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# A $\beta$ Cephei pulsator and a changing orbital inclination in the high-mass eclipsing binary system VV Orionis

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## ABSTRACT

We present an analysis of the high-mass eclipsing binary system VV Ori based on photometry from the *TESS* satellite. The primary star (B1 V, 9.5  $M_{\odot}$ ) shows  $\beta$  Cephei pulsations and the secondary (B7 V, 3.8  $M_{\odot}$ ) is possibly a slowly pulsating B star. We detect 51 significant oscillation frequencies, including two multiplets with separations equal to the orbital frequency, indicating that the pulsations are tidally perturbed. We analyse the *TESS* light curve and published radial velocities to determine the physical properties of the system. Both stars are only the second of their pulsation type with a precisely measured mass. The orbital inclination is also currently decreasing, likely due to gravitational interactions with a third body.

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

## 1 INTRODUCTION

The study of eclipsing binary systems (EBs) is our primary source of empirical measurements of the masses and radii of normal stars (Andersen 1991; Torres, Andersen & Giménez 2010). From light and radial velocity (RV) curves, the masses and radii can be determined to high precision and accuracy (reaching 0.2 per cent; see Maxted et al. 2020), then used to check and calibrate theoretical models (e.g. Claret & Torres 2018; Tkachenko et al. 2020) or as distance indicators (e.g. Pietrzyński et al. 2019). Massive EBs are of particular interest because massive stars ( $\gtrsim 8 M_{\odot}$ ) have high multiplicity (Sana et al. 2012) and are important drivers in the chemical and dynamical evolution of galaxies (Langer 2012). However, a detailed understanding of their interior rotation and angular momentum transport mechanisms remains elusive (Aerts, Mathis & Rogers 2019).

Another method to constrain the properties of massive stars is via asteroseismology (Aerts, Christensen-Dalsgaard & Kurtz 2010). Each pulsation mode in a star is sensitive to a specific pulsation cavity, so multiperiodic pulsations are excellent tracers of the properties of stellar interiors (e.g. Aerts et al. 2003; Briquet et al. 2007, 2013). Two classes of massive pulsators are the  $\beta$  Cephei stars (Lesh & Aizenman 1978) and the slowly pulsating B-type (SPB) stars (Waelkens 1991). The pulsations in  $\beta$  Cephei stars are gravity (g) and pressure (p) modes of low radial order, are found in dwarfs and giants of mass 8–15  $M_{\odot}$ , and have amplitudes up to a few tenths of a magnitude and pulsation periods of approximately 2–6 h (Stankov & Handler 2005). SPB pulsations occur in stars of roughly

3–9  $M_{\odot}$  and are high-order g modes with observationally challenging periods of 1–4 d. Space-based observations have recently revealed p- and g-mode pulsations in many massive stars above their canonical mass regimes, and demonstrated the diverse nature of variability for early-type stars (Pedersen et al. 2019; Burssens et al. 2020).

A promising avenue for constraining the interior physics in massive stars is to study pulsating stars in EBs, as this permits the confrontation of theoretical predictions with observed pulsation periods for stars of known mass and radius. Although several  $\beta$  Cephei stars in EBs are known (see Ratajczak, Pigulski & Pavlovski 2017), so far only one has a precisely measured mass and radius: V453 Cyg A (Southworth et al. 2020). SPB stars in EBs are even rarer: only one has been characterized in detail (V539 Ara; Clausen 1996) and no other examples are known. An important characteristic of binary stars is that tidal effects in eccentric systems may drive (Welsh et al. 2011; Hambleton et al. 2013; Fuller 2017) or perturb (Bowman et al. 2019; Fuller et al. 2020; Handler et al. 2020; Kurtz et al. 2020) pulsations.

VV Ori contains components of spectral types B1 V and B7 V in a circular orbit of period 1.485 d. Its eclipsing nature was discovered by Barr in 1903 (Barr 1905) and the early history of its study has been summarized by Wood (1946) and Duerbeck (1975). The two most recent studies of the system, Sarma & Vivekananda Rao (1995) and Terrell, Munari & Siviero (2007, hereafter T07), were the first to reliably determine its physical properties.

The multiplicity of the VV Ori system is not well established. The excess scatter seen in early RVs led to reluctant suggestions of a third body with an orbital period of 120 d (Daniel 1916; Struve & Luyten 1949), a finding that has not been substantiated (T07; Van Hamme & Wilson 2007). Horch et al. (2017) resolved a companion at an angular separation of 0.23 arcsec using speckle

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interferometry. The magnitude differences between this companion and the binary system are 3.88 mag at 692 nm and 3.43 mag at 880 nm. At a distance of  $377 \pm 31$  pc (Gaia Collaboration 2018), this corresponds to a physical separation of 87 au and thus a minimum orbital period of about 180 yr. The resolved companion cannot therefore be responsible for the putative 120 d orbital variations.

## 2 OBSERVATIONS

VV Ori was observed using the NASA *TESS* satellite (Ricker et al. 2015). *TESS* is currently observing the majority of the sky, with each hemisphere divided up into 13 sectors based on ecliptic longitude. Observations in each sector last for 27.4 d, with an interruption for data download near the mid-point. VV Ori was observed in Sector 6 (2018 December 11–2019 January 07) and is scheduled to be re-observed in Sector 32 (2020 November 19–2020 December 17). The Sector 6 data were acquired at a cadence of 2 min, which are made available through the Mikulski Archive for Space Telescope portal, and yield a Nyquist frequency of  $359.7 \text{ d}^{-1}$ . Fig. 1 shows the simple aperture photometry light curve (Jenkins et al. 2016) of VV Ori.

## 3 LIGHT-CURVE ANALYSIS

The *TESS* light curve of VV Ori was first modelled using the JKTEBOP code in order to remove the signals of binarity (see Fig. 1). We used the orbital ephemeris from this fit to phase-bin the *TESS* data into 300 data points. The binned data were then analysed using the 2004 version of the WILSON–DEVINNEY code, which represents the stars using Roche geometry (hereafter WD2004; Wilson & Devinney 1971), driven by the JKTWD wrapper (Southworth et al. 2011). We fitted separately for the light produced by the two stars, the ‘third light’ from additional star(s) in the system, the potentials of the two eclipsing stars, and the orbital inclination. We did not fit for the effective temperatures ( $T_{\text{eff}}$  values) directly because the *TESS* passband is not implemented in the WD code. Limb darkening was included using the square-root law, with coefficients fixed to values from the tables of Van Hamme (1993). Fitting for the coefficients did not improve the quality of the fit. We searched for the possibility of an eccentric orbit but found no combination of eccentricity or argument of periastron that improved the fit compared to the assumption of a circular orbit. We adopted a mass ratio of 0.376 from T07.

The adopted model is given in Table 1 and plotted in Fig. 2, where the residuals come primarily from incomplete removal of the pulsations. Because the photon noise in the photometry is negligible, the uncertainties in the fitted parameters are dominated by choices made in the modelling process. We sought to capture these by quantifying the change in fitted parameter values between the adopted model and a range of alternative models with different values or treatments of albedo, stellar rotation rate, gravity darkening, limb darkening law, limb darkening coefficients, the reflection effect, numerical precision, and mass ratio. All uncertainties in Table 1 are the quadrature addition of the differences in parameters for each alternative model versus the adopted model, and are much larger than the formal errors computed by WD2004.

## 4 PHYSICAL PROPERTIES

Determination of the physical properties of VV Ori requires combining the results of the light-curve analysis with spectroscopic measurements of the  $T_{\text{eff}}$  values and velocity amplitudes ( $K_1$  and

$K_2$ ) of the two stars. For  $T_{\text{eff}}$ , we adopted the values given by T07 and assigned a conservative uncertainty of  $\pm 1000$  K. Improved estimates of the  $T_{\text{eff}}$  values would be helpful in future.

RVs were measured by T07, who determined the stellar masses but not velocity amplitudes. We therefore fitted the RVs with JKTEBOP to determine  $K_1 = 126.2 \pm 1.8 \text{ km s}^{-1}$  and  $K_2 = 316.4 \pm 6.5 \text{ km s}^{-1}$ . These uncertainties were calculated using Monte Carlo simulations (Southworth 2008) and with data errors estimated from the scatter around the best fit. Under the assumption that the orbital inclination decreased by  $0.200 \pm 0.013^\circ \text{ yr}^{-1}$  in recent years (see below),  $K_1$  and  $K_2$  should be multiplied by a factor of  $(\frac{\sin i_{2018}}{\sin i_{2005}})^3 = 0.979 \pm 0.002$  to correct them from the mean epoch of the spectra to that of the *TESS* data. The velocity amplitudes at the epoch of the *TESS* observations are therefore  $K_1 = 123.5 \pm 2.0 \text{ km s}^{-1}$  and  $K_2 = 309.6 \pm 7.3 \text{ km s}^{-1}$ .

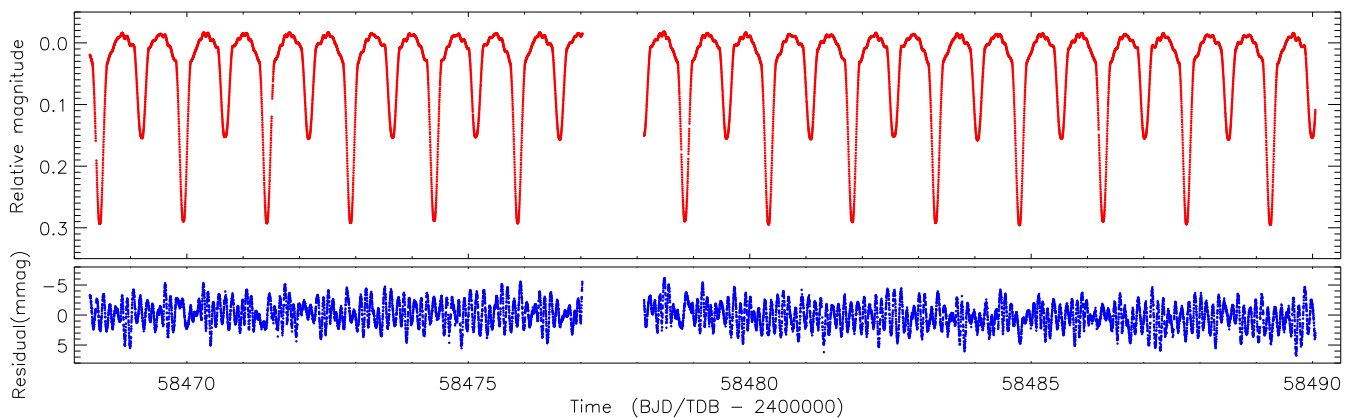
The physical properties of the system were then calculated using the JKTEBOP code (Southworth, Maxted & Smalley 2005), which propagates uncertainties using a perturbation analysis. The distance to the system was calculated from the *UBVRI* magnitudes from Ducati et al. (2001), assuming an uncertainty of 0.02 mag on each, the *JHK<sub>s</sub>* magnitudes from 2MASS (Skrutskie et al. 2006), and the bolometric corrections from Girardi et al. (2002). An interstellar extinction of  $E(B - V) = 0.10 \pm 0.05$  mag was specified to bring the optical and IR distances into agreement. The resulting distance agrees well with the *Gaia* value. We find substantially smaller masses for the two stars than T07, and this can be traced to a lower value of  $K_2$ . The uncertainties in both mass and radius are dominated by the contribution from the uncertainty in  $K_2$ , and also show that the formal errors from the WD code (quoted by T07) are too small. More extensive spectroscopy of VV Ori is needed to improve its measured properties.

## 5 ORBITAL EVOLUTION

Orbital inclination changes have been observed in a small number of EBs; this number is growing due to the multitude of photometric surveys in operation. The list includes V907 Sco (Lacy, Helt & Vaz 1999), SS Lac (Torres 2001), HS Hya (Zasche & Paschke 2012), and systems discovered with the *Kepler* satellite (Kirk et al. 2016) and the OGLE survey (Soszyński et al. 2016).

The *TESS* light curve of VV Ori shows deep partial eclipses, but previous photometric studies have revealed the system to display obvious total eclipses (e.g. Duerbeck 1975; Eaton 1975; Chambliss & Leung 1982). To demonstrate this, we show in Fig. 2 a light curve obtained by phase binning the data obtained in the Johnson *BV* filters and the Strömgren *vby* filters by Chambliss & Leung (1982). The shapes of the two light curves clearly differ. We can rule out a problem with the *TESS* photometry because a light curve from the MASCARA survey (Burggraaf et al. 2018) shows similar partial eclipses. Our fit to the *TESS* data gives an orbital inclination of  $i = 78:28 \pm 0:52$ , significantly different to the values of  $85:9 \pm 0:2$  found by T07 from the light curve of Chambliss & Leung (1982) and  $84:5 \pm 0:5$  found by Eaton (1975) from his OAO2 data. This suggests that the orbital inclination is changing.

VV Ori benefits from a rich observational history stretching back over a century, but unfortunately none of the early light curves are easily accessible. Investigation of possible changes in  $i$  are therefore not trivial. We have found two items of evidence that the inclination was lower in the 1940s. First, Dufay (1947) presents a light curve that shows either partial or marginally total eclipses. His fit to these data, which are rather scattered, gives  $i = 77:2$ . Secondly, Huffer & Kopal (1950) state that the period of totality in primary eclipse



**Figure 1.** Top: *TESS* simple aperture photometry light curve of VV Ori. Bottom: residuals of the best JKTEBOP fit showing the pulsations.

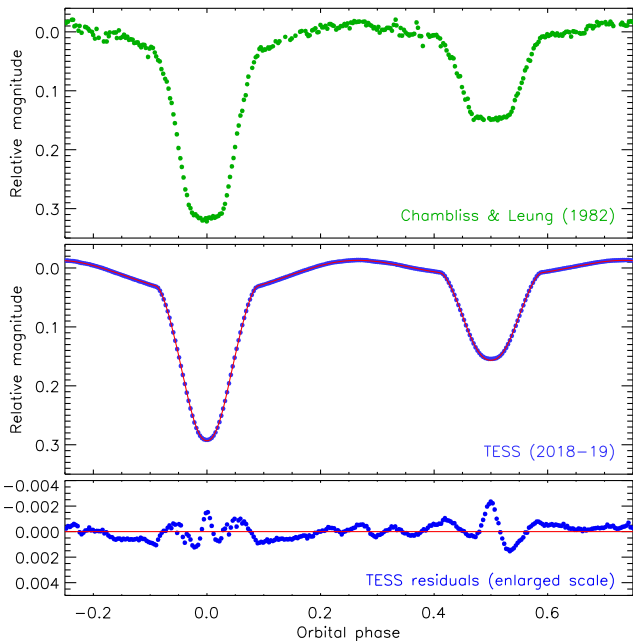
**Table 1.** Brief summary of the parameters for the WD solution of the *TESS* light curve of VV Ori. Detailed descriptions of the control parameters can be found in the WD2004 user guide (Wilson & Van Hamme 2004). Uncertainties are only quoted when they account for the variation in that parameter over a full set of alternative solutions.

Parameter	Star A	Star B
<i>Control parameters:</i>		
WD2004 operation mode		0
Treatment of reflection		1
Number of reflections		1
Limb darkening law		3 (square-root)
Numerical grid size (normal)		60
Numerical grid size (coarse)		40
<i>Fixed parameters:</i>		
Orbital period (d)		1.485 3784
Primary eclipse time (BJD/TDB)		2458480.33468
Mass ratio		0.376
Orbital eccentricity		0.0
Rotation rates	1.0	1.0
Bolometric albedos	1.0	1.0
Gravity darkening	1.0	1.0
Bolometric linear LD coefficients	0.6288	0.7121
Linear LD coefficient	-0.1188	-0.0612
Square-root LD coefficient	0.4694	0.4073
<i>Fitted parameters:</i>		
Orbital inclination ( $^{\circ}$ )		$78.28 \pm 0.52$
Third light		$0.005 \pm 0.069$
Light contributions	$11.24 \pm 0.88$	$1.299 \pm 0.069$
Potentials	$3.132 \pm 0.028$	$3.397 \pm 0.102$
<i>Derived parameters:</i>		
Fractional radii	$0.3718 \pm 0.0010$	$0.1817 \pm 0.0034$
Orbital separation ( $R_{\odot}$ )		$13.51 \pm 0.05$
Mass ( $M_{\odot}$ )	$9.52 \pm 0.56$	$3.80 \pm 0.16$
Radius ( $R_{\odot}$ )	$4.958 \pm 0.088$	$2.360 \pm 0.061$
Log surface gravity (cgs)	$4.026 \pm 0.011$	$4.272 \pm 0.018$
$T_{\text{eff}}$ (K)	$26\,200 \pm 1000$	$16\,100 \pm 1000$
Log luminosity ( $L_{\odot}$ )	$4.02 \pm 0.07$	$2.53 \pm 0.11$
Absolute bolometric magnitude	$-5.36 \pm 0.17$	$-1.65 \pm 0.27$
Distance (pc)		$371 \pm 12$

lasts for  $0.042 \pm 0.003$  phase units. Our by-eye measurement of the duration of totality in the Chambliss & Leung (1982) light curves is  $0.060 \pm 0.005$  in phase units.

Due to the symmetry inherent in spatially unresolved two-body motion, the light curves of EBs have no indication of whether  $i$  is above or below  $90^{\circ}$ , so by convention inclinations are quoted as the smaller of  $i$  or  $(90^{\circ} - i)$ . We therefore suggest that VV Ori is undergoing orbital precession that manifests as a change in  $i$ ,

that it used to show partial eclipses, that the inclination rose to the maximum of  $i = 90^{\circ}$  some time in the 1950s or 1960s, and is now decreasing by approximately  $0.2^{\circ} \text{ yr}^{-1}$ . Using WD2004, we find that the lower limit for eclipses to occur in this system is  $56.8^{\circ}$ . When – or if – VV Ori will cease to eclipse in the future will be investigated in detail in a future work. One other relevant constraint is that the binarity of the system was discovered through visual observations of its photometric variability in 1903 (Barr 1905). This almost certainly



**Figure 2.** Top: light curve from Chambliss & Leung (1982) obtained by phase binning the  $BV$  and  $vby$  data together. Middle: phase-binned light curve of VV Ori (filled blue circles) with the best fit from the WD code (red solid line). Bottom: residuals of the fit to the *TESS* data.

indicates it was eclipsing at this time because the amplitude of the proximity effects in this system is very low for visual observations: roughly 0.04 mag at  $i = 60^\circ$ .

## 6 PULSATION ANALYSIS

To examine the pulsational properties of VV Ori, we subtracted a multifrequency harmonic model of the orbital frequency,  $\nu_{\text{orb}} = 0.673229 \pm 0.000001 \text{ d}^{-1}$ , from the light curve and calculated a residual amplitude spectrum using a discrete Fourier transform (Kurtz 1985). We employed iterative pre-whitening to extract all significant frequencies using the standard amplitude signal-to-noise (S/N) criterion of Breger (1993), such that significant frequencies have  $S/N \geq 4$ . The S/N of each peak was calculated using its amplitude and the average amplitude within a  $1 \text{ d}^{-1}$  window at the location of the extracted frequency. In total, we extracted 51 significant frequencies between 1.4 and  $27.8 \text{ d}^{-1}$ . The frequencies, amplitudes, and phases and their corresponding  $1\sigma$  uncertainties were obtained from a multifrequency non-linear least-squares fit to the light curve (Kurtz et al. 2015; Bowman 2017), and are provided in Table A1. The amplitude spectra before and after pre-whitening all significant pulsation modes are shown in Fig. 3.

VV Ori exhibits two multiplets of pulsation modes split by the orbital frequency (centred at  $\nu_1 = 9.1766 \pm 0.0001$  and  $\nu_2 = 9.0324 \pm 0.0002 \text{ d}^{-1}$ ), as indicated in Fig. 3, and several additional pulsation frequencies. Given the frequencies of the two dominant modes,  $\nu_1$  and  $\nu_2$ , we attribute them to the  $\beta$  Cep primary. In slowly rotating pulsators, symmetric frequency multiplets are plausible (see Bowman 2020). However, the inferred rotation rate assuming  $\nu_1$  and  $\nu_2$  as the retrograde and prograde components of a non-radial mode would imply an uncommonly slow rotation rate for such a massive star. On the other hand, such multiplets are the signature of tidally perturbed modes (Bowman et al. 2019; Bowman 2020; Jerzykiewicz et al. 2020; Southworth et al. 2020), amplitude

modulation during the orbit caused by a changing light ratio, and tidally tilted pulsators (Fuller et al. 2020; Handler et al. 2020; Kurtz et al. 2020). Our analysis reveals that the pulsation amplitudes are not maximal at a specific orbital phase (see Fig. 1). Hence, if VV Ori is a tidally tilted pulsator, it is different to those studied by Handler et al. (2020) and Kurtz et al. (2020).

There are several independent g-mode frequencies below  $3 \text{ d}^{-1}$ , which we suggest arise from the less-massive secondary star, making it a possible SPB star. We also find that the high-frequency doublets (shown in yellow in Fig. 3) can be explained by high-order combination frequencies of the orbital frequency and the two dominant modes  $\nu_1$  and  $\nu_2$  [e.g.  $\nu_1 + \nu_2 + n \nu_{\text{orb}}$ , where  $n \in (6, 8, 10)$ ]. The remaining significant frequencies are shown in green in Fig. 3, and we interpret these as independent given that only high-order coincidental combination relations are possible. In Table A1, we provide the identifications of the extracted frequencies. Additional ‘missing’ component frequencies of the multiplets can clearly be seen in Fig. 3, but these fall below our S/N criterion.

At the suggestion of the referee, we investigated whether imperfections in the binary modelling (Section 3) could have affected the pulsation frequencies we have identified in VV Ori. To do this, we generated a set of slightly different models of the *TESS* light curve using JKTEBOP, by ignoring third light, or fitting for  $\text{ecos } \omega$ , or fixing the sum of the fractional radii of the stars to a value  $4\sigma$  smaller than the fitted value, or changing the mass ratio and thus the shapes of the stars. The frequency spectra of these data sets show differences at the orbital harmonics, but the pulsation multiplets we find are essentially unaffected. This shows that our pulsation analysis is robust against changes in the modelling of binarity, and that the multiplets are not methodological in origin.

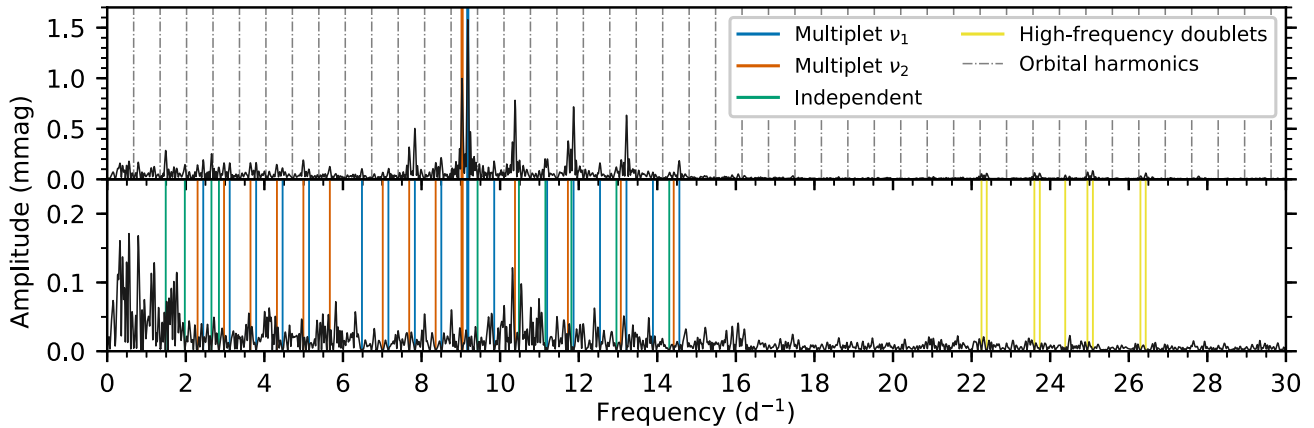
## 7 SUMMARY AND DISCUSSION

VV Ori is an early-type binary system containing a  $9.5$  and  $3.8 M_\odot$  star on a short-period orbit. It used to have total eclipses but the *TESS* photometry shows that these eclipses are now partial. We have fitted the *TESS* light curve and published RVs, and determined the physical properties of the stars. The orbital inclination is significantly lower than found in previous studies, and this change is probably driven by dynamical interactions with a third body. Together with the directly imaged companion at an angular separation of  $0.23$  arcsec, this means that the VV Ori system is at least quadruple.

The *TESS* data reveal 51 significant frequencies, including independent g- and p-mode pulsations. We interpret the p-mode pulsations as arising from the primary star, making VV Ori A the second  $\beta$  Cephei star in an EB with a precisely measured mass (after V453 Cyg A; Southworth et al. 2020). The g-mode pulsations possibly originate from the secondary star, in which case VV Ori B is the second known SPB star in an EB (after V539 Ara B; Clausen 1996). Two frequency multiplets of the dominant p modes with a spacing of the orbital frequency are also evident. The equilibrium tide in short-period circular binaries can give rise to a spheroidal bulge and ellipsoidal variability, but is also predicted to perturb self-excited non-radial pulsations and produce such pulsation frequency multiplets (Reyniers & Smeyers 2003; Balona 2018). Such multiplets of pulsation modes have recently been detected in a handful of short-period EBs (Bowman et al. 2019; Fuller et al. 2020; Handler et al. 2020; Jerzykiewicz et al. 2020; Kurtz et al. 2020; Southworth et al. 2020).

The multiperiodic frequency spectrum makes VV Ori a prime target for future asteroseismic modelling (see Schmid & Aerts 2016; Johnston et al. 2019). Furthermore, such pulsating stars in





**Figure 3.** Amplitude spectra of VV Ori after removal of the binary model (top), and after removal of the significant pulsation frequencies too (bottom). The location and identity of extracted frequencies are shown as coloured lines, and the dashed grey lines represent harmonics of the orbital frequency.

EBs open up new avenues to perform tidal asteroseismology and inspect the currently mysterious interiors of massive stars. In the near future, VV Ori will be re-observed using *TESS*, giving a new data set to further refine the asteroseismic analysis and study the orbital evolution of the system. We have also begun a spectroscopic campaign on this system with the aim of measuring masses and  $T_{\text{eff}}$  values to higher precision, and detecting and identifying line-profile variability due to the pulsations in both components.

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#### DATA AVAILABILITY

All data underlying this article are available in the MAST archive (<https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html>) and from Terrell et al. (2007).

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## SUPPORTING INFORMATION

Supplementary data are available at [MNRASL](#) online.

**Table S1.** Frequencies, amplitudes, and phases of significant frequencies in VV Ori.

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# List of astronomical key words (Updated on 2020 January)

This list is common to *Monthly Notices of the Royal Astronomical Society*, *Astronomy and Astrophysics*, and *The Astrophysical Journal*. In order to ease the search, the key words are subdivided into broad categories. No more than *six* subcategories altogether should be listed for a paper.

The subcategories in boldface containing the word ‘individual’ are intended for use with specific astronomical objects; these should never be used alone, but always in combination with the most common names for the astronomical objects in question. Note that each object counts as one subcategory within the allowed limit of six.

The parts of the key words in italics are for reference only and should be omitted when the keywords are entered on the manuscript.

## **General**

editorials, notices  
errata, addenda  
extraterrestrial intelligence  
history and philosophy of astronomy  
miscellaneous  
obituaries, biographies  
publications, bibliography  
sociology of astronomy  
standards

## **Physical data and processes**

acceleration of particles  
accretion, accretion discs  
asteroseismology  
astrobiology  
astrochemistry  
astroparticle physics  
atomic data  
atomic processes  
black hole physics  
chaos  
conduction  
convection  
dense matter  
diffusion  
dynamo  
elementary particles  
equation of state  
gravitation  
gravitational lensing: micro  
gravitational lensing: strong  
gravitational lensing: weak  
gravitational waves  
hydrodynamics  
instabilities  
line: formation  
line: identification  
line: profiles  
magnetic fields  
magnetic reconnection  
(*magnetohydrodynamics*) MHD  
masers  
molecular data  
molecular processes  
neutrinos  
nuclear reactions, nucleosynthesis, abundances  
opacity  
plasmas  
polarization

radiation: dynamics  
radiation mechanisms: general  
radiation mechanisms: non-thermal  
radiation mechanisms: thermal  
radiative transfer  
relativistic processes  
scattering  
shock waves  
solid state: refractory  
solid state: volatile  
turbulence  
waves

## **Astronomical instrumentation, methods and techniques**

atmospheric effects  
balloons  
instrumentation: adaptive optics  
instrumentation: detectors  
instrumentation: high angular resolution  
instrumentation: interferometers  
instrumentation: miscellaneous  
instrumentation: photometers  
instrumentation: polarimeters  
instrumentation: spectrographs  
light pollution  
methods: analytical  
methods: data analysis  
methods: laboratory: atomic  
methods: laboratory: molecular  
methods: laboratory: solid state  
methods: miscellaneous  
methods: numerical  
methods: observational  
methods: statistical  
site testing  
space vehicles  
space vehicles: instruments  
techniques: high angular resolution  
techniques: image processing  
techniques: imaging spectroscopy  
techniques: interferometric  
techniques: miscellaneous  
techniques: photometric  
techniques: polarimetric  
techniques: radar astronomy  
techniques: radial velocities  
techniques: spectroscopic  
telescopes



## Astronomical data bases

astronomical data bases: miscellaneous  
atlases  
catalogues  
surveys  
virtual observatory tools

## Software

software: data analysis  
software: development  
software: documentation  
software: public release  
software: simulations

## Astrometry and celestial mechanics

astrometry  
celestial mechanics  
eclipses  
ephemerides  
occultations  
parallaxes  
proper motions  
reference systems  
time

## The Sun

Sun: abundances  
Sun: activity  
Sun: atmosphere  
Sun: chromosphere  
Sun: corona  
Sun: coronal mass ejections (CMEs)  
Sun: evolution  
Sun: faculae, plages  
Sun: filaments, prominences  
Sun: flares  
Sun: fundamental parameters  
Sun: general  
Sun: granulation  
Sun: helioseismology  
Sun: heliosphere  
Sun: infrared  
Sun: interior  
Sun: magnetic fields  
Sun: oscillations  
Sun: particle emission  
Sun: photosphere  
Sun: radio radiation  
Sun: rotation  
(*Sun:*) solar–terrestrial relations  
(*Sun:*) solar wind  
(*Sun:*) sunspots  
Sun: transition region  
Sun: UV radiation  
Sun: X-rays, gamma-rays

## Planetary systems

comets: general

## comets: individual: . . .

Earth  
interplanetary medium  
Kuiper belt: general

## Kuiper belt objects: individual: . . .

meteorites, meteors, meteoroids

minor planets, asteroids: general

## minor planets, asteroids: individual: . . .

Moon

Oort Cloud

planets and satellites: atmospheres  
planets and satellites: aurorae  
planets and satellites: composition  
planets and satellites: detection  
planets and satellites: dynamical evolution and stability  
planets and satellites: formation  
planets and satellites: fundamental parameters  
planets and satellites: gaseous planets  
planets and satellites: general

## planets and satellites: individual: . . .

planets and satellites: interiors  
planets and satellites: magnetic fields  
planets and satellites: oceans  
planets and satellites: physical evolution  
planets and satellites: rings  
planets and satellites: surfaces  
planets and satellites: tectonics  
planets and satellites: terrestrial planets  
planet–disc interactions  
planet–star interactions  
protoplanetary discs  
zodiacal dust

## Stars

stars: abundances  
stars: activity  
stars: AGB and post-AGB  
stars: atmospheres  
(*stars:*) binaries (*including multiple*): close  
(*stars:*) binaries: eclipsing  
(*stars:*) binaries: general  
(*stars:*) binaries: spectroscopic  
(*stars:*) binaries: symbiotic  
(*stars:*) binaries: visual  
stars: black holes  
(*stars:*) blue stragglers  
(*stars:*) brown dwarfs  
stars: carbon  
stars: chemically peculiar  
stars: chromospheres  
(*stars:*) circumstellar matter  
stars: coronae  
stars: distances  
stars: dwarf novae  
stars: early-type  
stars: emission-line, Be  
stars: evolution  
stars: flare  
stars: formation  
stars: fundamental parameters  
(*stars:*) gamma-ray burst: general  
(*stars:*) **gamma-ray burst: individual: . . .**  
stars: general  
(*stars:*) Hertzsprung–Russell and colour–magnitude diagrams  
stars: horizontal branch  
stars: imaging  
**stars: individual: . . .**  
stars: interiors

stars: jets  
 stars: kinematics and dynamics  
 stars: late-type  
 stars: low-mass  
 stars: luminosity function, mass function  
 stars: magnetars  
 stars: magnetic field  
 stars: massive  
 stars: mass-loss  
 stars: neutron  
 (*stars:*) novae, cataclysmic variables  
 stars: oscillations (*including pulsations*)  
 stars: peculiar (*except chemically peculiar*)  
 (*stars:*) planetary systems  
 stars: Population II  
 stars: Population III  
 stars: pre-main-sequence  
 stars: protostars  
 (*stars:*) pulsars: general  
 (*stars:*) **pulsars: individual: . . .**  
 stars: rotation  
 stars: solar-type  
 (*stars:*) starspots  
 stars: statistics  
 (*stars:*) subdwarfs  
 (*stars:*) supergiants  
 (*stars:*) supernovae: general  
 (*stars:*) **supernovae: individual: . . .**  
 stars: variables: Cepheids  
 stars: variables: Scuti  
 stars: variables: general  
 stars: variables: RR Lyrae  
 stars: variables: S Doradus  
 stars: variables: T Tauri, Herbig Ae/Be  
 (*stars:*) white dwarfs  
 stars: winds, outflows  
 stars: Wolf–Rayet

### Interstellar medium (ISM), nebulae

ISM: abundances  
 ISM: atoms  
 ISM: bubbles  
 ISM: clouds  
 (*ISM:*) cosmic rays  
 (*ISM:*) dust, extinction  
 ISM: evolution  
 ISM: general  
 (*ISM:*) HII regions  
 (*ISM:*) Herbig–Haro objects

### ISM: individual objects: . . .

(*except planetary nebulae*)  
 ISM: jets and outflows  
 ISM: kinematics and dynamics  
 ISM: lines and bands  
 ISM: magnetic fields  
 ISM: molecules  
 (*ISM:*) photodissociation region (PDR)  
 (*ISM:*) planetary nebulae: general  
 (*ISM:*) **planetary nebulae: individual: . . .**  
 ISM: structure  
 ISM: supernova remnants

### The Galaxy

Galaxy: abundances  
 Galaxy: bulge  
 Galaxy: centre  
 Galaxy: disc  
 Galaxy: evolution  
 Galaxy: formation  
 Galaxy: fundamental parameters  
 Galaxy: general  
 (*Galaxy:*) globular clusters: general  
 (*Galaxy:*) **globular clusters: individual: . . .**  
 Galaxy: halo  
 Galaxy: kinematics and dynamics  
 (*Galaxy:*) local interstellar matter  
 Galaxy: nucleus  
 (*Galaxy:*) open clusters and associations: general  
 (*Galaxy:*) **open clusters and associations: individual: . . .**  
 (*Galaxy:*) solar neighbourhood  
 Galaxy: stellar content  
 Galaxy: structure

### Galaxies

galaxies: abundances  
 galaxies: active  
 galaxies: bar  
 (*galaxies:*) BL Lacertae objects: general  
 (*galaxies:*) **BL Lacertae objects: individual: . . .**  
 galaxies: bulges  
 galaxies: clusters: general

### galaxies: clusters: individual: . . .

galaxies: clusters: intracluster medium  
 galaxies: disc  
 galaxies: distances and redshifts  
 galaxies: dwarf  
 galaxies: elliptical and lenticular, cD  
 galaxies: evolution  
 galaxies: formation  
 galaxies: fundamental parameters  
 galaxies: general  
 galaxies: groups: general

### galaxies: groups: individual: . . .

galaxies: haloes  
 galaxies: high-redshift

### galaxies: individual: . . .

galaxies: interactions  
 (*galaxies:*) intergalactic medium  
 galaxies: irregular  
 galaxies: ISM  
 galaxies: jets  
 galaxies: kinematics and dynamics  
 (*galaxies:*) Local Group  
 galaxies: luminosity function, mass function  
 (*galaxies:*) Magellanic Clouds  
 galaxies: magnetic fields  
 galaxies: nuclei  
 galaxies: peculiar  
 galaxies: photometry  
 (*galaxies:*) quasars: absorption lines  
 (*galaxies:*) quasars: emission lines  
 (*galaxies:*) quasars: general

*(galaxies:)* **quasars: individual: . . .**  
*(galaxies:)* quasars: supermassive black holes  
galaxies: Seyfert  
galaxies: spiral  
galaxies: starburst  
galaxies: star clusters: general

**galaxies: star clusters: individual: . . .**  
galaxies: star formation  
galaxies: statistics  
galaxies: stellar content  
galaxies: structure

### **Cosmology**

*(cosmology:)* cosmic background radiation  
*(cosmology:)* cosmological parameters  
*(cosmology:)* dark ages, reionization, first stars  
*(cosmology:)* dark energy  
*(cosmology:)* dark matter  
*(cosmology:)* diffuse radiation  
*(cosmology:)* distance scale  
*(cosmology:)* early Universe  
*(cosmology:)* inflation  
*(cosmology:)* large-scale structure of Universe  
cosmology: miscellaneous  
cosmology: observations  
*(cosmology:)* primordial nucleosynthesis  
cosmology: theory

### **Resolved and unresolved sources as a function of wavelength**

gamma-rays: diffuse background  
gamma-rays: galaxies  
gamma-rays: galaxies: clusters  
gamma-rays: general  
gamma-rays: ISM  
gamma-rays: stars  
infrared: diffuse background  
infrared: galaxies  
infrared: general  
infrared: ISM  
infrared: planetary systems  
infrared: stars  
radio continuum: galaxies  
radio continuum: general  
radio continuum: ISM  
radio continuum: planetary systems  
radio continuum: stars  
radio continuum: transients  
radio lines: galaxies  
radio lines: general  
radio lines: ISM  
radio lines: planetary systems  
radio lines: stars  
submillimetre: diffuse background  
submillimetre: galaxies  
submillimetre: general  
submillimetre: ISM  
submillimetre: planetary systems  
submillimetre: stars  
ultraviolet: galaxies

ultraviolet: general  
ultraviolet: ISM  
ultraviolet: planetary systems  
ultraviolet: stars  
X-rays: binaries  
X-rays: bursts  
X-rays: diffuse background  
X-rays: galaxies  
X-rays: galaxies: clusters  
X-rays: general  
**X-rays: individual: . . .**  
X-rays: ISM  
X-rays: stars

### **Transients**

*(transients:)* black hole mergers  
*(transients:)* black hole - neutron star mergers  
*(transients:)* fast radio bursts  
*(transients:)* gamma-ray bursts  
*(transients:)* neutron star mergers  
transients: novae  
transients: supernovae  
transients: tidal disruption events