Observational studies of early-type binary stars: VV Orionis

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ABSTRACT

New and previously published observations of the bright eclipsing binary VV Orionis are analyzed. We present new radial velocities and interstellar reddening measurements from high-resolution spectra of this detached, short-period (P=1.48 d) binary. We discuss the validity of prior claims for the existence of a third body and show that our new velocities and light curve solution cast doubt on them. The components of VV Ori are shown to be a B1 V primary with a mass $M_1 = 10.9 \pm 0.1 \, M_\odot$ and a radius $R_1 = 4.98 \pm 0.02 \, R_\odot$ and a B4.5 V secondary with a mass $M_2 = 4.09 \pm 0.05 \, M_\odot$ and a radius $R_2 = 2.41 \pm 0.01 \, R_\odot$.

Key words: binaries: eclipsing – binaries: spectroscopic

1 INTRODUCTION

VV Orionis (HD 36695) is a bright ($V=5.4$), double-lined eclipsing binary consisting of main sequence B-type stars in a detached configuration. The inclination is high enough to produce complete eclipses, enabling the very accurate determination of fundamental parameters of the system. Since the discovery of its photometric variability over a century ago, the system has been the subject of several spectroscopic and photometric studies as discussed by Sarma & VivekanandaRad (1995). Unfortunately, the derived absolute parameters in these previous studies vary considerably and this led us to obtain additional spectroscopic and photometric data on the system as part of our program on early-type binaries (viz. Terrell, et al. (2003), Terrell, et al. (2005)).

Dating back to the first comprehensive spectroscopic study by Daniel (1915), spectroscopic investigators, including Struve & Luyten (1949), Beltrami & Galeotti (1969), Duerbeck (1975) and Popper (1993), have concluded that a third star orbits the eclipsing pair. The evidence for claims of this third body rests solely on higher than expected residuals in fits to the radial velocities of the primary as the third body’s lines are not seen in the system’s spectrum. Daniel (1915) offered the third body hypothesis "with great reserve" and Struve & Luyten (1949) pointed out that the observed variation in the systemic velocity did not necessarily imply that the system was a triple. Duerbeck (1975) analyzed his radial velocities along with those of Daniel (1915), Struve & Luyten (1949) and Beltrami & Galeotti (1969) to arrive at orbital parameters for a third body orbiting with a period of about 119 days. A goal of the current study was to investigate this third body hypothesis.

2 OBSERVATIONS

2.1 Photometry

VV Ori was observed with a 0.25m Schmidt-Cassegrain telescope, Santa Barbara Instrument Group ST-7XE CCD camera and standard $BVIC$ filters. The main goal of the new photometric observations was to cover at least one primary eclipse for the purpose of extending the baseline of eclipse timings so that any small changes in the period could be detected. Given the extensive photometric datasets previously published, we did not attempt to observe complete light curves for the system.

The CCD images were reduced using IRAF. Bias and dark frame subtraction and flatfielding were done in the usual way. PyRAF scripts automated the frame calibrations and aperture photometry which was performed using the IRAF DAOFFIND and PHOT routines. The comparison star for the differential photometry was HD 36779.
2.2 Spectroscopy

High resolution, high signal-to-noise spectra of VV Ori were obtained with the Echelle+CCD spectrograph of the 1.82m telescope operated in Asiago by the INAF Astronomical Observatory of Padova. The CCD is an E2V thinned, back illuminated 1K chip of 13.5 µm pixel size. The slit was always aligned with the parallactic angle and its projected width was 1.5 arcsec. The spectra cover the range from atmospheric cut-off around 3250Å to 7100Å at a resolving power 30,000. The accuracy of the zero point of the wavelength scale is derived on each observed spectrum by cross-correlation against a synthetic template of the rich telluric absorption spectrum at wavelengths 6860-7050Å. 6270-6310Å, 5880-5950Å and found to be affected by no systematic shift larger than 0.2 km sec$^{-1}$, consistent with the high efficiency of the instrument in deriving accurate radial velocities evaluated by Munari & Lattanzi (1992). The exposure times for the spectra were 5 minutes (0.002 in orbital phase), eliminating any concerns about phase smearing effects on the radial velocities. In all, 31 spectra were obtained over the period from November, 2004 to February, 2006.

Figure 1 shows the appearance of the He$^i$ 5876 Å line in the spectrum of VV Ori. The line components originating from the primary and secondary star are labeled “p” and “s”, respectively, and $\theta$ is the orbital phase. The interstellar sodium doublet and the telluric absorption lines longward of 5885 Å are also marked.

Figure 2. The interstellar line of Na$^i$ D2 with the two-component Gaussian fit used in the reddening determination. The thick line is the observed profile and the thin line shows the two-component fit. The dashed lines show the individual components of the fit.

2.2.1 Reddening

The Na$^i$ lines have two interstellar components with radial velocities of $+9.3\pm0.2$ and $+26.1\pm0.1$ km sec$^{-1}$. The FWHM of both components is 14.4 km/sec, which is dominated by the instrumental PSF. The equivalent widths of the two components are 0.066±0.003 and 0.160±0.006 Å for the Na$^i$ D2 line at 5890Å, and 0.040±0.002 and 0.130±0.005 Å for the Na$^i$ D1 line at 5896Å. Using the Munari & Zwitter (1997) calibration on Na$^i$ line at 5890 Å this corresponds to a reddening of $E(B-V)=0.078\pm0.004$.

The Tycho $B_p - V_p = -0.20 \pm 0.01$ corresponds, according to Bessell (2000), to a Johnson $B-V = 0.17 \pm 0.01$. We denote an intrinsic (i.e., unreddened) color by $(B-V)^i$ and an observed color by $(B-V)$ with subscripts 1, 2 and C denoting the primary component, the secondary component and the composite value for the binary respectively. With an assumed intrinsic color for the primary, $(B-V)^i_1$, and the magnitude differences between the two components in each filter, $\Delta m_B$ and $\Delta m_V$, from our light curve solution, we can compute the intrinsic composite color of the binary, $(B-V)^i_C$, as

$$(B-V)^i_C = (B-V)^i_1 - 2.5 \log \left( \frac{1 + 10^{-0.4 \Delta m_B}}{1 + 10^{-0.4 \Delta m_V}} \right)$$

Assuming a value of $(B-V)_1^i = -0.27$ for the B1V primary (Straizys 1992) and the $\Delta m_B$ and $\Delta m_V$ values of 2.58 and 2.49 respectively from the light curve solution, we find $(B-V)_C^i = -0.26$. This result, combined with the observed $(B-V)_C$, yields a reddening of $E(B-V) = 0.09$, in good agreement with the results from the analysis of the interstellar Na$^i$ lines. These values also agree well with the value of 0.07 measured by both Donahue & Field (1975) and Chambliss & Leung (1982).

2.2.2 Radial velocities

Radial velocity measurements for the primary have been derived from measurements of seven hydrogen Balmer lines ($\alpha$, $\beta$, $\gamma$, $\delta$, $\epsilon$, H8, H9) and eight He I lines (7065, 5876, 5016, 4472, 4388, 4026, 4009, 3820 Å).

Given the weakness of its spectral features (cf. Figure 1), the measurement of the radial velocity of the secondary has been possible only in a few spectra, those with the highest S/N near quadrature, and for only a subset of the
Table 1. Heliocentric radial velocities of VV Ori.

| HJD (mid-exposure) | Primary R.V. (km sec$^{-1}$) | Secondary R.V. (km sec$^{-1}$) |
|-------------------|-------------------------------|-------------------------------|
| 2453314.5470      | -88.29                        |                               |
| 2453373.4771      | 97.01                         |                               |
| 2453373.4804      | 93.64                         |                               |
| 2453373.4828      | 95.12                         |                               |
| 2453392.4492      | 140.27                        | 241.88                        |
| 2453392.4538      | 142.14                        | 241.59                        |
| 2453392.4581      | 142.12                        | 246.59                        |
| 2453393.4475      | -77.80                        | 288.75                        |
| 2453393.4521      | -76.09                        | 275.65                        |
| 2453393.4565      | -72.99                        | 269.44                        |
| 2453394.3750      | 52.35                         |                               |
| 2453394.3794      | 47.78                         |                               |
| 2453394.3841      | 47.40                         |                               |
| 245411.3610       | -37.56                        |                               |
| 245411.3689       | -34.81                        |                               |
| 245411.3767       | -32.80                        |                               |
| 245411.4244       | -11.41                        |                               |
| 245411.4323       | -7.48                         |                               |
| 245411.4400       | -7.59                         |                               |
| 245412.3884       | -58.46                        |                               |
| 245412.3963       | -57.64                        |                               |
| 245412.4044       | -63.07                        |                               |
| 2453775.2939      | -59.49                        |                               |
| 2453777.3065      | 144.07                        | -274.19                       |
| 2453777.3125      | 144.42                        | -282.39                       |
| 2453777.3389      | 142.22                        | -279.10                       |
| 2453780.2507      | 147.63                        |                               |
| 2453780.2551      | 147.51                        |                               |
| 2453780.3954      | 118.14                        | -234.42                       |
| 2453780.4003      | 114.54                        | -230.26                       |
| 2453780.4050      | 112.87                        | -226.48                       |

For He I lines. Table 2 gives the radial velocities of both components.

3 DATA ANALYSIS

We performed a simultaneous analysis of the Chambliss & Leung (1982) $UBV$ and $vyb$ photometry, our $UBV$ photometry and our radial velocities with the 2003 version of the Wilson-Devinney (Wilson & Devinney 1971; Wilson 1973; Drake & Wilson 1991, hereafter, WD) program. We originally included the $uv$ observations of Chambliss & Leung (1982) but found, as they did, that we could not get satisfactory fits to those data. Inspection of the light curves shows that the system is detached so we used WD mode 2 in the solution. The parameters adjusted in the simultaneous solution were the semi-major axis of the relative orbit ($a$), the binary centre of mass radial velocity ($v_c$), orbital inclination ($i$), secondary mean effective temperature ($T_{\text{eff}}$), modified surface potentials of the components ($\Omega_1$ and $\Omega_2$), mass ratio ($q$), and the bandpass-specific luminosity of the primary ($L_1$). We used time as the independent variable and adjusted the orbital period ($P$), and the reference epoch ($HJD_0$). No evidence for an orbital eccentricity was found in light curve fits so we fixed it at zero for the final solution. Certain parameters, such as the bolometric albedos and gravity brightening exponents, were held fixed at their expected theoretical values. The logarithmic limb darkening law was used with coefficients from Van Hamme (1993). The rotational velocities of the primary (167 ± 4 km sec$^{-1}$) and the secondary (83 ± 8 km sec$^{-1}$) are consistent with the assumption of synchronous rotation and that was assumed in the solution. The mean effective temperature of the primary was set to 26199 K based on the unreddened $B-V$ and the calibration of Flower (1996). Kurucz atmosphere models (Kurucz 1993) were used for both stars. Data set weights were determined by the scatter of the observations.

Given the frequent claims of the existence of a third body in the system, we also adjusted third light but we could not find statistically significant values for any of the light curves. Chambliss & Leung (1982) also found no indication of third light in their data. Sarma & Vivekananda Rao (1995) analyzed the $UBV$ data of Duerbeck (1974) and the $H_\alpha$ data of Chambliss & Davan (1987) and also found no evidence of third light. Chambliss (1984), however, did find a third light contribution but did not give error estimates on which to judge the significance of the result. Table 2 shows the results of the simultaneous solution and Figures 3 and 4 show the fits to the Chambliss & Leung (1982) data. Figure 5 shows the fits to the radial velocities. The primary appears to have absolute dimensions consistent with a slightly evolved main sequence star of its spectral type. Using a stellar evolution code (Han, et al. 1994, Eggleton (1973), Eggleton (1973), Eggleton (1973)) kindly supplied to us by P. Eggleton, we find that the VV Ori primary reaches its current radius at an age of 8.3 Myr, with the error in the radius leading to an uncertainty in the age of 0.2 Myr. At that age, the models predict a secondary radius of 2.44 $R_\odot$ in reasonably good agreement with our observed value of 2.41 $R_\odot$, given the uncertainties in the masses. Chambliss & Leung (1982) found that the secondary was much smaller than expected for the mass they derived. Our derived mass is considerably smaller and our radius slightly larger than their values, easing this mass-radius discrepancy. Table 4 shows our results for the component masses and radii compared with previously published values.

Hopp (1993) estimates the spectral type of the secondary as B5 V. Our derived effective temperature results in a B4.5 classification according to the tables of Straizys (1992) and Bertone, et al. (2004). The radius of 2.41 $R_\odot$ is consistent with an unevolved B4 V star (Straizys 1992) and the surface gravity is also consistent with that spectral type. The secondary’s bolometric magnitude is $-1.57$ and that value is in good agreement with the Straizys (1992) tables for a B4.5 V star. Experiments with composite reference spectra and the strength of the He I 5876 line both point to a B4.5 V spectral classification. Based on these factors, we estimate that the secondary’s spectral type is B4.5 V.

Assuming a ratio of total to selective absorption of $R = 3.1$ and using the bolometric corrections from Flower (1996), we find that the distance to VV Ori is $388 \pm 30$ parsecs with the error dominated by the uncertainty in the effective temperature of the primary. Unfortunately, the Hipparcos parallax is not very precise, yielding a 1σ distance range of 390 pc to 1060 pc. Our distance places the system in the Orion OB1 association consistent with the distance to the 1a subgroup (Blaauw 1964) measured by de Zeeuw, et al. (1990). Sarma & Vivekananda Rao (1995) estimate that the
age of VV Ori is 10 ± 1 Myr. This value, along with the age found from our evolutionary calculations, supports the membership of VV Ori in the 1a subgroup of Orion OB1 whose age was measured to be 11.4 ± 1.9 Myr. The barycentric radial velocity we measure, 23.5 ± 0.5 km sec$^{-1}$, agrees well with the average radial velocity of the Ori OB1 members found by Morrell & Levato (1991). At the galactic latitude of $-18^\circ$ and our distance, VV Ori is 110 pc from the galactic plane, within the scale height of the galactic thin disk.

### 4 THE PUTATIVE TERTIARY COMPONENT

Daniel (1915) was the first to suggest the existence of a tertiary component in VV Ori. Larger than expected residuals from the fit to his radial velocity observations of the primary led him to examine the possibility of a third body and he gave orbital parameters for it "with great reserve ... and not with any idea that they are even approximately true." Later, Struve & Luyten (1949) also noted systematic trends in the residuals to the fits of their velocities but did not feel justified in solving for the orbit of a third body, stating that "... we cannot be certain that the slow variation necessarily means that the system is triple." Duerbeck (1975) analyzed the velocity residuals for the Daniel (1915), Struve & Luyten (1949) and Beltrami & Galeotti (1970) data sets, as well as his own, concluding that a third body orbit with an period of about 119 days fit the data best. Assuming an inclination

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**Table 1.** Parameters of VV Ori

| Parameter | Value |
|-----------|-------|
| $a$       | 13.49 ± 0.05 R$_\odot$ |
| $V_r$     | 23.5 ± 0.3 km sec$^{-1}$ |
| $i$       | 85$^\circ$.9 ± 0.2 |
| $T_1$     | 26199 K |
| $T_2$     | 16073 ± 42 K |
| $\Omega_1$ | 3.152 ± 0.004 |
| $\Omega_2$ | 3.433 ± 0.008 |
| $q$       | 0.376 ± 0.001 |
| $HJD_0$   | 2452500.2065 ± 0.0003 |
| $P$       | 1.48537423 ± 0.0000005 days |
| $L_1/(L_1 + L_2)_{UV}$ | 0.9367 ± 0.0005 |
| $L_1/(L_1 + L_2)_{B}$ | 0.9150 ± 0.0005 |
| $L_1/(L_1 + L_2)_{V}$ | 0.9083 ± 0.0005 |
| $L_1/(L_1 + L_2)_{I}$ | 0.8999 ± 0.0014 |
| $L_1/(L_1 + L_2)_{R}$ | 0.9165 ± 0.0005 |
| $L_1/(L_1 + L_2)_{b}$ | 0.9111 ± 0.0005 |
| $L_1/(L_1 + L_2)_{y}$ | 0.9081 ± 0.0004 |
| $R_1$     | 4.98 ± 0.02 R$_\odot$ |
| $R_2$     | 2.41 ± 0.01 R$_\odot$ |
| $M_1$     | 10.9 ± 0.1 M$_\odot$ |
| $M_2$     | 4.09 ± 0.05 M$_\odot$ |
| $L_1$     | 10600 ± 1600 L$_\odot$ |
| $L_2$     | 350 ± 54 L$_\odot$ |
| $\log g_1$ | 4.08 ± 0.06 |
| $\log g_2$ | 4.29 ± 0.06 |

Quoted errors are formal 1σ errors from the solution. Luminosity errors are estimates based on an estimated uncertainty of 1000 K in the effective temperature of the primary. The log $g$ values are in CGS units.
of 90° for the orbit of the third body, he estimated that its spectral type was mid-to-late A and its luminosity was 13-14 $L_\odot$.

We repeated our light and velocity curve analysis after adding the velocities from Popper (1993), Duerbeck (1975) and Struve & Luyten (1949) to study the behaviour of the velocity residuals for each radial velocity data set. All radial velocities were given equal weight in the solution. Figure 6 shows the velocity residuals for the four sets of data phased with the third body ephemeris given by Duerbeck (1975). While the older data appear to show systematic trends, our more precise data do not, but we, unfortunately, do not have full coverage of the purported third body orbit.

One intriguing result of the analysis is a statistically significant value for the time derivative of the orbital period of the binary. The solution converged on a value of $\dot{P} = -3.6 \times 10^{-10} \pm 1.3 \times 10^{-10}$, perhaps indicating accretion of the primary’s wind by the secondary. We do not attach much significance to this result, its reality having to be assessed against additional precise radial velocities and accurate timing of eclipses to be secured in the years to come. In the case of conservative mass transfer between the two components, the mass exchange would amount to $2 \times 10^{-7} M_\odot \text{ yr}^{-1}$. This material would be easily ionized by the radiation field of the B1 V primary, and should give rise to emission lines easily detectable in high resolution spectra. Ours do not show any hint of emission lines originating in VV Ori

Another way to test for the existence of the third body, as pointed out by Duerbeck (1975), is through its effect on the O-C diagram for times of minimum of the binary. Unfortunately, VV Ori has not been a frequent target of observers of times of minimum. A concerted effort to observe as many times of minimum as possible over a couple of observing seasons could prove valuable in answering this critical question. Duerbeck (1975) predicts that the double amplitude of the variation would be 0.0014 days, a measurement within reach of a small telescope equipped with a CCD camera.

Given the large scatter in the older radial velocity data sets, the lack of any evidence for third light in the light curves and the lack of systematic trends in the residuals of our radial velocities, we see no strong evidence to support claims of the existence of a third body in VV Ori. More extensive radial velocity and time of minimum studies should be able to resolve the question with greater certainty.

5 CONCLUSIONS

VV Ori consists of a B1 V primary with $M_1 = 10.9 \pm 0.1 M_\odot$ and $R_1 = 4.98 \pm 0.02 R_\odot$ and a B4.5 V secondary with $M_2 = 4.09 \pm 0.05 M_\odot$ and $R_2 = 2.41 \pm 0.01 R_\odot$. The derived distance of 388 $\pm$ 30 pc and barycentric velocity of 23.5 $\pm$ 0.3 km sec$^{-1}$ are consistent with the system’s membership in the Orion OB1 association. We find no evidence of third light in the photometric data and the new radial velocities, although somewhat limited in temporal coverage, show no evidence of the third body discussed by previous authors.

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