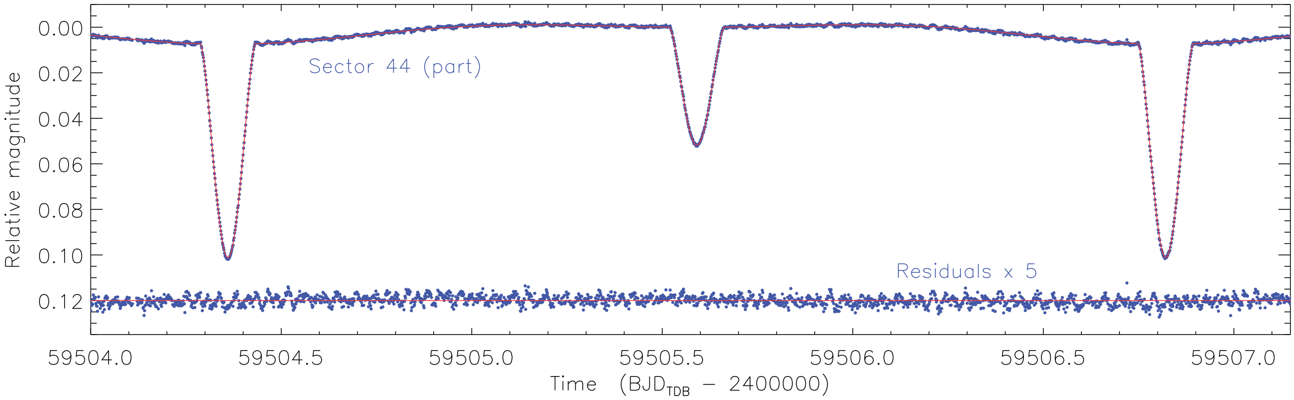

Figure 2. A short section of the *TESS* light curve, chosen at random, is shown (blue points) along with the JKTEBOP best fit (red line). The residuals are displayed offset to the base of the figure and magnified by a factor of 5 to make the pulsations visible.

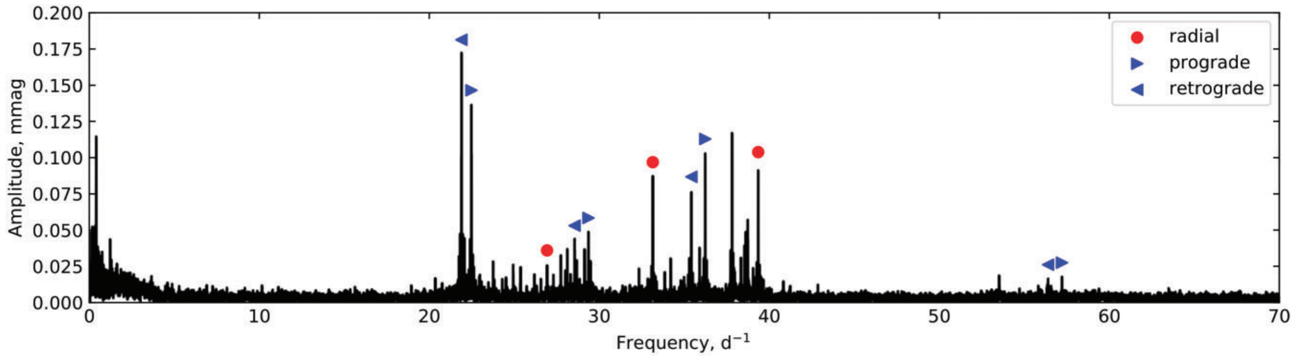

Figure 3. Fourier transform of the light-curve residuals, after subtracting the eclipse model, revealing several pulsations at the 0.1 mmag level. Mode identifications (Section 5) are overlaid, showing radial modes as well as a series of rotationally split dipole modes.

system is suitable for analysis with the JKTEBOP code (Southworth, Maxted & Smalley 2004b; Southworth 2013), for which we used version 43. We fitted for the fractional radii of the stars in the form of their sum ($r_A + r_B$) and ratio ($k = r_B/r_A$), the orbital inclination (i), the central surface brightness ratio of the two stars (J), the amount of third light (L_3), the reference time of mid-eclipse (T_0), and the orbital period (P). Limb darkening was included using the power-2 law (Hestroffer 1997) with the scaling coefficient for each star (c_1 and c_2) fitted and the power-law coefficients (α_1 and α_2) fixed at values from Claret & Southworth (2022). We also included one quadratic function per *TESS* half-sector to normalize the light curve to zero differential magnitude, to allow for the possibility of slow drifts in brightness for either instrumental or astrophysical reasons. The pulsations are of much lower amplitude than the eclipses, so were treated as red noise. A circular orbit was assumed.

Our initial solutions gave measurements of the fractional radii to a disappointing precision. This is caused by the ratio of the radii being poorly determined for shallow partial eclipses, a well-known phenomenon that has been noted before for this system (Southworth et al. 2005; David et al. 2016). We therefore imposed the spectroscopic light ratio from Section 3 as a Gaussian prior in our solution. This significantly improved the precision of the fitted parameters, and is the only viable approach in a system like this with shallow partial eclipses and a noise limit set by the presence of pulsations. Uncertainties in the fitted parameters were determined by Monte Carlo and residual-permutation simulations (Southworth 2008), taking the larger of the two options for each quantity. The values and uncertainties of the parameters are given in Table 1. We have added an extra uncertainty of ±0.0010 in quadrature to the uncertainties in r_A and r_B to account for the variations in these parameters between different model choices, specifically about whether or not to fit for L_3 or limb darkening.

We determined the physical properties of the system from the results of the JKTEBOP analysis and the velocity amplitudes of the stars measured by Torres et al. (2021). This was done using the JKTABSDIM code (Southworth et al. 2005) modified to report results on the IAU scale (Prša et al. 2016). The full set of measured system properties is given in Table 1. Our masses are in good agreement with those found by other authors, with minor differences due to the newer velocity amplitudes adopted. The rotational velocities of the stars determined by Southworth et al. (2005), 37 ± 2 and 33 ± 3 km s^{-1}, are in agreement with the synchronous values, suggesting that both stars are rotating synchronously.

The measured radii, however, are significantly different from previous values (Munari et al. 2004; Southworth et al. 2005; Groenewegen et al. 2007; David et al. 2016) in the sense that R_A is larger and R_B is smaller. This solves an existing problem with HD 23642 B, which was previously found to be significantly larger than predicted by theoretical evolutionary models for the Pleiades' age and metallicity. We attribute this change to differences in the spectroscopic light ratios adopted in those studies, which are slightly larger than the one measured in the current work. Both components of HD 23642 are known to be chemically peculiar, so light ratios determined from metal lines are unreliable. Our new light ratio should be preferred because it is based on the Hα line, so is not affected by the chemical peculiarity, and is also close to the

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wavelengths transmitted by the *TESS* passband. A visual comparison of the masses, radii, and $T_{\rm eff}$s of the primary star to predictions from the PARSEC evolutionary models (Bressan et al. 2012) for solar metallicity shows good agreement for an age of 170 ± 20 Myr. We note that this is at the upper limit of accepted ages of the Pleiades cluster (Gossage et al. 2018; Murphy et al. 2022). The secondary component is 1.5 σ smaller than expected: further investigation is needed to understand this.

To determine the distance (d) and interstellar reddening (E_{B-V}) to the system we used the *BV* apparent magnitudes from the Tycho satellite (Høg et al. 2000), the $JHK_{\rm s}$ apparent magnitudes from 2MASS (Skrutskie et al. 2006) converted into the Johnson system using transformations from Carpenter (2001), and bolometric corrections from Girardi et al. (2002). We determined the value of E_{B-V} that results in consistent distances across the *BVJHK* bands, finding $E_{B-V} = 0.040 \pm 0.010$ and $d = 134.7 \pm 2.0$ pc. This distance is slightly shorter than the 138.3 ± 0.1 pc determined by simple inversion of the parallax from *Gaia* EDR3 (Gaia Collaboration 2021). This E_{B-V} is specific to HD 23642, is consistent with previous studies (Taylor 2008), and is not affected by reddening variations between Pleiades members.

5 ANALYSIS OF THE PULSATIONS

The residual light curve after subtraction of the JKTEBOP model shows several pulsation modes at the 0.1 mmag level (Fig. 3). We used the PERIOD04 code (Lenz & Breger 2004) to extract 46 pulsations at frequencies $f > 20\,{\rm d}^{-1}$ down to 0.015 mmag amplitude, and used non-linear least squares to optimize the frequencies. The table of frequencies is given in the supplementary online material. From the frequencies and $T_{\rm eff}$s of the stars we deduce that they represent δ Scuti pulsations in the secondary component, as the primary is hotter than the δ Scuti instability strip.

We used the ECHELLE package (Hey & Ball 2020) to manually find values of the asteroseismic large spacing, $\Delta\nu$, that give vertical patterns in an Échelle diagram. At $\Delta\nu = 6.97\,{\rm d}^{-1}$, there are two parallel ridges on the left-hand side of the Échelle (Fig. 4), at an *x*-location suggestive of $\ell = 1$ modes (Bedding et al. 2020; Murphy et al. 2021). With the same $\Delta\nu$, part of a radial mode series can also be identified, with period ratios consistent with low-order radial modes (Netzel et al. 2022). It is noteworthy that the independently determined $\Delta\nu$ is consistent with the value of five other δ Scuti stars in the Pleiades (6.82–6.99 ${\rm d}^{-1}$; Murphy et al. 2022), and also suggests that the system is relatively young ($\lesssim$200 Myr).

Since $\ell = 1$ doublets are seen, which are interpretable as $m = \pm 1$ pairs, the inclination of the pulsating star is not small (Gizon & Solanki 2003). However, at some orders, most notably at $n = 3$, there is a peak slightly offset from halfway between the two identified $\ell = 1$ modes that could be a central component, after second-order effects of rotation are accounted for. To evaluate this possibility would require the calculation of rotating evolutionary and pulsation models. If confirmed, it implies that the stellar inclination is also not completely edge-on, and given the measured orbital inclination, implies that the spin and orbital axes of the pulsating star are aligned.

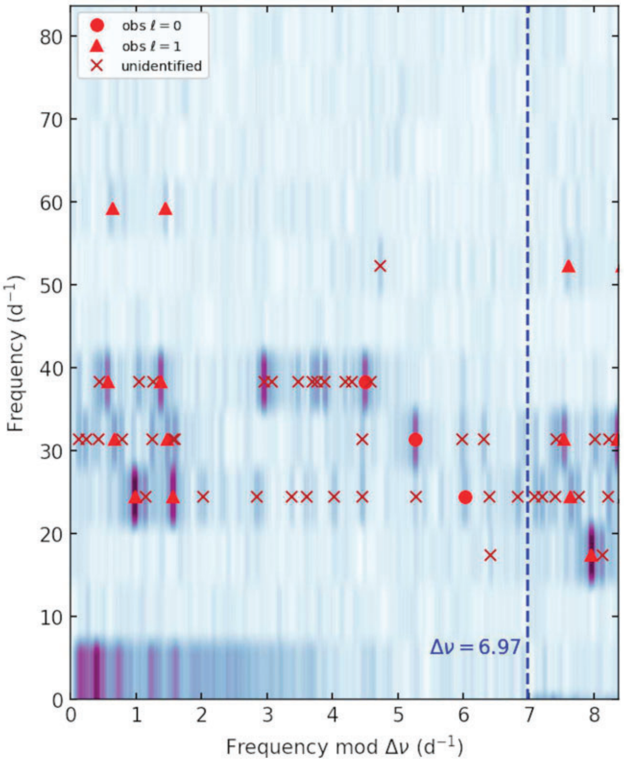

Figure 4. Échelle diagram for HD 23642, marked with mode identifications. Radial modes are shown as circles, dipole modes are triangles. Modes without an identifications are shown as crosses, some of which may belong to the other star; most will be modes of higher degree ($\ell \geq 2$).

The identification of four $\ell = 1$ doublets offers the chance of a consistency check on the mode identification. If the doublets all have approximately the same splitting, it strengthens the proposed mode identifications. For the doublets at $n = 6$, 3, 2, and 1 we measure splittings of 0.813, 0.813, 0.812, and 0.586 ${\rm d}^{-1}$, respectively. Thus, the $n = 6$, 3, and 2 doublets seem secure, but the $n = 1$ doublet does not. Since the Ledoux constant, $C_{n,\,\ell}$, is close to zero for p modes, we can estimate the stellar rotation rate, Ω, to first order based on these frequency splittings (Aerts et al. 2010):

$$\nu_{n,\ell,{\rm m}} = \nu_0 + m\Omega(1 - C_{n,\ell}), \tag{1}$$

where ν_0 is the rest-frame frequency of the pulsation mode (we adopt the convention that prograde modes have positive m). The stellar rotation frequency is therefore 0.41 ${\rm d}^{-1}$, corresponding to a rotation period of 2.46 d. This is equal to the orbital period of the system, and the stars are known to rotate approximately synchronously (see Section 4), so this supports our inference of the stellar rotational inclination.

6 SUMMARY AND CONCLUSIONS

HD 23642 has it all: youth, eclipses, pulsations, chemical peculiarity, and membership of the Pleiades. We establish its physical properties to high precision for the first time, helped particularly by the measurement of a spectroscopic light ratio immune to the chemical peculiarity. We determine a distance and interstellar reddening to the system in good agreement with previous measurements, and infer an age of 170 ± 20 Myr for the Pleiades by comparison to PARSEC evolutionary model predictions.

A total of 46 pulsation frequencies are detected to high significance from the three consecutive sectors of *TESS* photometry. We attribute them to δ Scuti pulsations in the secondary star. We use an échelle diagram to assign modes to 11 of the pulsations, based on the identification of $\ell = 1$ doublets. An asteroseismic large spacing of $\Delta\nu = 6.97\,{\rm d}^{-1}$ allows identification of a series of radial modes with period ratios consistent with other δ Scuti stars in the Pleiades. The stellar rotation rate we find from the mode splittings is in agreement with the spectroscopic $v\sin i$ and the orbital period of the system.

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This implies that the spin axis of the pulsating secondary component is aligned with the orbital axis of the system. HD 23642 is well suited to detailed analysis with evolutionary and pulsation models including rotation.

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DATA AVAILABILITY

The *TESS* data used in this work are available in the *MAST* archive (https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html). The FIES spectra are available in reduced form from the NOT archive (http://www.not.iac.es/archive/).

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SUPPORTING INFORMATION

Supplementary data are available at *MNRASL* online.

Table S1. Extracted frequencies with corresponding amplitudes and provisional mode identifications for the pulsating component of HD23642.

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