A model-based interpretation of H_α dynamics in V1334 Cyg spectra

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Background

High resolution spectra were taken of the Cepheid variable V1334 Cygni, around the Hα line, over five nights between 26th August 2019 and 6th September 2019. The observations were made with a Lhires III spectrograph and C11 OTA. During calibration it became apparent that, while the atmospheric H_2O lines were well aligned with their expected wavelengths, the Hα minimum was consistently blue shifted and varied from night to night. The blue shift could not be accounted for by the radial velocity of -1.8Km/s given in Simbad, and so I investigated the literature to see what else could explain this phenomenon. Possibilities include a Doppler shift due to a radial velocity component from the Cepheid pulsation. While Cepheid pulsation is easily accessible photometrically, it is interesting to explore the possibility that the expansion/contraction can be observed in a different way.

Data preparation

Fig 1 shows part of one of the spectra I took (31 August 2019) over a range of just over 35Å. The water absorption line is very close to its nominal position at 6543.91Å, whereas Hα is clearly displaced to the blue end of the spectrum.[1]

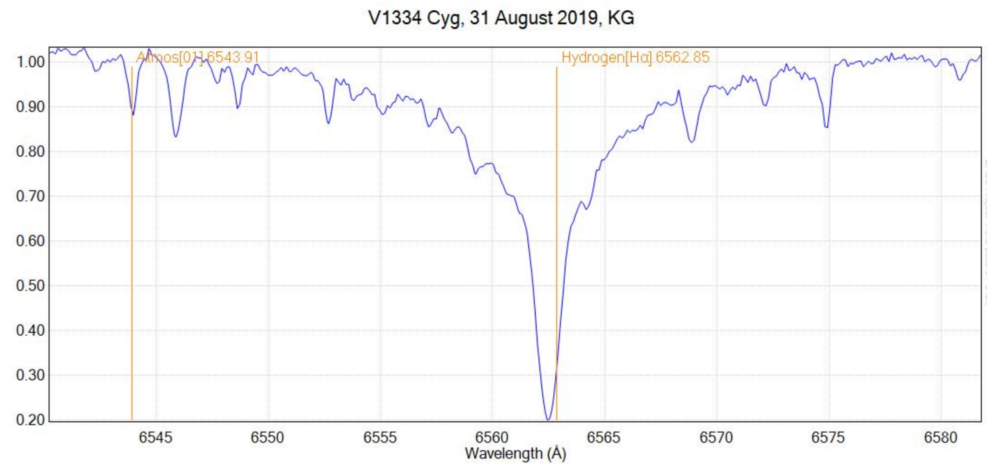

Figure 1: Part of spectrum of V1334 Cyg from 31 August 2019, showing atmospheric H_2O, and stellar Hα absorption lines

Each minimum for the Hα line, $\lambda \mathrm{H}\alpha_{\mathrm{obs}}$, was calibration-corrected by aligning it against the H_2O line at 6543.91Å. The resulting minimum, $\lambda \mathrm{H}\alpha_{\mathrm{calcor}}$, was then used to calculate a Doppler shift $\Delta V = (\lambda \mathrm{H}\alpha_{\mathrm{calcor}} - \lambda_0)/c$, where λ_0 is the reference wavelength for Hα and c is the speed of light (in Km/s). This shift was then adjusted to accommodate heliocentric velocity to give an estimated radial velocity, ΔV_{cor}, for V1334 Cyg. The results are shown in the first three columns of Table 1

[1]The mean of the absolute value of the wavelength difference between data and reference for the H_2O line was 0.037Å (simple mean of signed values was 0.001Å). The mean difference for Hα was 0.25Å, all blue shifted.

Observation time (JD-2458700)	$\lambda H\alpha_{obs}$	ΔV_{cor}	V_{orb}	V_{res}
22.492	6562.552	-7.43	-12.15	4.72
24.533	6562.441	-14.52	-12.22	-2.30
27.391	6562.473	-17.23	-12.31	-4.92
28.385	6562.564	-8.37	-12.35	3.98
33.443	6562.627	-10.77	-12.51	1.74

Table 1: Observed quantities and their relation to the model of Gallenne et. a 2018 [1]. $\lambda H\alpha_{obs}$ is the observed minimum of the Hα line in the spectrum. ΔV_{cor} is the heliocentric corrected Doppler shift, derived from the difference between this minimum - corrected against the H_2O line at 6543.91Å- and the Hα reference 6562.801Å. V_{orb} is the orbital velocity of the Cepheid extracted from the model, and V_{res} is the difference between this and the observed Doppler shift, ΔV_{cor}.

The radial velocities were all blue shifted which is inconsistent with a simple interpretation in terms of a Cepheid-like, pulsation phenomenon. However a recent model of V1334 Cyg is able to give insight as to why this might he so.

A model of V1334 Cyg

The study by Gallenne et. a 2018 [1] reports work unique to V1334 Cyg. It transpires this star is a triple system. The Cepheid itself has a very close (but faint) companion and this pair has a wider companion which is just about separable visually; the paper by Gallenne et al. focuses on the wide pairing. In spite of this complexity, the visible spectrum is dominated by the Cepheid itself [2]. This allows us to interpret the spectra I observed as plausibly derived from the main Cepheid component. Further, Gallenne et al provide a model of the radial velocity of the Cepheid, split into components due to the orbital motion and pulsation. The results of the model and fit to data are shown in Fig. 2.

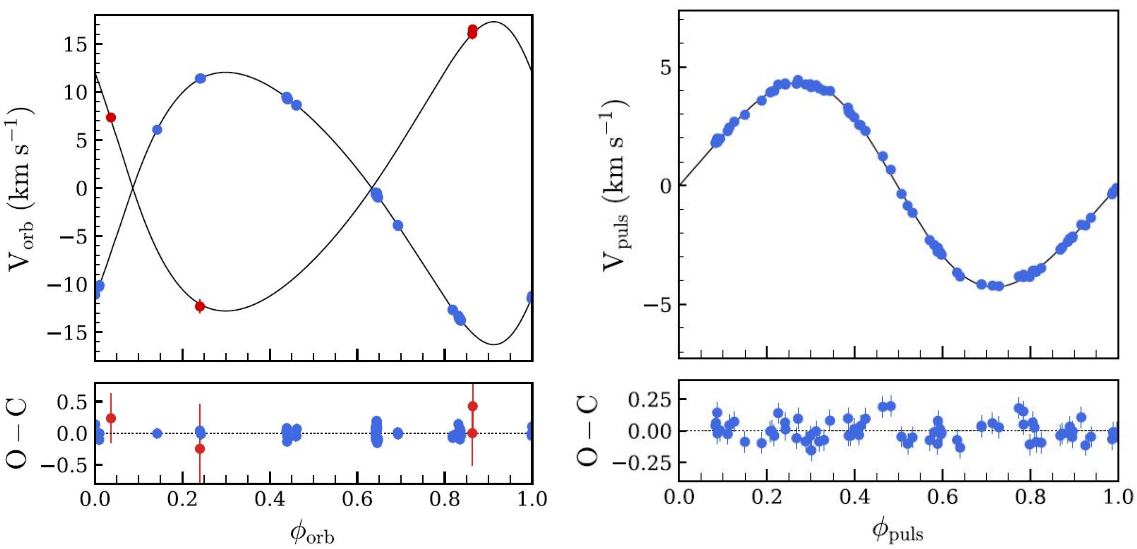

Figure 2: Figures from Gallenne et al 2018. Left - model of orbital motion for wide binary components of V1334 Cyg from [1]. Blue and red data dots identify models for primary and secondary components respectively. Right - model of pulsation radial velocity of primary component. [1]

The period of the orbit is around 5.4 years and so any contribution from this to my data will be almost constant. It may, however, account for some of the blue shift if the orbital phase of my observations is appropriate. The period of pulsation is around 3.3 days and so may figure in any variation I saw as observations were taken over an 11 day period.

Using the model

Orbital component of radial velocity

The orbital solution for radial velocity against phase in Fig 2 is analytic but is given implicitly, and would require (a non-trivial) numerical solution. I therefore fitted a polynomial to the primary component curve ('blue dots') which I had extracted using *Datathief* [3]. Then, using the ephemeris of Gallenne et al., (with time-of-origin 2453316.75, and period 1932.8) I mapped my observation times to an orbital phase and read off radial velocities, $V_{\rm orb}$, from the polynomial; see column four of Table 1. The values are all close to 12Km/s which is of the same order as my velocities $\Delta V_{\rm cor}$.

Pulsation component of radial velocity

Subtracting the orbital component of radial velocity from the Doppler shift in my data (that is forming $V_{\rm cors} - V_{\rm orb}$, gives a residual observed velocity, $V_{\rm res}$, which might be due to pulsation of V1334 Cyg. These are given in column 5 of Table 1. It is encouraging that these values are comparable with those in the pulsation model function given in the right hand panel of Fig 2. That is, they take both negative and positive values and have have magnitudes extending over a range of around 5.

To explore this possibility further, I converted my observations times to a phase $\phi_{\rm pulse}$ using the pulsation ephemeris of Gallenne et al.; that is, time-of-origin, T_0, equal to 2445000.55, and period 3.33242 days. It is important to note that T_0 was chosen somewhat arbitrarily by Gallenne et al to allow a convenient fitting procedure in their model, with zero radial velocity at zero phase. Thus, we anticipate that any real relation, $V_{\rm pulse}(\phi_{\rm pulse})$, between pulsation velocity and phase, to have a phase offset other than zero.

I therefore fitted[2] a simple sinusoid to the data pairs of $(V_{\rm cors}, \phi_{\rm pulse})$ with two parameters of amplitude and phase offset. The original model included two sinusoids, but one very much dominated and, given the sparsity of my data, there was no merit in over-fitting with extra complexity. The vertical offset of the sinusoid was also kept to zero to ensure the physical result that total distance traveled in a pulsation is zero. The results are shown Fig. 3

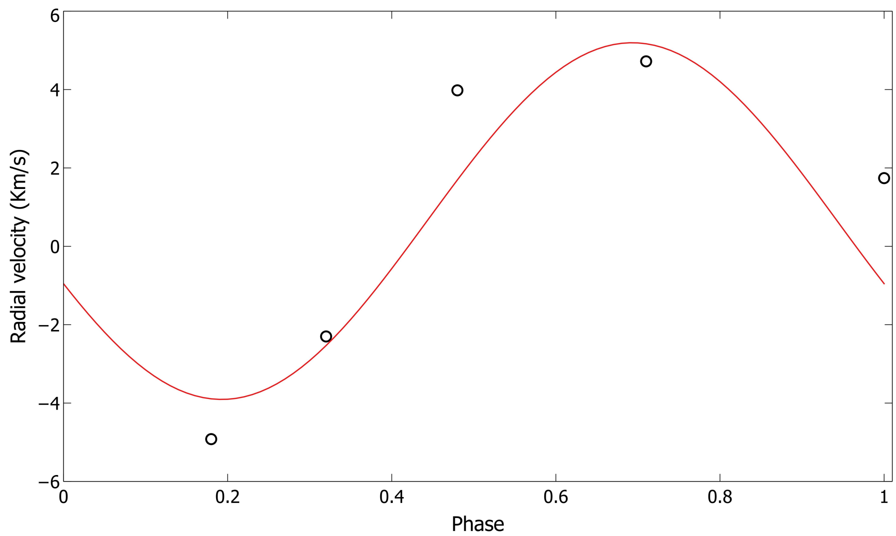

Figure 3: Fitting a sinusoid to the residual Doppler shifts $V_{\rm cors} - V_{\rm orb}$. Open circles are these data expressed as a function of pulsation phase (with arbitrary time origin - see text). The red line is the best fitted sinusoid

[2]Using `fminserarch` in the *octave* language

Fortunately, my five observations are scattered fairly evenly across phase values which highlights any pattern in the results. There is some indication of a sinusoidal trend, and the phase offset was 0.56. Further the amplitude is similar to that shown in Fig2

Notwithstanding the fact there are only a few data points, I ran a Kolmogorov-Smirnov goodness-of-fit test against the sinusoid and found a test statistic of 0.225. According to [4], in order to not have to reject the null hypothesis (of fitting) the test statistic should be less than $1.36/\sqrt{n}$. Here, with $n = 5$, this criterion is 0.61, so that we cannot conclude the data do not come from a sinusoid.

The exercise of fitting against the pulsation model makes the prediction that the phase offset (with respect to nominal ephemeris of the model) is 0.56. It is possible to test this against photometric data which should show a similar sinusoidal patterning.

Comparison with photometric data

Fortunately there was some data for V1334 Cyg available from the AAVSO database. It is visual data from observer Sherrill Shaffer (SSHA) covering the last two years (JD 2458377.7 - 2458762.5). A similar procedure to that used for the Doppler shifts was used to convert times to phase and fit a sinusoid with two parameters of amplitude and phase offset. This time, however, the data were mean-subtracted first, and the mean was then added back afterwards; the mean of the data (i.e. magnitudes) is not zero *a priori*. The results are shown in Fig 4

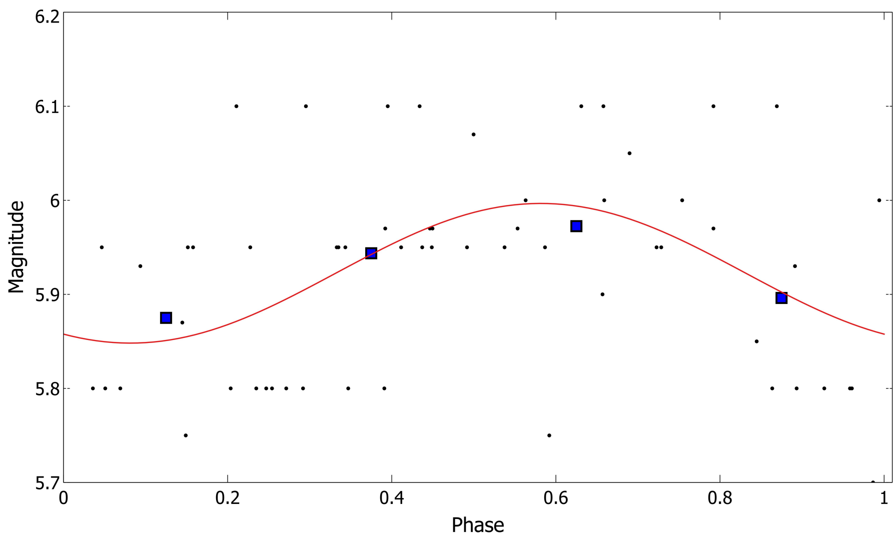

Figure 4: Fitting a sinusoid to the photometric data for V1334 Cyg. Black dots are the raw data, filled squares are the data binned over four equal periods, and the red line the best sinusoidal fit.

The data are quite noisy, and the sinusoidal trend is best highlighted by binning them into four periods. Interestingly, the phase offset here is 0.67 which is reasonably close to the prediction from the Doppler shift analysis (0.56).

Summary

The Doppler shifts observed in my spectra appear to be consistent with a dual component analysis into orbital and pulsation periods, as described in the model of Gallenne et al 2018 [1]. I suspect the wavelength differences being used in this analysis are close to the resolution possible with the instrument (Lhires III) but it appears that basic trends and some information (like phase offset and amplitude) can be obtained with limited precision. It would interesting to obtain more data on this system and see how much it can sharpen up the outcomes given here.

References

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[4] S Massa. Lecture 13: Kolmogorov Smirnov Test & Power of Tests, 2016. `http://www.stats.ox.ac.uk/~massa/Lecture 13.pdf`.