V410 Puppis: A useful laboratory for early stellar evolution

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ABSTRACT

New spectrometric (HERCULES) and ground-based multi-colour photometric data on the multiple star V410 Puppis are combined with satellite photometry (HIPPARCOS and TESS), as well as historic astrometric observations. Absolute parameters for V410 Pup Aab are derived: $M_{Aa} = 3.15 \pm 0.10$, $M_{Ab} = 1.83 \pm 0.08$ (M\odot); $R_{Aa} = 2.12 \pm 0.10$, $R_{Ab} = 1.52 \pm 0.08$ (R\odot); $a = 6.57 \pm 0.04$ R\odot; $T_{Aa} = 12500 \pm 1000$, $T_{Ab} = 9070 \pm 800$ (K), and photometric distance 350 ± 10 (pc). We report the discovery of a low-amplitude SPB variation in the light curve and also indications of an accretion structure around V410 Pup B as well as emission cores in V410 Pup C. We argue that V410 Pup is probably a young formation connected with the Vela 2 OB Association. The combined evidence allows an age in the range 7-25 Myr from comparisons with standard stellar evolution modelling.

Key words: stars: binaries (including multiple) close — stars: early type — stars: individual V410 Pup

1 INTRODUCTION

1.1 General

The present article forms part of a ‘Southern Binaries Programme’ which in recent years has presented a number of studies of massive young close binary systems, often associated with star-forming regions. An interim summary was given by Idaczyk et al. (2013), and a recent example is the paper of Budding et al. (2021) on V Pup. Binary stars are an important source of fundamental data on stellar properties such as their masses and luminosities. The ready availability of high-precision photometry from the TESS satellite (section 2) as well as access to the high-resolution HERCULES spectrometer (section 3) allows ongoing refinement of our knowledge of such properties. The relatively fast development of massive stars presents a special testing-ground for evolution mechanisms — structural and dynamical. The importance of precision in the parametrization of stars has been stressed, for example in Eker et al. (2015).

Popper (1980)’s classic paper analysed 45 close binary examples to provide detailed facts on stellar structure and evolution. He set parameter accuracy limits of a few percent, which Andersen (1991) later improved to a cited ∼ 2%. Andersen et al. (1993) also drew attention to the interesting role close young binaries might play in understanding the relationship of stellar properties to their galactic environment (see also Southworth 2007, Gies 2013, Feiden 2015). Ruciński (2006) pointed out the observational neglect of binaries with declinations south of −15°. Such discussions provide a springboard for the work presented here.

In the next subsection we review what is known about the V410 Pup system. Section 2 examines new and historic photometry, including data from the HIPPARCOS and TESS satellites as well as our new BVR light curves. In section 3 we present observational work on data from the HERCULES spectrograph at the University of Canterbury Mt John Observatory in New Zealand. In subsection 3.1, we demonstrate radial velocity variations clearly identifiable with orbital motion of the close binary. Subsection 3.2 presents analysis of absorption line profiles to determine rotational angular velocities consistent with synchronized rotation and also raises...
the question of phase-dependence of the line equivalent width (the Struve-Sahade effect). Subsection 3.3 discusses application of the KOREL disentangling technique and to the complexities of this multiple star.

The variable in V410 Puppis is identified with the most massive A-component of a visual system containing at least three main objects: the B component having been discovered by R. Innes in 1906 and the C component by J. Herschel in 1836. The separation of the AB-C system at ~30 arcsec implies that there would be little, if any, detectable orbital motion in the years since discovery. However, this is not the case for the AB binary, which appears to have completed, since 1906, about one third of an eccentric orbit on the sky, whose semi-major axis is ~0.3 arcsec.

Section 4 presents astrometric data and analysis on the AB system, allowing a check on derived masses. Resulting absolute parameters are given in Section 5 and in the final Section 6 these are compared with recent theoretical models published by the Padova school (Bressan et al. 2012). While alternative scenarios for the age and evolutionary status of the system are possible, circumstantial evidence favours a relatively young configuration. Further detailed observations are recommended to improve our understanding of this interesting object.

1.2 V410 Pup

V410 Pup (HD 66079, HIP 39084, WDS J07598-4718AB) is a magnitude 6.716 V (Tycho, see Fabricius et al. 2002) multiple star, assigned a B8V spectral classification. It is located in the region of the Vela OB2 association, with a distance of 346 ± 35 pc (GAIA eDR3, Gaia Collaboration, 2021). The ICRS (2000) coordinates are 07h 59m 45.93 (RA) and −47° 18’ 12.7” (Dec), or galactic λ 261.90 and β 9.08 (deg). It was identified as an eclipsing binary in the 74th name list of variable stars by Kazarovets et al. (1999), based on data from the HIPPARCOS survey (de Zeeuw et al. 1995), used in the HIPPARCOS survey. For reviews of the Vela OB2 Association see Jeffries et al. (2009) and Cantat-Gaudin et al. (2019). Another recent study (Kervella et al. 2019) used information from Gaia to examine the incidence of binarity in the Vela OB2.

The location of a complex multiple system such as V410 Pup relative to Vela OB2 recalls that of V831 Cen in relation to the nearer (~ 100 pc), young (~ 10 My) Scorpius-Centaurus OB2 association, where inclusion of astrometric analysis revealed additional parameters (Budding et al. 2010).

2 PHOTOMETRY

Since the discovery of variability of HIP 39084 was an outcome of the HIPPARCOS survey, examination of the relevant data in the HIPPARCOS Epoch Photometry Annex forms a natural starting place for this project. ESA (1997) reported the ephemeris based on HIPPARCOS data as:

\[ \text{Min I} = \text{HJD 2448500.3377} + 0.87617E. \]

We applied the light-curve modelling program WinFitter, which is described in detail by Rhodes (2021). An early discussion of its optimization method was presented by Banks & Budding (1990). WinFitter parametrizes a physically appropriate model that includes the effects of tidal distortion of the stellar envelopes (the Radau model, cf. Kopal, 1959). Its
Table 1. Optimal parameters for the photometric model fits. WinFitter was used to model the HIPPARCOS, ground-based BVR, and TESS data from Sectors 9 and 35. Similar results were obtained for the Sector 7 data. Estimates from the Monte Carlo Wilson-Devinney program (WD + MC) are given in the rightmost column, fitting the TESS data from Sector 35. These fittings specify near-equal ‘potentials’ $\Omega_{AA} = 3.743 \pm 0.033, \Omega_{AB} = 3.736 \pm 0.077$. The mass ratios $q$ were fixed for each of these fittings. The limb-darkening requires an effective wavelength and this is determined from the assigned surface temperature $T_{eff}$ values and filter transmission data. A mean wavelength of 800 nm was taken for the TESS photometry. Coefficients $(\omega)$ from the TESS data from Sectors 9 and 35. Similar results were obtained for the Sector 7 data. Estimates from the Monte Carlo Wilson-Devinney technique (Figure 2), and the quadratic formulation of Claret (2017) was adopted in the WD + MC technique, with values being set to $(X_{AA}, Y_{AA}) = (0.116, 0.238)$ and $(X_{AB}, Y_{AB}) = (0.186, 0.246)$.

| Parameter | HIPPARCOS | B | V | R | TESS Sec 9 | TESS Sec 35 | WD+MC |
|-----------|-----------|---|---|---|------------|------------|-------|
| $M_{Ab}/M_{Aa}$ | 0.95 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.58 |
| $L_{Aa}$ | 0.32 ± 0.06 | 0.54 ± 0.09 | 0.42 ± 0.10 | 0.29 ± 0.07 | 0.24 ± 0.04 | 0.305 ± 0.005 | 0.25 ± 0.02 |
| $L_{Ab}$ | 0.11 ± 0.04 | 0.20 ± 0.03 | 0.17 ± 0.08 | 0.17 ± 0.05 | 0.12 ± 0.03 | 0.110 ± 0.006 | 0.08 ± 0.01 |
| $L_B$ | 0.55 ± 0.06 | 0.26 ± 0.03 | 0.41 ± 0.05 | 0.53 ± 0.05 | 0.65 ± 0.04 | 0.574 ± 0.007 | 0.67 ± 0.02 |
| $r_{Aa}$ (mean) | 0.297 ± 0.006 | 0.30 ± 0.01 | 0.30 ± 0.02 | 0.30 ± 0.02 | 0.295 ± 0.005 | 0.298 ± 0.001 | 0.32 ± 0.02 |
| $r_{Ab}$ (mean) | 0.296 ± 0.01 | 0.29 ± 0.03 | 0.27 ± 0.05 | 0.29 ± 0.05 | 0.286 ± 0.013 | 0.276 ± 0.005 | 0.23 ± 0.01 |
| $i$ (deg) | 67.1 ± 1.0 | 66 ± 2 | 67 ± 3 | 70 ± 2 | 74.0 ± 0.5 | 70.3 ± 0.2 | 72.96 ± 0.36 |
| $T_{Aa}$ (K) | 11500 | 13000 | 13000 | 13000 | 13000 | 13000 | 12500 |
| $T_{Ab}$ (K) | 9000 | 9000 | 9000 | 9000 | 9000 | 9000 | 9070 |
| $u_{Aa}$ | 0.48 | 0.44 | 0.38 | 0.31 | 0.48 | 0.48 |
| $u_{Ab}$ | 0.50 | 0.54 | 0.46 | 0.36 | 0.50 | 0.50 |
| $\chi^2/\nu$ | 1.02 | 0.72 | 0.67 | 1.90 | 1.04 | 0.73 | 1.13 |
| $\Delta l$ | 0.007 | 0.01 | 0.01 | 0.01 | 0.001 | 0.001 | 0.001 |

Table 2. Magnitude and Colours of V410 Pup C and V410 Pup AB.

|          | V410 Pup AB | V410 Pup C |
|----------|-------------|------------|
| V        | 6.716 ± 0.024 | 9.461 ± 0.021 |
| $B - V$  | $-0.056$ ± 0.034 | $0.074$ ± 0.030 |
| $V - R$  | $-0.014$ ± 0.035 | $0.028$ ± 0.031 |

Table 3. Eclipse timings based on the BVR photometry. HJD is Heliocentric Julian Date.

| HJD       | Error (days) | Eclipse type |
|-----------|--------------|--------------|
| 2458488.0254 | 0.0061 | Secondary |
| 2458494.1599 | 0.0051 | Secondary |
| 2458548.0423 | 0.0039 | Primary |

optimization procedures are in keeping with the discussion of Bevington (1969), particularly his chapter 11. After locating an optimal parameter-set, WinFitter numerically inverts the Hessian of the $\chi^2$ variate (in the vicinity of its minimum) to derive the error matrix. This Hessian should be positive definite for a properly posed data-modelling problem. The resulting parameter uncertainties then include the effects of inter-correlations between the optimised parameters.

A preliminary WinFitter model for the HIPPARCOS light curve is shown in Fig 1 and a corresponding set of parameters listed in the first column of Table 1. The appearance of the light curve together with the context of a young multiple star suggested a pair of Main Sequence (MS) stars of closely comparable mass. The mass ratio was thus tentatively set at 0.95. Stellar effective temperatures are required to be able to parametrize the surface limb-darkening values. The listed B8 spectral type (Wenger et al. 2000) permitted an initial estimate of $\sim 11500$ K for the primary star Aa. Later determinations of the likely individual colours of the components caused an increase in this estimate for Aa to $\sim 13000$ K. The ratio of eclipse depths is easily seen to equal the ratio of surface mean fluxes over corresponding eclipsed areas. The trend of the latter towards the effective temperature ratio in the Rayleigh-Jeans region of the spectrum applies to early type stars observed in the V and R ranges, allowing a rough estimate of $T_{eff} \approx 9000$ K for Ab.

The Transiting Exoplanet Survey Satellite (TESS) (Ricker et al. 2014) has been operational since 2018. V410 Pup was observed with 30-minute cadence by TESS in sectors 7 (January 7th to February 1st 2019), 8 (February 2 to February 27th 2019) and 9 (February 28th to March 26th 2019). More recently there have been observations with 10-minute cadence in sector 35 (February 9th to March 6th 2021). We have processed these data using the ELEANOR Python package (Feinstein et al. 2019). These were first analysed using WinFitter. We also applied the numerical integration code of Wilson & Devinney (1971) combined with the Monte-Carlo optimization procedure as discussed by Zola et al. (2004), which is referred to as WD + MC in what follows.

Although the form of the light curve was at first taken to be from a pair of relatively similar unevolved and detached Main Sequence stars, the relative luminosities $L_{Aa,Ab}$, together with indications from the spectroscopy (discussed in section 3) pointed towards an early-type semi-detached arrangement, such as holds for V Pup (Budding et al., 2021). With this in mind we carried out a ‘q-search’, allowing optimal light curve fittings for given mass ratios ($q$) in the range $0.2 < q < 1$ to be checked. A minimum $\chi^2$ was found at around $q \approx 0.58$ with the WD+MC technique (Figure 2), and similarly $q \approx 0.55$ for WinFitter. The parameter estimates from WinFitter and WD + MC fits with $q$ set to 0.55 and 0.58 are given in Table 1. The best-fitting WinFitter model light curve for TESS Sector 35 data is plotted in Fig 3 against the observations, together with a subplot showing the residuals.
\[ \sum W(O - C)^2 \] values corresponding to the optimal solutions by WD+MC for the range \( 0.4 < q < 0.7 \), using Sector 35 TESS photometry of V410 Pup. Similar searches were made using WinFitter with the Sector 7 and 9 data, with comparable results.

New photometric observations of V410 Pup were obtained over three nights in January 2019 using an 80mm F6 refractor telescope, stopped down to 50-mm aperture, at the Congarinni Observatory, NSW, Australia (152° 52′ E, 30° 44′ S, 20 meters above mean sea level). The light curves are shown in Figure 4. The images were captured by an ATIK\textsuperscript{TM} One 6.0 Charge-Coupled Detector (CCD) camera equipped with Johnson-Cousins BVR filters. Further photometric observations were made on one night in March 2019 using the same equipment with the addition of a 2× tele-extender to increase the image scale, allowing measurement of V410 Pup C separately from V410 Pup AB (see Table 2). The comparison star was HD65817 (\( V = 8.223, \ B - V = -0.021, \ V - R = 0.004 \)). The MAXIM DL\textsuperscript{TM} software package (George 2000) was used for image capture, calibration and aperture photometry.

We determined 1 primary and 2 secondary times of minimum (see Table 3) via polynomial fitting available in the PERANSO\textsuperscript{TM} package (Paunzen & Vanmuster 2016). The results of applying WinFitter to this standard BVR photometry are shown in Fig 4, and key parameters tabulated in Table 1 together with the earlier fitting results. The relatively long time baseline HJD 2448500.3377 to 2458548.0423 permitted an improved estimate of the mean period as \( P = 0.8761514 \) d. This shorter period reduced some of the apparent scatter in the data phasing.

A key result coming from the new photometry and the modelling results presented in Table 1 is that the proportion of background light increases significantly with increasing wavelength. Fainter optical sources within the ABC system’s separation are visible in the SDSS imaging (Blanton et al. 2017). These may be cooler stars adding light into the 21-arcsec wide pixels of the TESS CCDs. To pursue this, Gaia’s eDR3 database was checked, covering the sky around V410 Pup within a 1 arcminute radius. Although over 200 sources were thus located, they are, by far, stars with \( V \) mag fainter than 15. The only listed stars brighter than 13th magnitude are the AB and C components of V410 Pup. We thus rule out field stars, and look only within the multiple star itself for the source of increasing brightness at longer wavelength. Given the relative faintness of star C (Table 2), this extra light can be reasonably associated with star B (cf. Table 4).

Component Aa is clearly a blue star, attaining a typical
mid-B type colour when interstellar reddening is taken into account. Using the procedure of Cardelli et al. (1989), with the adopted distance (see Section 1.2), implies we subtract 0.09 from the B – V value of −0.18 deduced from Table 4.

Component Ab appears to have the zero colour appropriate to an A0 type spectrum, although its relative luminosity in comparison to Aa is high for both to be typical Main Sequence stars. Component B looks to have colours corresponding to a temperature of $\sim 7500$ K, but it is also too bright to be a Main Sequence star. It also displays increasing luminosity towards longer wavelengths.

Figure 3 (on page 4) shows a thick band of residuals in the phased TESS high cadence lightcurve data, with a greater amplitude than should be expected from the precision of TESS data. After fitting the eclipsing model we converted the phased residuals of the lightcurve back to an absolute time series. The resulting residual plot appeared to show regular variation over timeframes of a few hours (Figure 5). We used period04 software (Lenz & Breger 2004) to pre-whiten the frequency plot for harmonics of the orbital frequency. (Figure 6). The period here is noticeably shorter than the HIPPARCOS value given at the beginning of this section.

From the top diagram in Fig 7 it is seen that the (O – C) behaviour has some additional systematic variation. A second-order polynomial model was then least-squares fitted to this variation. The corresponding model is shown in the middle diagram of Figure 7, corresponding to the equation:

$$T_{\text{min}}(\text{HJD}) = 2448500.3334(10) + (0.8761577(3) \times E) - (4.90(26) \times 10^{-10} \times E^2)$$

The quadratic term reveals that the orbital period of V410

Table 4. BVR Magnitudes of V410 Pup Aa, Ab and B.

| Source | B | V | R | Error |
|--------|---|---|---|-------|
| Aa     | 7.48 | 7.66 | 7.83 | 0.02 |
| Ab     | 8.35 | 8.41 | 8.40 | 0.04 |
| B      | 8.00 | 7.80 | 7.65 | 0.03 |

Figure 5. Pulsations observed in the residual light curve of V410 Puppis once the modelled eclipsing binary light curve has been removed.

Figure 6. Frequency plot of pulsations after removal of harmonics of the orbital frequency.

2.1 Orbital Period

The possibility of a semi-detached configuration for V410 Pup motivated checking the times of minimum light (ToMs), leading to a comparison of these observed ToMs with those calculated from an adopted linear ephemeris (i.e., observed minus calculated, abbreviated as O – Cs). Although the system is relatively bright, no ToMs have been published in the literature. Relevant photometric data are found in the HIPPARCOS, ASAS-3 (see Pojmanski 2002 for background), OMC (Alfonso-Garzón et al. 2012), and TESS data-bases. ToMs can be calculated directly from the TESS photometry, but observations in the other data-bases usually contain only one or two points on a given night. We therefore employed a method similar to that of Zasche et al. (2014) to derive appropriate ToMs. This led to four times of minima from HIPPARCOS, 7 from ASAS-3, 3 from OMC, and 5 from TESS being obtained in addition to the three reported above. Many more individual ToMs could have been taken from the full range of TESS data, but it is sufficient here to determine only representative minima given the short duration of a TESS sector.

Using the light elements from HIPPARCOS and these 22 ToMs, (O – C)s were calculated and plotted against the (orbital) cycle number (cf. the top diagram of Figure 7). The diagram shows the result from optimizing a linear model to derive a representative mean ephemeris. The linear model for all the (O – C)s is shown with a solid line, which can be compared with the best-fit linear model for only the TESS ToMs (dashed line). The following equation was derived:

$$T_{\text{min}}(\text{HJD}) = 2448500.3377(30) + 0.8761516(3) \times E$$

The period here is noticeably shorter than the HIPPARCOS value given at the beginning of this section.
Figure 7. O–C trend using historical data and the TESS 35 ToMs discussed in section 2.1. Top panel: Linear fit. Middle panel: quadratic fit. Bottom panel: quadratic residuals.

Pup is decreasing at the relatively large rate of $0.035 \pm 0.002$ s/year over the last $\sim 30$ years, implying significant loss of orbital angular momentum. This may result from various mechanisms. A close binary context, such as for this system, suggests interactive evolution. Alternatively, given the primary’s early spectral type, hot stellar winds may remove angular momentum from the system. A classical Algol configuration, hinted at in the beginning of this subsection, would be more often expected to show period lengthening, i.e., an upturned parabola in the O–C diagram, opposite to that of Fig 7, though that is not always the case (cf. Chapter 8 of Budding & Demircan 2007).

3 SPECTROSCOPY

The High Efficiency and Resolution Canterbury University Large Échelle Spectrograph (HERCULES, Hearnshaw et al. 2002) provided our spectroscopic data. HERCULES was used with the 1m McLellan telescope at the University of Canterbury Mt. John Observatory (UCMJO) near Lake Tekapo ($\sim 43^\circ59^\prime$ S, $174^\circ27^\prime$ E). Images were collected with a 4k×4k Spectral Instruments (SITe) camera. Starlight was passed from the telescope to the spectrograph through a 100 µ fibre equipped with a microlens at the fibre entrance, that produces an entrance pupil of effectively 4.5 arcsec diameter. This is suited to typical seeing conditions at Mt. John. An instrumental resolution of $\sim 40000$ is generally attained. The normal procedure for wavelength and relative flux calibration was followed (cf. Blackford et al., 2019). Exposure times were usually about 500 seconds in mostly clear weather.

3.1 Spectrum measurements

33 spectra of V410 Pup were selected from spectral images taken over the years 2011-15 and early 2020. A recent version of the software package HRSP (Skuljan 2020) was used to produce wavelength calibrated and normalized output in FITS formatted files. About 40 useful spectral orders in the image plane were examined, covering the region of 450 to 700 nm. The spectra are mostly without strong features, apart from highly broadened lines of H$_\alpha$ and H$_\beta$, with the former affected by telluric intrusions. Spectra were inspected using VSPEC (Desnoux 2011). Broad and shallow He I lines are typically observed for this type of hot close binary system. In the present instance the additional light of V410 Pup B, as well as the late B classification (Houk 1978), rendered the primary poorly measurable and we were not able to identify secondary helium lines with any confidence. Tentatively identified features are listed in Table 5. The He I lines had sufficient definition to enable velocity estimation through the Doppler-shift principle, though the blend at $\lambda 4922$ Å introduces complications, causing us to neglect this feature in these direct radial velocity (RV) determinations.

If the resolution is sufficiently high, spectral line profiles can be modelled with a parameter set that determines the radial velocity of the centre of light, as well as the source’s bodily rotation and the scale of turbulence in the surrounding plasma. Such modeling has been carried out at least since the work of Shajn & Struve (1929); for a review, see Collins (2004). Shajn & Struve’s model involved the convolution of rotational and Gaussian broadening functions. Such a fitting function was used within the optimization program PROF, introduced in Oláh et al. (1992) (see also Budding & Zeilik, 1994). Application of PROF to the He I $\lambda 6678$ and $\lambda 5876$ features resulted in the RV values listed in Table 6.

The last entry in Table 6 refers to an exposure of V410 Pup C — the outer member of the system. We deduced from the photometry that this star would not show any helium lines.

Table 5. Identified spectral lines for V410 Pup based on comparison with synthetic spectra from Gummersbach & Kaufer (1996). Only primary (Aa) lines are confidently detected except for the H lines, whose varying widths and asymmetries evidence the secondary (Ab) contribution.

| Species | Order no. | Adopted $\lambda$ | Comment |
|---------|-----------|-------------------|---------|
| He I    | 85        | 6678.1            | measurable Aa |
| H$_\alpha$ | 87      | 6562.8            | strong, blended Aa & Ab |
| Fe II   | 89        | 6376.0            | very weak |
| Si II   | 90        | 6347.8            | broad & shallow blend |
| He I    | 97        | 5875.7            | measurable Aa |
| Fe II   | 110       | 5169.0            | very weak |
| Si II   | 112       | 5056.0            | weak blend |
| He I/Si II | 115  | 4921.9            | detectable Aa |
| H$_\beta$ | 117     | 4861.3            | strong, blended Aa & Ab |
| Fe II   | 124       | 4583.8            | very weak |
| Fe II   | 125       | 4549.5            | weak blend |

Table 6. RV determinations for He I and H lines of V410 Pup B.

| Species | Order no. | Adopted $\lambda$ | Comment |
|---------|-----------|-------------------|---------|
| He I    | 85        | 6678.1            | measurable Aa |
| H$_\alpha$ | 87      | 6562.8            | strong, blended Aa & Ab |
| Fe II   | 89        | 6376.0            | very weak |
| Si II   | 90        | 6347.8            | broad & shallow blend |
| He I    | 97        | 5875.7            | measurable Aa |
| Fe II   | 110       | 5169.0            | very weak |
| Si II   | 112       | 5056.0            | weak blend |
| He I/Si II | 115  | 4921.9            | detectable Aa |
| H$_\beta$ | 117     | 4861.3            | strong, blended Aa & Ab |
| Fe II   | 124       | 4583.8            | very weak |
| Fe II   | 125       | 4549.5            | weak blend |
Table 6. Radial velocity data of the primary component from the He I lines. Phase was calculated using equation 1.

| BJD 2450000+ | Orbital phase | RV1 km s$^{-1}$ | σ km s$^{-1}$ | EW |
|--------------|--------------|----------------|--------------|----|
| 5879.9288   | 0.733        | 165            | 15           | 0.131 |
| 5880.1346   | 0.968        | 83             | 10           | 0.120 |
| 5880.8750   | 0.813        | 163            | 20           | 0.196 |
| 5880.9035   | 0.846        | 155            | 20           | 0.131 |
| 5883.0634   | 0.311        | −73            | 10           | 0.127 |
| 5883.0845   | 0.335        | −65            | 8            | 0.127 |
| 5883.1259   | 0.382        | −40            | 8            | 0.118 |
| 6257.8766   | 0.106        | −36            | 8            | 0.161 |
| 6257.9458   | 0.185        | −78            | 10           | 0.131 |
| 6259.0672   | 0.465        | −10            | 5            | 0.121 |
| 6259.1049   | 0.508        | 24             | 5            | 0.123 |
| 6667.0650   | 0.135        | −57            | 8            | 0.117 |
| 6669.9055   | 0.377        | −51            | 8            | 0.153 |
| 6669.9385   | 0.415        | −36            | 6            | 0.128 |
| 6670.8979   | 0.510        | 25             | 5            | 0.021 |
| 6671.8944   | 0.647        | 110            | 15           | 0.087 |
| 6673.9285   | 0.969        | 76             | 8            | 0.077 |
| 6994.1309   | 0.230        | −24            | 5            | 0.098 |
| 6998.9403   | 0.927        | 110            | 10           | 0.074 |
| 7006.0139   | 0.996        | 65             | 18           | 0.022 |
| 7351.1053   | 0.869        | 135            | 20           | 0.077 |
| 7352.0590   | 0.957        | 79             | 7            | 0.078 |
| 7355.0689   | 0.393        | −42            | 5            | 0.088 |
| 7356.0614   | 0.525        | 41             | 6            | 0.071 |
| 7357.1201   | 0.737        | 153            | 15           | 0.096 |
| 7358.0074   | 0.746        | 155            | 15           | 0.093 |
| 7359.9993   | 0.920        | 21             | 5            | 0.108 |
| 7369.9513   | 0.106        | −25            | 10           | 0.141 |
| 8887.9102   | 0.909        | 87             | 15           | 0.096 |
| 8887.9225   | 0.927        | 74             | 6            | 0.093 |
| 8887.9729   | 0.981        | 62             | 8            | 0.091 |
| 8887.9831   | 0.992        | 42             | 8            | 0.073 |
| 8890.9390 (C) | —            | 29             | 2            | —    |

Figure 8. HERCULES order 87 showing the H$\alpha$ line of V410 Pup C with an emission core.

Figure 9. He I $\lambda$6678 equivalent width measures plotted against orbital phase.

and indeed the spectrum seems mostly featureless against a relatively noisy continuum. While the target is a faint (for the observational setup of this paper) magnitude 9.5 (Table 2), some comments can be made from the observation. Low and narrow levels of H line emission can be seen, and to a greater extent in H$\alpha$. An RV of $\sim 29 \pm 2$ km s$^{-1}$ was measured for the well-defined H$\alpha$ emission peak (Figure 8).

PROF estimates the equivalent width of a line by numerical integration. The results are given in Table 6. The mean value of the measured estimated widths (EWs) for the 32 inner system data-sets in Table 6 is 0.105 $\pm$ 0.006. With a representative value of $L_{AB} = 0.4$ deduced from Table 1 for the relevant spectral region, 0.26 $\pm$ 0.1 is an appropriate value of the primary’s $\lambda$ 6678 EW. There is a small but distinct asymmetry in the distribution of the EWs, in that the primary-approach phases (excluding the outlier at phase 0.8 and a small number of points close to the central eclipses) show a mean EW of 0.125, while those in recession average at 0.094. The standard deviation of the complete sample is 0.036, so the probable error of the two half-range means works out at about 0.010. The difference in the two means is around 3 times this value, so the ‘Struve-Sahade effect’ is confirmed in these observations as a $\sim$3-sigma event.

From comparison with the calibration data of Leone & Lanzzafre (1998), we estimate the primary’s temperature to be 13000 $\pm$ 2000 K. This corresponds to a B5 spectral type: i.e., a hotter and more massive MS star than would correspond with the Michigan Spectral Survey assignation (Houk 1978). The latter would have been affected by the significant light contributions from the other stars (Ab and B).

If the stellar rotations (of Aa and Ab) are synchronized to the orbit, as would be expected for this relatively very close pair (Zahn 1977), projected equatorial speeds would be of order 120 km s$^{-1}$ for the primary and 85 km s$^{-1}$ for the secondary, i.e., rotational half-widths of around 2 A at $\lambda$ 6678. Generally, the best defined non-hydrogenic stellar absorption feature in our spectra is the He I line at $\lambda$ 6679.996 ($in \text{ vacuo}$).

In Table 7 we present output parameters averaged from PROF fittings to 6 well defined examples. EWs are shown by orbital phase in Figure 9, while Figure 10 shows an example of such a fitting.

In Table 7, the reference ordinates $I_c$ and $I_d$ correspond to the mean level of the local continuum and central line.
Table 7. Main profile fitting parameters for the λ6678 He I (primary) absorption line (see text)

| Parameter | Value        |
|-----------|--------------|
| $I_c$     | 0.998 ± 0.001 |
| $I_d$     | −0.021 ± 0.005 |
| $r$       | 2.76 ± 0.42   |
| $s$       | 0.56 ± 0.20   |
| $\chi^2/\nu$ | 1.08       |
| $\Delta t$ | 0.005       |

The well-known form of the mass-function $f(M)$ for a binary system can be written as (Ludendorff 1911):

$$f(M) = C(1 - c^2)^{3/2}K_1^2P = M_1 q^3 \sin^2 i / (1 + q)^2,$$  

with symbols having their usual meanings and where $C$ is a constant ≈ 1.0361 × 10⁻⁷ for $K_1$ in km s⁻¹ and $P$ in days.

For example, if V410 Pup were a semi-detached system with $q \approx 0.5$ and the primary a Main Sequence-like star of mass ≈ 3 M⊙, we would have $f \approx 0.138$. $K_1$ would then be ≈ 115 km s⁻¹. The model of an unevolved, near equal mass pair would however require a much higher value of $K_1$ ≈ 190 km s⁻¹.

This point bears strongly on our understanding of the implications of the radial velocity data. Although the value of $f(M)$ listed in Table 8 is a little greater than the foregoing
Table 9. Orbital parameters deduced from korel disentanglement

| Parameter      | Value     | Formal error |
|----------------|-----------|--------------|
| $T_0$          | 2456256.9190 | 0.0001       |
| $K_{Aa} \sin i$ (km s$^{-1}$) | 133.9 | 0.4 |
| $K_{Ab} \sin i$ (km s$^{-1}$) | 230.4 | 0.8 |
| $a \sin i$ R$_\odot$ | 6.30 | 0.05 |
| $q$            | 0.581     | 0.002        |

3.3 Disentangling the spectra

To separate the blended spectral lines of the Aa and Ab components and to uncover information on the secondary RVs, we applied the code korel for Fourier disentangling (Hadrava 1995). Because the light of component B enters the spectrograph together with that of Aa and Ab, it is required to disentangle the three components in a hierarchical structure. The spectroscopic observations cover only a small part of the orbit of component B around the inner binary A and the amplitude of its RV variation is small. Consequently, there is no real chance to find in the currently available spectra either changes in RVs of the centre of mass of sub-system A and component B, or a corresponding light-time effect. We can thus treat component B as static by selecting the priors: (i) low amplitude of third star RVs, (ii) mass ratio of order unity and (iii) long orbital period.

Because of the variation in flux due to the eclipses of the subsystem A, it is advantageous to disentangle all three components with free line-strength factors (Hadrava 1997). In addition, the flux ratio of the components A and B can change between different exposures depending on the telescope orientation (on the sky) and weather conditions. This is because the angular distance between these components is not completely negligible compared to the entrance pupil of the spectrograph. This variation, however, should be small owing to the typical size of seeing, which is larger than the current separation of the components close to the periastron. Regarding the short orbital period of the inner pair Aa and Ab, which is well established from the photometry, we can safely assume the inner orbit to be circular and solve for three orbital parameters – (1) the time $T_0$ of primary eclipse, (2) RV amplitude $K_{Aa}$ of the primary, and (3) the mass ratio $q = M_{Ab}/M_{Aa}$.

For the disentangling we used 30 exposures in the spectral region 4831 – 4891 Å around the H$\beta$ line. This region was sampled in 4096 bins with a step size corresponding to RV ~0.9 km/s. The separated line-profiles of all three components are displayed in green lines in the lower part of Fig. 12. The observed spectra are shown by blue lines in the upper part of the figure. They are overplotted in red by their reconstruction from the superposition of the separated spectra, which are Doppler-shifted and amplified appropriately for each exposure. The residual noise is ~0.01 of the normalized continuum level. Component B contains several narrow features which seem to be of an instrumental origin and hence are imprinted to the component with small Doppler shifts. The line-strength factors of components Aa and B are anti-correlated with a correlation coefficient ~0.84, corresponding to the varying flux ratio of these components. This trend is hardly noticeable for the component Ab, given the relatively large uncertainties of its line-strength factors, due to the inherent shallowness of its line-profile.

The values of disentangled parameters with their Bayesian errors (Hadrava 2016) are given in Table 9. These errors indicate how the fit for each model parameter can be influenced by photon noise. They are thus termed formal errors. Usually they are smaller for high S/N spectra than differences between parameter values obtained from different lines. Low formal errors arise because the model only takes into account the Keplerian Doppler shift and the line-profile changes in the line-strength factors. It neglects other effects, such as the tidal distortion, reflection, the influence of circumstellar matter or other such complications. In this way, line profile constructions need not follow precisely the motion of the stellar centres of mass.

The radial velocities obtained in korel by fitting each exposure independently as a superposition of the disentangled profiles have the following root mean square errors (i.e., deviations from the RVs given by the disentangled orbital parameters) of 0.2 km/s for the primary (Aa), 1.0 km/s for the secondary (Ab), and 0.4 km/s for the component B. The relatively large error for the component Ab is due to its shallow profile. The deviations are particularly high in certain exposures, where this component has a very small s-factor. The korel RV determinations of the components of V410 Pup A are given in Table 10 and are shown in Fig. 13.

The disentangled H$\beta$ profile of component B is of evidently
Table 10. KOREL RV determinations of the components of V410 Pup. BJD is the Barycentric Julian Date of the observations. The stellar component is indicated by the subscript, Aa for the primary and Ab for the secondary. The \((O-C)\) columns refer to differences between the observed versus the theoretical model, as shown in Figure 13.

| BJD      | \(RV_{\text{Aa}}\) (km/s) | \((O-C)_{\text{Aa}}\) (km/s) | \(RV_{\text{Ab}}\) (km/s) | \((O-C)_{\text{Ab}}\) (km/s) |
|----------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| (-2400000) |                              |                              |                              |                              |
| 55879.9288 | 131.77                      | 0.08                         | -226.58                     | -0.10                       |
| 55880.1346 | 36.96                       | 0.09                         | -63.45                      | -0.08                       |
| 55880.8750 | 127.15                      | -0.07                        | -218.56                     | 0.20                        |
| 55880.9055 | 116.05                      | 0.00                         | -199.59                     | -0.02                       |
| 55883.0634 | -127.75                     | 0.02                         | 219.70                      | -0.09                       |
| 55883.0845 | -120.20                     | 0.07                         | 207.45                      | 0.58                        |
| 55883.1259 | -97.68                      | 0.08                         | 168.70                      | 0.54                        |
| 56257.8766 | -74.10                      | 0.02                         | 132.57                      | 5.08                        |
| 56257.9458 | -118.35                     | -0.06                        | 203.23                      | -0.25                       |
| 56259.0672 | -39.47                      | 0.12                         | 68.21                       | 0.09                        |
| 56259.1049 | -3.81                       | 0.17                         | 6.62                        | -0.24                       |
| 56667.0650 | -93.21                      | 0.01                         | 160.34                      | -0.03                       |
| 56669.9055 | -100.83                     | -0.13                        | 173.23                      | -0.01                       |
| 56669.9385 | -77.66                      | -0.47                        | 132.75                      | -0.05                       |
| 56670.8979 | -2.26                       | 0.05                         | 5.00                        | 0.99                        |
| 56671.8944 | 100.17                      | -0.09                        | -172.41                     | 0.00                        |
| 56672.9285 | 36.45                       | 0.06                         | -62.54                      | 0.01                        |
| 57351.1053 | 104.93                      | -0.75                        | -181.68                     | 0.05                        |
| 57352.0590 | 46.34                       | 0.03                         | -79.65                      | -0.03                       |
| 57355.0698 | -91.85                      | -0.31                        | 157.28                      | -0.20                       |
| 57356.0614 | 9.84                        | -0.25                        | -17.25                      | 0.07                        |
| 57357.1201 | 131.43                      | -0.20                        | -227.05                     | -0.68                       |
| 57358.0074 | 132.75                      | -0.44                        | -228.77                     | 0.28                        |
| 57359.9993 | -5.82                       | -0.34                        | 9.60                        | 0.14                        |
| 57360.9513 | -74.11                      | -0.17                        | 127.20                      | -0.01                       |
| 58887.9102 | 82.18                       | 0.18                         | -141.83                     | 0.28                        |
| 58887.9225 | 72.42                       | 0.07                         | -124.46                     | -0.08                       |
| 58887.9729 | 27.79                       | -0.03                        | -47.91                      | -0.12                       |
| 58887.9831 | 18.19                       | 0.03                         | -32.71                      | -1.52                       |
| 58890.9390 | -107.14                     | 0.15                         | 184.64                      | 0.05                        |

The order of tens of mas. Outcomes include orbit sizes, nodal angles and inclinations, as well as, from Kepler’s laws, masses of the stars.

The *Washington Double Star Catalogue* (Mason et al. 2010) lists 19 position angle \((\theta)\) and separation \((\rho)\) measures for the V410 Pup AB system \((AB = I 1070, Innes 1899)\), as well as 14 measures of the AB-C system \((HJ 4032, Herschel 1836)\). The source also appears in the cross-calibration of Hipparcos and Gaia EDR3 by Brandt (2021).

These measures can be referred to standard formulae for the co-ordinates of the relative orbit (Ribas et al. 2002):

\[
X = \frac{a(1 - e^2)}{1 + e \cos \nu} \left\{ \cos(\nu + \omega) \sin \Omega + \sin(\nu + \omega) \cos \Omega \cos i \right\},
\]

and

\[
Y = \frac{a(1 - e^2)}{1 + e \cos \nu} \left\{ \cos(\nu + \omega) \cos \Omega - \sin(\nu + \omega) \sin \Omega \cos i \right\}.
\]

The equations are related to the differential positional measurements \(\rho\) and \(\theta\), since \(\rho = \sqrt{X^2 + Y^2}\) and \(\tan \theta = X/Y\); so that the measures are directly related to the 5 orbital parameters \(a, e, \omega, i, \text{ and } \Omega\). To fix the configuration at a given time, we also need the period \(P\) and the epoch of periastron passage \(T_0\), a provisional value for \(T_0\) for component B can be estimated from the shape of the apparent orbit, which appears to currently be close to periastron.

Optimization is a practical method to estimate the parameter values in which, by using an appropriate search algorithm, an orbital ellipse based on the parameter estimates is progressively matched to the data so as to minimize residuals (see Chapter 5 of Budding & Demircan 2007 and Rhodes & Budding 2022). The procedure involves the seven aforementioned parameters. Formally, we can write for the solution of the inverse problem:

\[
a_{\text{opt}} = \left[ \chi^2 \right]^{-1} \text{Min} [\chi^2(a)],
\]

where \(a_{\text{opt}}\) is the vector of best estimates of each parameter in the adjustable set \(\{a_1, a_2, a_3, ..., a_m\}\). The quantity \(\chi^2\) depends on the squared differences of observed and calculated quantities, and the optimal estimate for each \(a_j\) is taken to occur when \(\chi^2\) is minimized. \(\left[ \chi^2 \right]^{-1}\) expresses functionally the inverse nature of the operation.

The adopted result for V410 Puppis B is shown in Figure 14, and the corresponding parameters listed in Table 11.
The radial velocity of star B relative to A, according to the orbit model of Figure 13, corresponds at the observed phase of about 0.9 to about 12.0 km s$^{-1}$ in approach (using formula 9.8 in Budding & Demircan 2007). The spectroscopic mean RV of $36 \pm 2$ km s$^{-1}$ for the close binary (Table 8) is then an acceptable $\sim 6$ km s$^{-1}$ greater than the mean velocity (+30 km s$^{-1}$) of the AB system.

In addition to observations of V410 Pup AB, Mason et al. (2010) also provided observations for HJ 4032 (star C in the AB-C system). These trace out an almost linear short trend when plotted; implying that this limited coverage of C’s orbit could not be used to establish a full set of orbital parameters. The data cover only about 180 years of a period that could well be in the order of five thousand years.

### 5 Absolute Parameters

The well-known ‘eclipse method’ combines photometric and spectroscopic findings, together with the use of Kepler’s third law, or other available relationships, to derive basic physical parameters of the component stars. Taking the orbital inclination from the WD+MC solution in Table 1, the average distance between components from the RV solution in Fig. 13, and the calculated period all in an application of Kepler’s third law, then the combined mass of the close components (Aab) is found to be $4.97 \pm 0.18$ M$_\odot$. The masses of the individual components are then calculated from the spectral mass-ratio ($q = 0.58$).

Using the known separation $a$ of the close binary stars, the fractional radii of components ($r_A$, $r_B$) obtained from WD+MC solution in Table 1 lead to the absolute radii ($R_A$, $R_B$). Surface gravities ($g_A$, $g_B$) are then directly derived. Determination of the bolometric magnitudes ($M_{bol}$) and luminosities ($L$) of the component stars requires the effective temperatures that were determined from the colours in Table 12.

### Table 12. Absolute parameters of V410 Pup (solar units).

| Parameter | Value | Uncertainty |
|-----------|-------|-------------|
| $M_A$     | 3.15  | 0.10        |
| $M_B$     | 1.83  | 0.08        |
| $M_C$     | 3.02  | 0.20        |
| $a_{Aab}$ | 6.57  | 0.04        |
| $R_A$     | 2.12  | 0.10        |
| $R_B$     | 1.52  | 0.08        |
| $R_C$     | 3.62  | 0.20        |
| $T_A$ (K) | 12500 | 1000        |
| $T_B$ (K) | 9070  | 800         |
| $T_C$ (K) | 7500  | 1000        |
| $\log L_A$| 2.00  | 0.17        |
| $\log L_B$| 1.15  | 0.15        |
| $\log L_C$| 1.57  | 0.18        |
| $M_{bol A}$| -0.23 | 0.43       |
| $M_{bol B}$| 1.88  | 0.48        |
| $M_{bol C}$| 0.82  | 0.45        |
| $M_{V A}$ | 0.63  | 0.43        |
| $M_{V B}$ | 2.00  | 0.48        |
| $M_{V C}$ | 0.82  | 0.20        |
| $\log g_A$| 4.28  | 0.05        |
| $\log g_B$| 4.34  | 0.06        |
| $\log g_C$| 3.96  | 0.40        |

Together with indicative error estimates. With only a third of the orbit completed and, understandably low precision of the early data, the determinacy of the model is not high. The results of Table 11 may therefore be regarded as provisional. This concerns the correlation between parameters (important for the purpose of finding masses) inclination $i$ and eccentricity $e$. A higher $i$ to a wide orbit, for a given apparent eccentricity, entails a lower true value of $e$; so the greater travel implied in the fixed period requires higher total mass. The derived masses thus have relatively large uncertainties, but a moderately low $i$ produces masses in keeping with those of the system components found in the preceding sections.

The semi-major axis, at the Gaia distance of 346 pc, produces a mean physical separation of $\sim 110$ AU for V410 Pup AB. Kepler’s law then yields $\sim 8$ M$_\odot$ for the total mass of the system. The photometric + spectroscopic solutions suggested masses of 3.15 and 1.83 M$_\odot$ for the close binary (A), so the total mass of the A-B system is in agreement with this if the third star is a $\sim 3.02$ M$_\odot$ object. A larger distance to the system (see below) would increase the mass of V410 Pup B.
able 2. In these calculations, the solar calibration values are adopted as: effective temperature $T_{\text{e}} = 5772$ K, $M_{\text{bol}} = 4.755$ mag, $BC = -0.107$ mag and $g_0 = 27423$ cm/s$^2$, following the listings of Pecaut & Mamajek (2013), with the bolometric corrections (BC) for the components taken from the tabulation of Flower (1996) according to the assigned effective temperatures. Our derived absolute parameters for the V410 Pup system are listed, with their uncertainties, in Table 12 (on page 11).

The anomalously low value of $T_{\text{e}}$ is clearly at variance with its mass, if star B had a MS character. This finding may be associated with the putative disk, given the korel results shown in Fig 12, and the colours of Table 4.

Fig 15 plots evolutionary tracks as derived from Padova modelling (Bressan et al. 2012, Pastorelli et al. 2020), together with the WD + MC findings in Table 1 and the korel results in Table 9 (p. 9). The WD + MC fitting gives a lower ratio of radii than the optimal Winfit\textsuperscript{2} fit to the Sector 35 TESS data, while the korel analysis indicates a somewhat higher mass ratio than was apparent from the mass function and $q$-search methods. These two results together allow marginal conformity of Aa and Ab to near-ZAMS positions. Star Ab appears significantly hotter and more luminous for its derived mass, suggesting a still condensing structure.

6 CONCLUSIONS

In this paper we have combined new spectrometric and Earth-based BVR observations together with satellite photometry (particularly TESS data) and modern data-processing techniques to produce credible absolute parameters of the close binary V410 Pup Aa-Ab. We included astrometric data analysis that reveals properties of the third major component V410 Pup B.

We have discovered a pulsation behaviour consistent with a slowly pulsating B-type (SPB) star. We associate this with the Aa (spectral-type B5) component. The magnitude and colour found for star B correspond to an object distinctly more cool and less massive than Aa, but we argue that B is affected by an accretion structure evidenced by its line profile and redward luminosity excess. We deduce from the relative brightness and colour of V410 Pup C that it is an A2e type Main Sequence dwarf with a mass around 2 $M_\odot$.

The system has sky-location, distance, and proper motion values ($\mu_\alpha \cos \delta = -5.716 \pm 0.353$ and $\mu_\delta = 9.134 \pm 0.379$ mas yr$^{-1}$; Gaia Collaboration 2021) consistent with membership of the Vela OB2 association, particularly with the ‘outer ring’ of the condensation around $\gamma$ Vel (Jeffries et al. 2009).

That the system may prove useful for the interpretation of the pulsation data and support for this programme has been shown by the School of Chemical & Physical Sciences of the Victoria

Figure 15. Location of the components (Aa and Ab) of V410 Pup in the HR diagram. The Padova evolutionary tracks (Bressan et al. 2012) for 3.15 $M_\odot$ and 1.83 $M_\odot$ main sequence stars are plotted for $Z = 0.017$. The Padova isochrone line of 25 Myr is indicated by the dotted line in the diagram.

The current physical status of stars B and C can also be fitted into this stellar youth scenario. The third spectrum produced in the korel disentangling is understood to result from emission filling in the H$_\beta$ line above a rapidly rotating condensation. The emission arises from circumstellar material, plausibly in the form of a protoplanetary disk. Component B is thus deduced to be a relatively young T Tau-like star, or perhaps an Ae type Herbig object (Appenzeller & Mundt 1989; Pérez & Grady 1997). Star C similarly shows hydrogen line emission, but with a lower degree of filling of the underlying absorption line.

The combined evidence on V 410 Pup thus favours a young age, most probably in the range 7 - 25 Myr, though circumstellar factors including the SPB variation and accretion structures associated with anomalous colours and line profiles compromise precise parametrization. Further and more detailed data-collection and modelling for the whole system is called for to elucidate this intriguing multiple star.

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DATA AVAILABILITY

The majority of data included in this article are available as listed in the paper or from the online supplementary material it refers to. The first exception is the BVR photometric data which will be shared on reasonable request to the corresponding author. The second exception is the spectroscopic imagery. We are currently working to store the unprocessed imagery associated with the Southern Binaries Project (of which V410 Puppis is part), and will be pleased to share details with requestors when that work is complete. The HIPPARCOS and TESS data are available online from the MAST and ESA repositories.

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