## **The VV Cep campaign – Current results** (May 2025)

Analysing high resolution spectra: (David Boyd)

- M2 giant radial velocity
- Determining absolute flux calibration
- Hα emission and absorption components
- Radial velocities of the Gaussian emission and absorption components
- Orbital solutions of the Gaussian emission and absorption radial velocities
- Combined radial velocity curves
- Visualising Hα emission line flux
- Analysis of the AAVSO V magnitude light curve

Intermediate report: (Ernst Pollmann)

- Hα equivalent width (EW) during the eclipse compared to the EW outside the eclipse
- Short-period oscillations particularly in the upper polar jet (V emission)
- Analysis of photometric V-band magnitude variability
- Nutation oscillation of the upper B star polar axis emission
- Radial velocity measurements of the upper polar jet of the B star (V emission component) relative to the M star
- Use of Hα FWHM to estimate the time of periastron

Attempt to simulate the binary system: (Manfred Schwarz)

- The website www.vvCephei.info has been updated to include the latest spectral data, along with spectra from previous observation campaigns conducted between 2019 and 2023.
- These results were made possible thanks to the large number of collected spectra and the valuable support of the VV Cephei simulation software.
- An updated version of the vvCepSimulator, featuring several enhancements, is scheduled for release in June.

**Analysing high resolution spectra of VV Cep – May 2025**

David Boyd

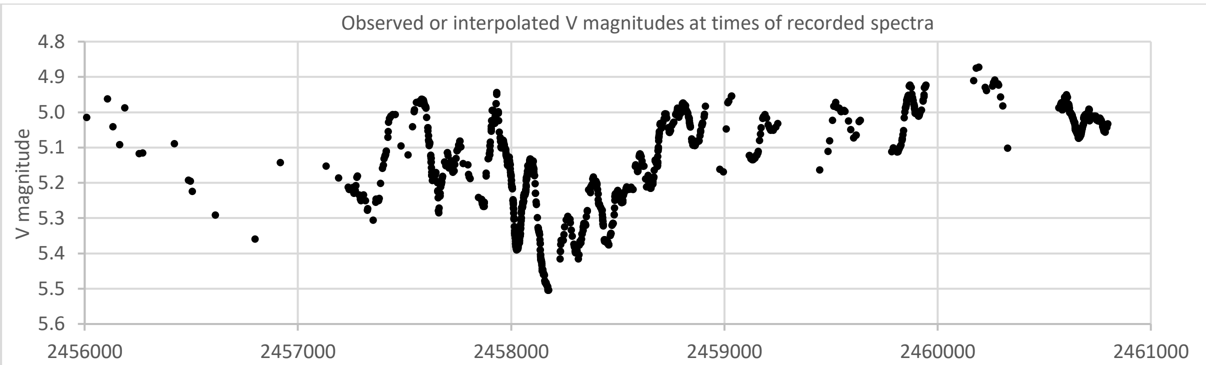
This report is based on analysing 1422 wavelength corrected, flux calibrated, high resolution Hα spectra of VV Cep obtained from several sources and over 40 observers.

Not all spectra contain information in the FITS header about the latitude and longitude of the observer. In order to enable barycentric correction to be calculated, this information was obtained by consulting maps based on the observer's stated location. Through the occasional use of remote telescopes, this information may not always be accurate. The barycentric correction has a period of 365.25 days and this signal is clearly visible in measured radial velocities before removing it.

The consensus of previous publications appears to be that the components of VV Cep are an M type supergiant (M2Iab) surrounded by a wind and a hot B type main sequence star, possibly with an accretion disc, which orbits within the giant wind. Both components are likely to be massive but there is debate on their relative masses. Measuring radial velocities of the components may help to clarify the situation.

**Obtaining a V magnitude for each spectrum**

Some observers were able to record the V magnitude of VV Cep concurrently with recording its spectrum. In other cases we downloaded the AAVSO V-band light curve, removed obvious outliers, averaged and interpolated to obtain a V magnitude at the time of each spectrum. The resulting V magnitude light curve at the times of each of our spectra are shown below.




**Establishing system rest frame**

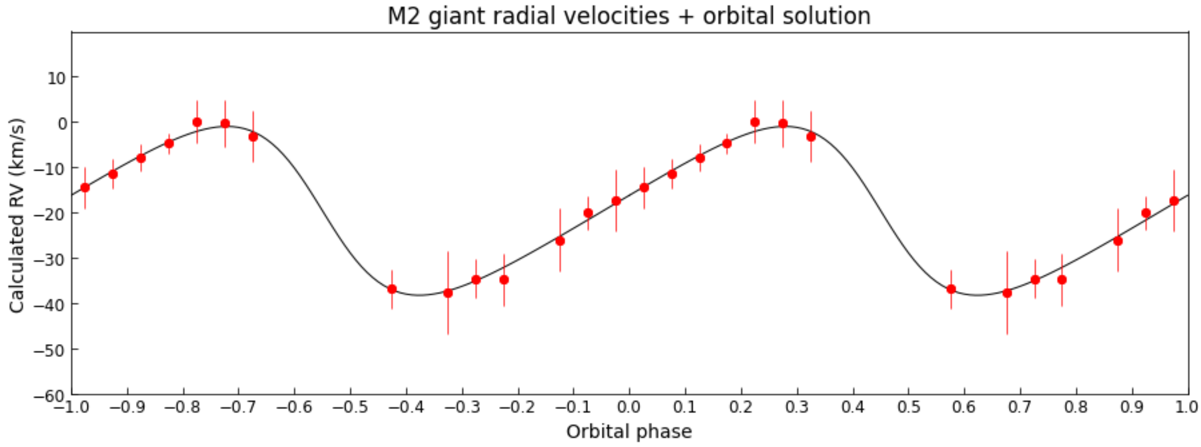
An M2 spectrum from the Melchiors library was adopted as a template for the M2 giant component of VV Cep and reduced in resolution to match the average spectral resolution of our VV Cep spectra. This template spectrum was wavelength calibrated using NIST wavelengths of several metal lines around Hα, and adopted as defining the system rest frame.

**M2 giant radial velocity**

VV Cep and the M2 template spectrum were interpolated to a common 0.1 Å grid and rectified. Each VV Cep spectrum was cross-correlated with the M2 template spectrum using 10 Å wide regions of the continuum on both sides of Hα line but excluding the line and its shoulders. Barycentric correction was then applied to the wavelength displacement from cross-correlation of each spectrum to obtain radial velocities of the M2 giant with respect to the system rest frame.

Wavelength calibration applied by observers is sometimes subject to inaccuracy. A small number of spectra were excluded from this part of the analysis based on inconsistency of their wavelength calibration with respect to other spectra obtained around the same time.

Radial velocities were averaged in phase bins and the Python code BinaryStarSolver was used to obtain the binary parameters of the M2 giant orbit. The measured radial velocities and the fitted orbital solution are shown below along with the fitted orbital parameters.




Systemic velocity = -19.632 ± 1.832 km/s
Semi-amplitude = 18.608 ± 1.564 km/s
Longitude of periastron = 89.082 ± 29.360 deg
Eccentricity = 0.247 ± 0.074
Time of periastron = 2454126.700 ± 760.169 RJD
Period = 7430.000 ± 0.000 d

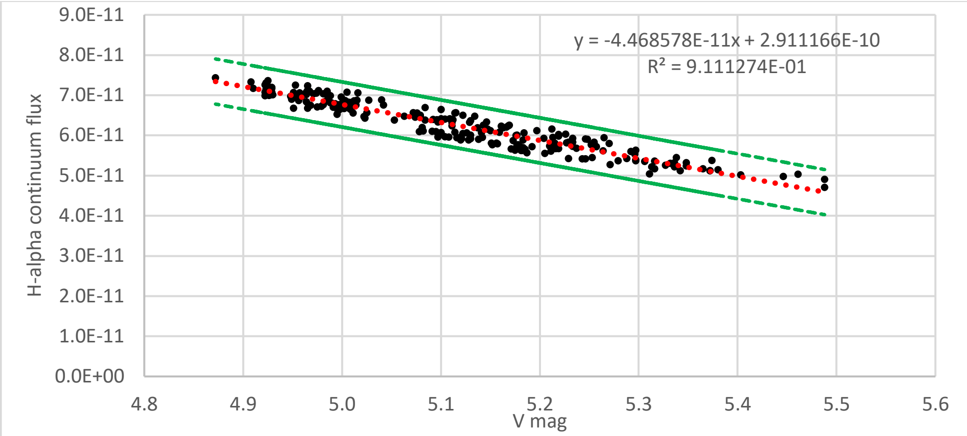
Each VV Cep spectrum was then wavelength-shifted by the barycentric-corrected cross-correlation displacement into the system rest frame and the M2 template spectrum subtracted from each spectrum. The resulting spectra are assumed to arise from a combination of the B star and its possible accretion disc plus Hα emission generated by UV radiation from the B star in the circumbinary environment.

**Determining absolute flux calibration**

Determining the absolute flux (in physical units of erg/cm$^2$/sec) of emission lines requires knowing the absolute flux of the spectral continuum adjacent to the lines. In the region above ~4700 Å, including the V-band, the spectrum of VV Cep is that of the M2 giant star. Observation shows that in Mira-type giant stars with shock-driven pulsations, the absolute flux level of the spectral continuum at Balmer lines, including Hα, is well-represented by a cubic function of V-band magnitude.

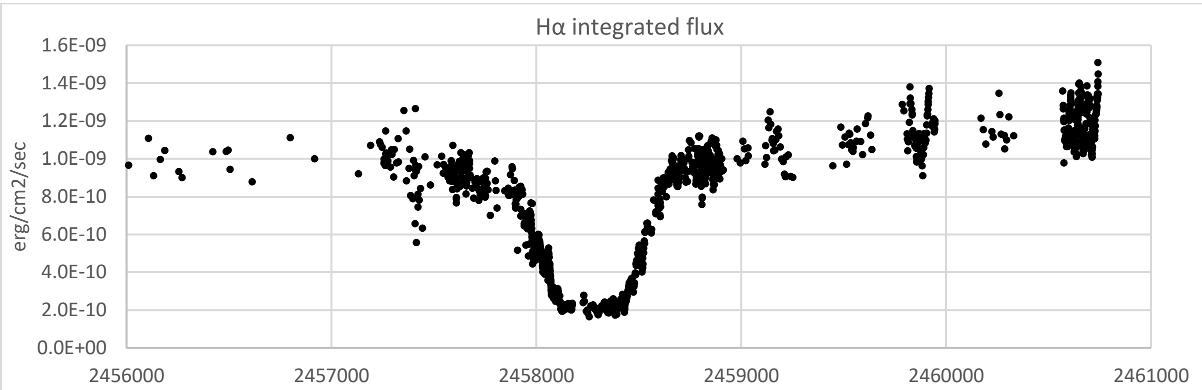
We have 231 VV Cep spectra covering both the V-band and the Hα region which have been corrected for instrumental and atmospheric losses by the observer to produce spectra with good relative flux calibration. Using the V magnitudes we obtained for each of our spectra, we calibrated each of the 231 spectra in absolute flux using the method described in https://britastro.org/wp-content/uploads/2021/05/absfluxcalibration.pdf.

As shown below, in our spectra of VV Cep there is a linear rather than a cubic relation between V magnitude and absolute flux of the continuum around Hα. This suggests that the M giant star in VV Cep does not experience Mira-type shock-driven pulsations.  This linear relation shown below was used to calibrated all our high resolution Hα spectra in absolute flux.




## Measuring flux in the Hα emission line

The integrated flux in the Hα emission line in each spectrum can be found by numerical integrating flux in the line above a linearly interpolated continuum. This shows the reduction of flux during eclipse and a gradual increase in flux as periastron as approached.



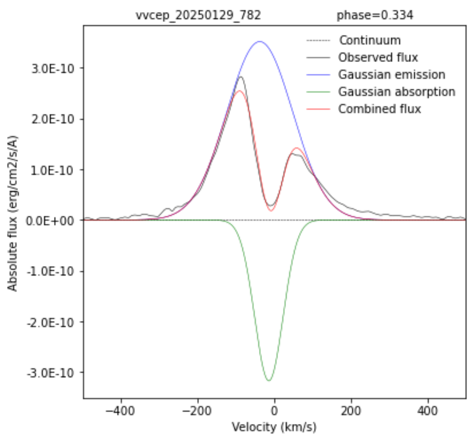

## Flux modulation frequency and amplitude

Rapid modulation of the Hα integrated flux is clearly measurable in the periods of intensive observation immediately after the eclipse and during recent weeks. The period of this modulation, measured with Peranso, is 43.3(1) days following the eclipse and 43.4(1) days in recent weeks, i.e. unchanged. However, the amplitude of this modulation is now ~50% larger as periastron is approached than following the eclipse.

## Hα emission and absorption components

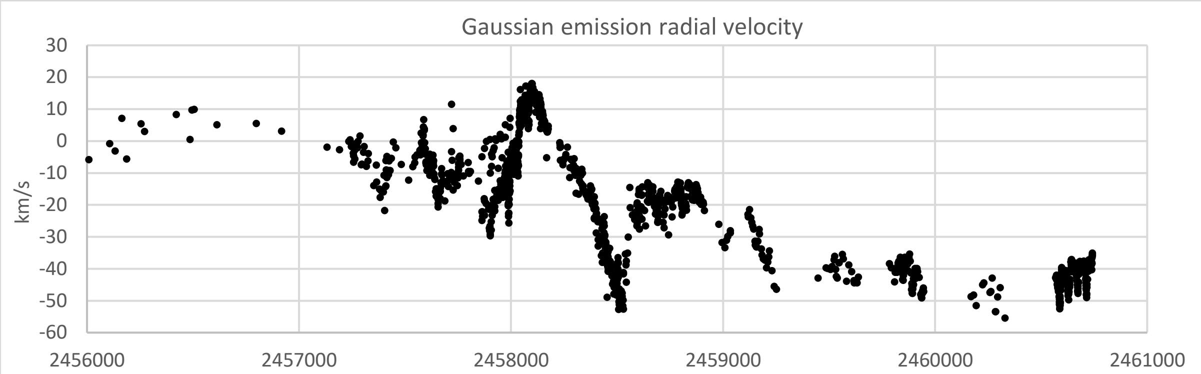
The observed Hα emission line consists of two emission components, one blue-shifted and one red-shifted with respect to the Hα rest wavelength. This may be interpreted as a combination of emission from the B star plus accretion disc and absorption of some of that emission by the M giant atmosphere and surrounding wind.

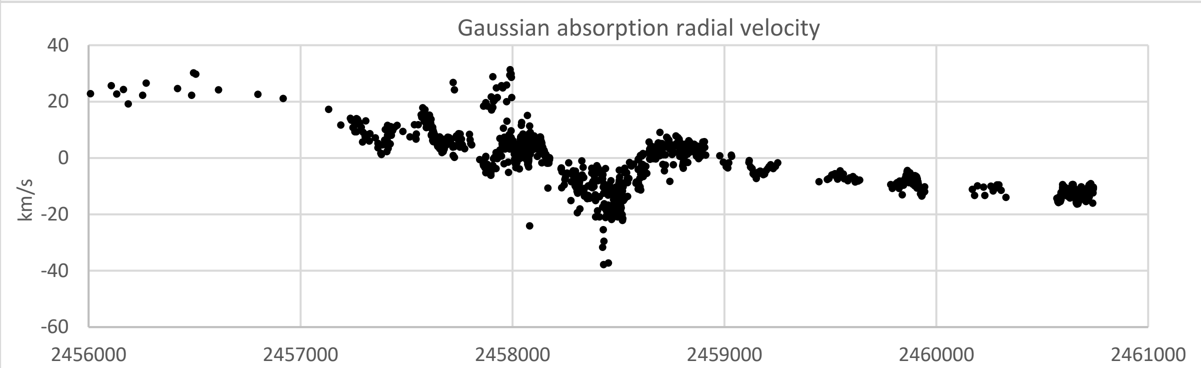
The Hα line profile can be numerically modelled by fitting it with two Gaussian profiles, one in emission and one in absorption as shown here.



**Radial velocities of the Gaussian emission and absorption components**

The peaks of these Gaussian profiles are cross-correlated with the M2 template spectrum representing the system rest frame to give radial velocities of the emission and absorption components.

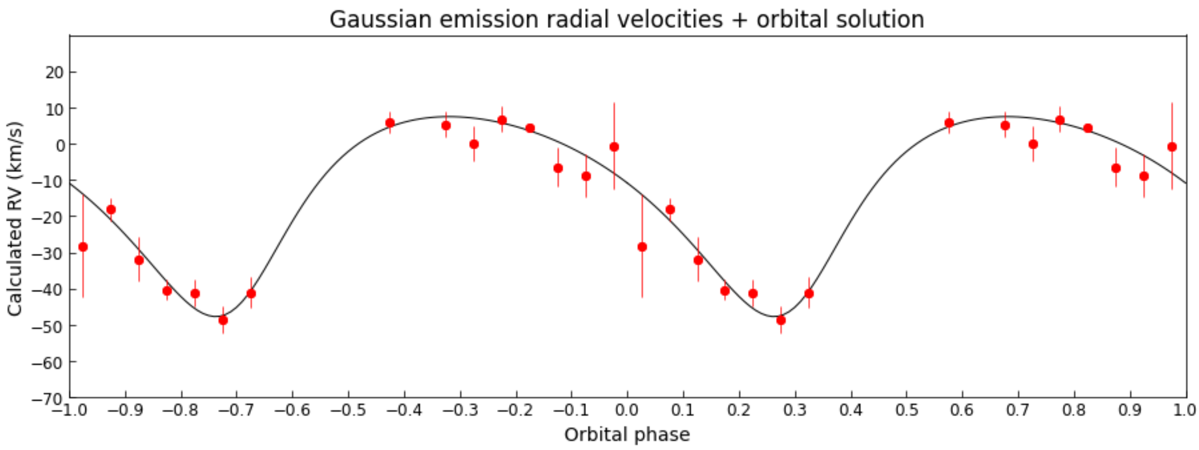


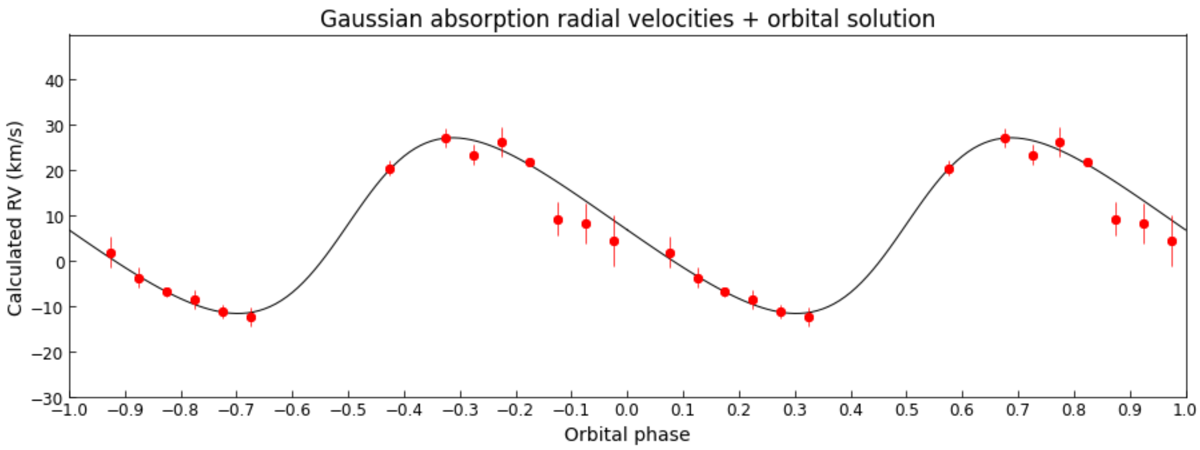

The asymmetry during the eclipse is due to the progressive eclipse of the side of the B star and its accretion disc that is rotating towards us, which results in the detected emission appearing red-shifted, followed by their progressive emergence from eclipse during which the emission appears blue-shifted. It appears in recent weeks that light from the B star is becoming red-shifted as its starts to move away from the observer in its orbit.

**Orbital solutions of the Gaussian emission and absorption radial velocities**

Radial velocities were averaged in phase bins and BinaryStarSolver used to obtain the binary solution and binary parameters of the Gaussian emission and absorption components.

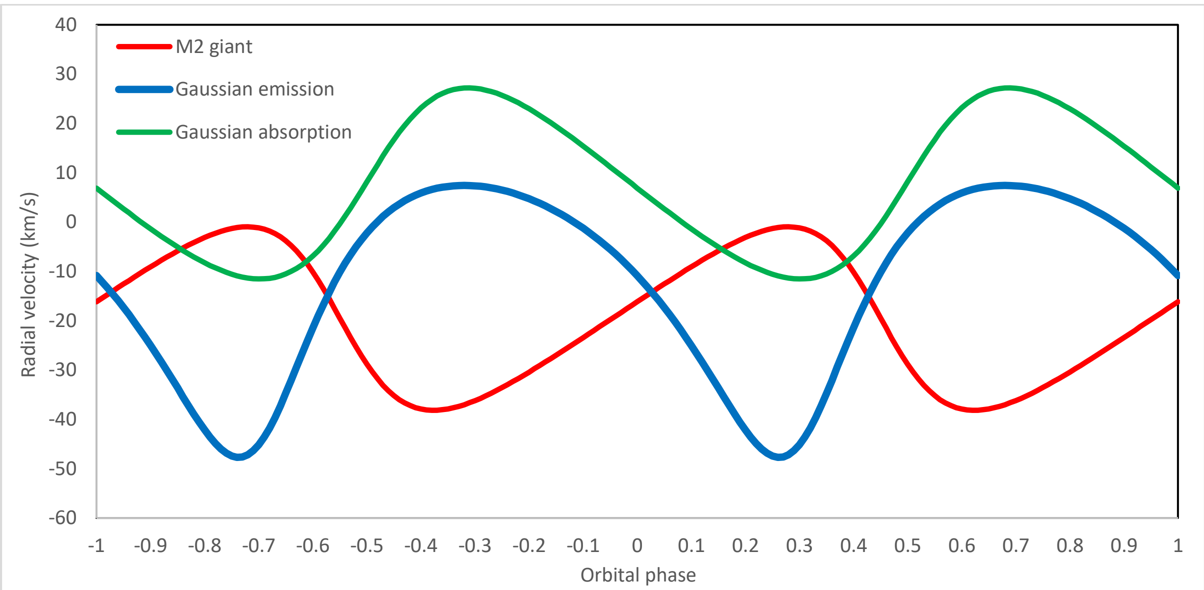


Systemic velocity = -13.006 ± 0.964 km/s
Semi-amplitude = 27.577 ± 1.025 km/s
Longitude of periastron = 205.891 ± 7.722 deg
Eccentricity = 0.288 ± 0.045
Time of periastron = 2460460.500 ± 148.581 RJD
Period = 7430.000 ± 0.000 d




Systemic velocity = 7.569 ± 0.489 km/s
Semi-amplitude = 19.365 ± 0.667 km/s
Longitude of periastron = 274.470 ± 10.367 deg
Eccentricity = 0.182 ± 0.034
Time of periastron = 2454554.700 ± 221.145 RJD
Period = 7430.000 ± 0.000 d

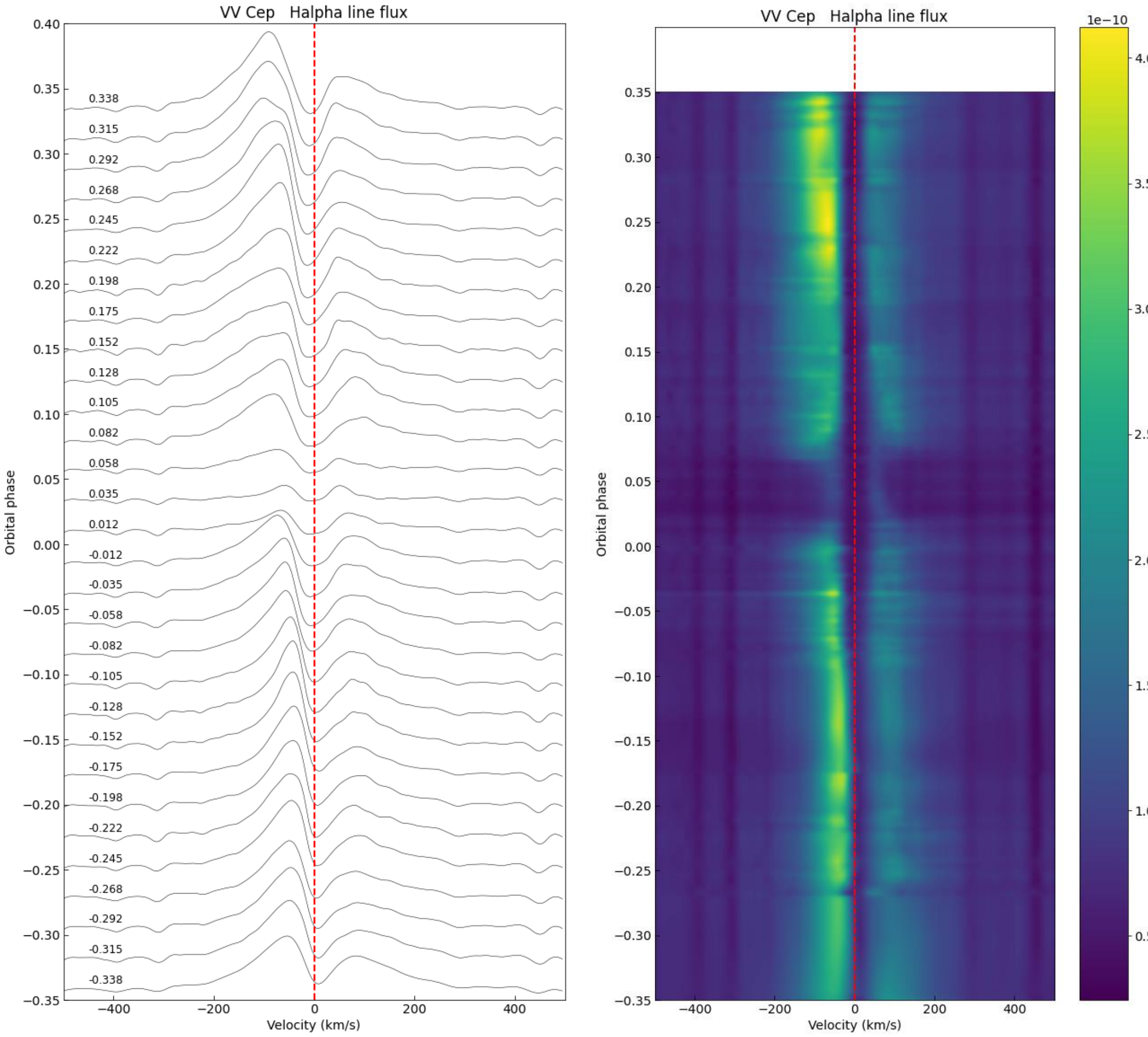
**Combined radial velocity curves**



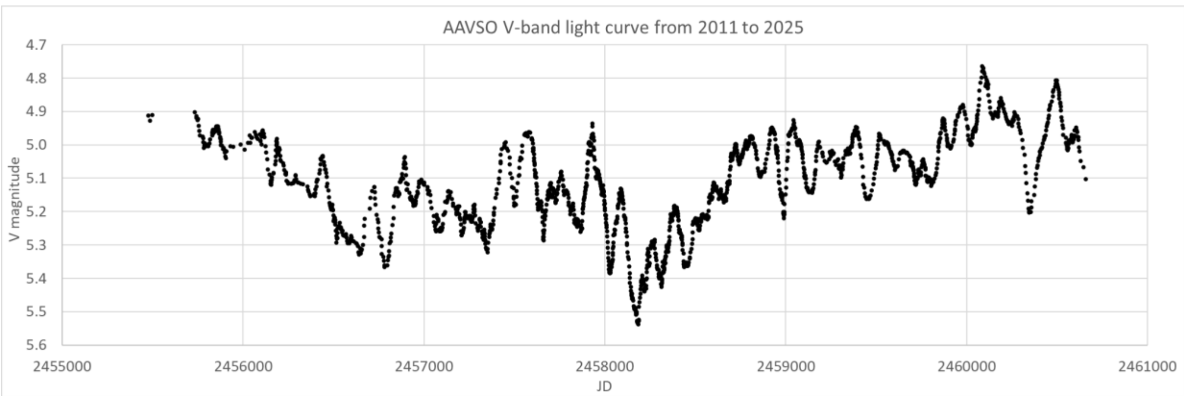

If we assume the Gaussian emission is likely to originate at the B star, we can take the radial velocity of the Gaussian emission as representing the radial velocity of the B star. Comparing the orbital semi-amplitudes of the M2 giant and the B star, 18.6 and 27.6 km/s respectively, this indicates the mass of the B star should be approximately 2/3 the mass of the M2 giant. However, we still do not have coverage of a complete orbital cycle and the orbital solutions may change.

## Visualising Hα emission line flux

Variation of the Hα emission line flux profile with orbital phase in the system rest frame, taking mid-eclipse as phase zero, can be visualised either using a stacked plot of bin-averaged line profiles or as a 2D interpolated colourised flux plot.



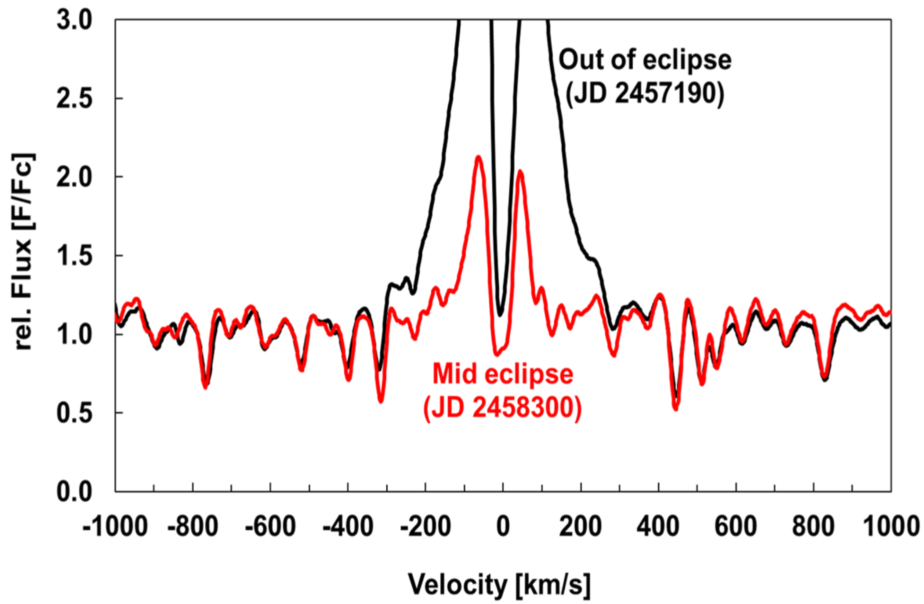

## Period analysis of the AAVSO V magnitude light curve of VV Cep

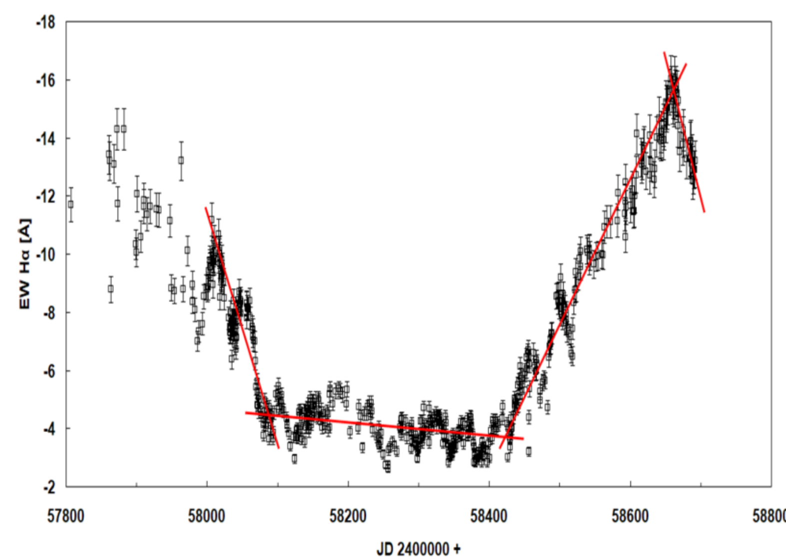


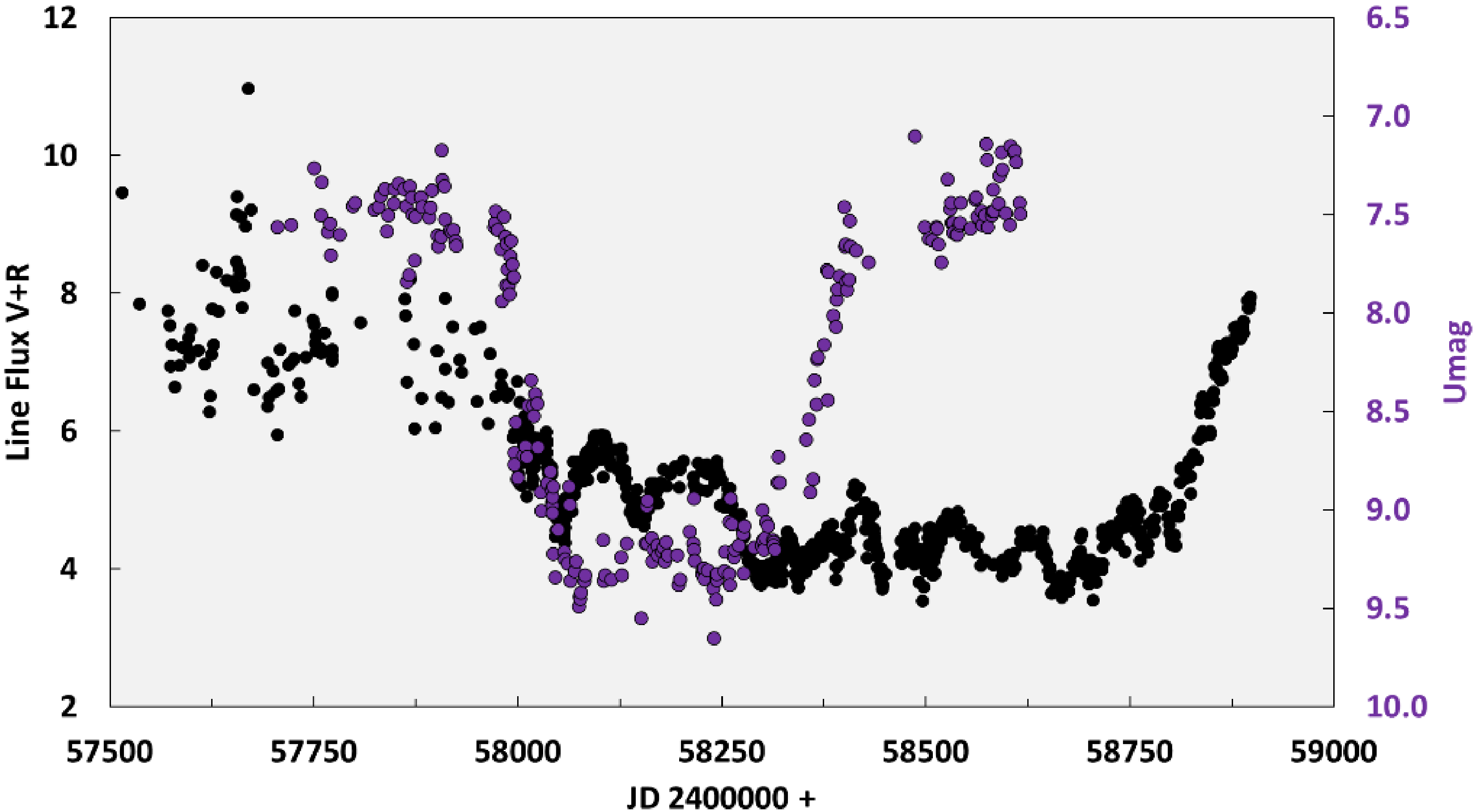
After removing obviously discrepant data and taking daily averages, I analysed the resulting AAVSO V band light curve of VV Cep from 2011 to 2024 by subtracting a running mean of 101 days and processing the resulting detrended light curve through different period finding algorithms in Peranso. The strongest signal in the resulting power spectrum was at 166 ± 1 days but the power spectrum was complex with multiple peaks and different subsets of the data gave different periods differing by several days. Using the data after JD 2457847, (the last 8 years) I found a period of 158 ± 1 days. I do not find evidence in the V-band light curve of VV Cep over these 13 years for a single persistent pulsation period of the M2 giant.

# Campaign VV Cep Intermediate report (Ernst Pollmann)

Observations conducted four years after the end of the eclipse in December 2018 revealed that the total Hα equivalent width (EW) during the eclipse exhibited a significantly lower amplitude compared to the EW measured in subsequent periods outside the eclipse. This suggests a partial eclipse, in which the emission along the upper polar axis of the B star remains visible, while the disk is fully obscured by the M star. The model proposed by Pollmann & Bennett supports this interpretation, indicating that the residual Hα emission observed during the eclipse can be attributed solely to the upper polar axis emission of the B star - specifically, the blue polar jet (V).



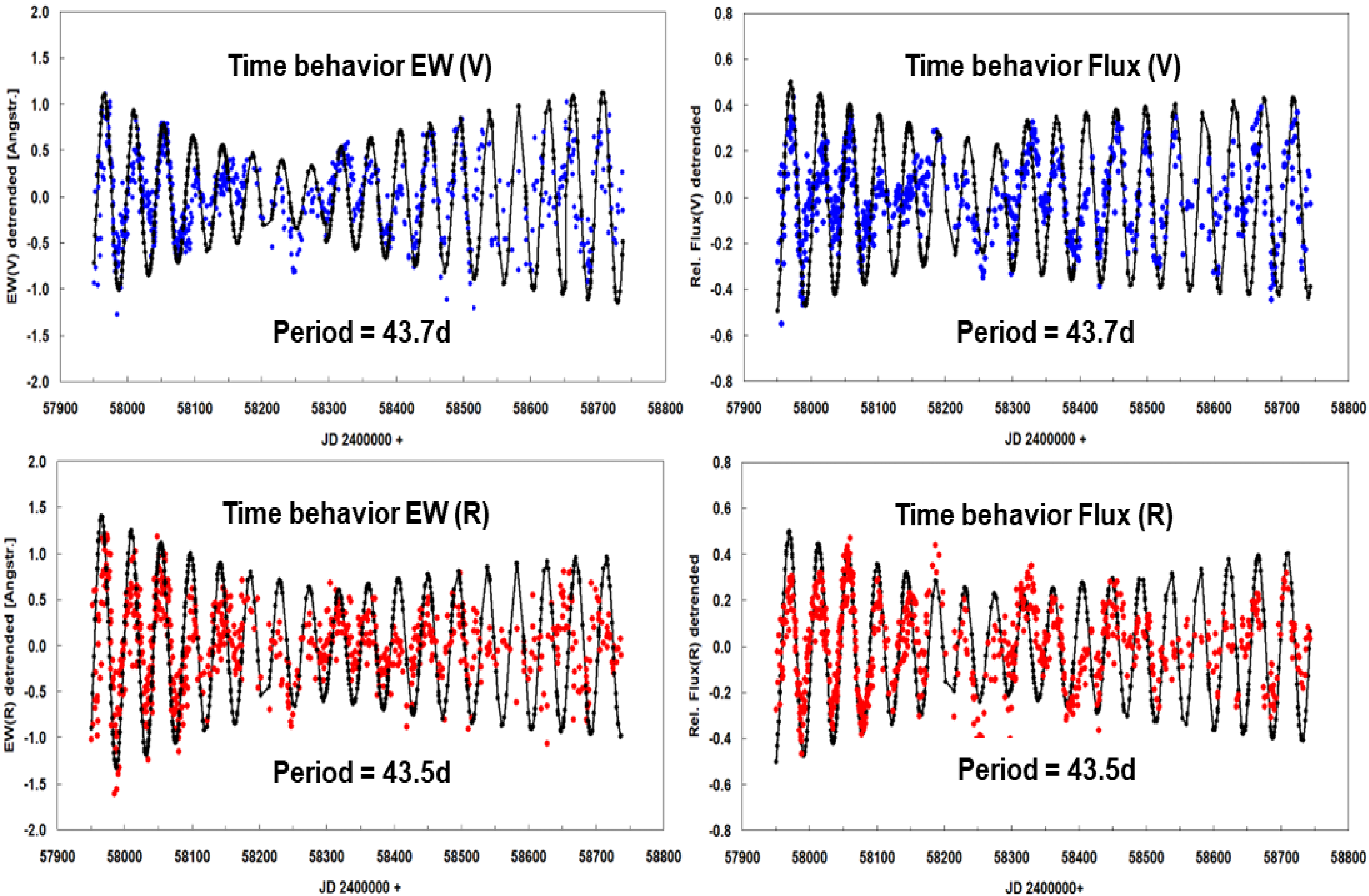





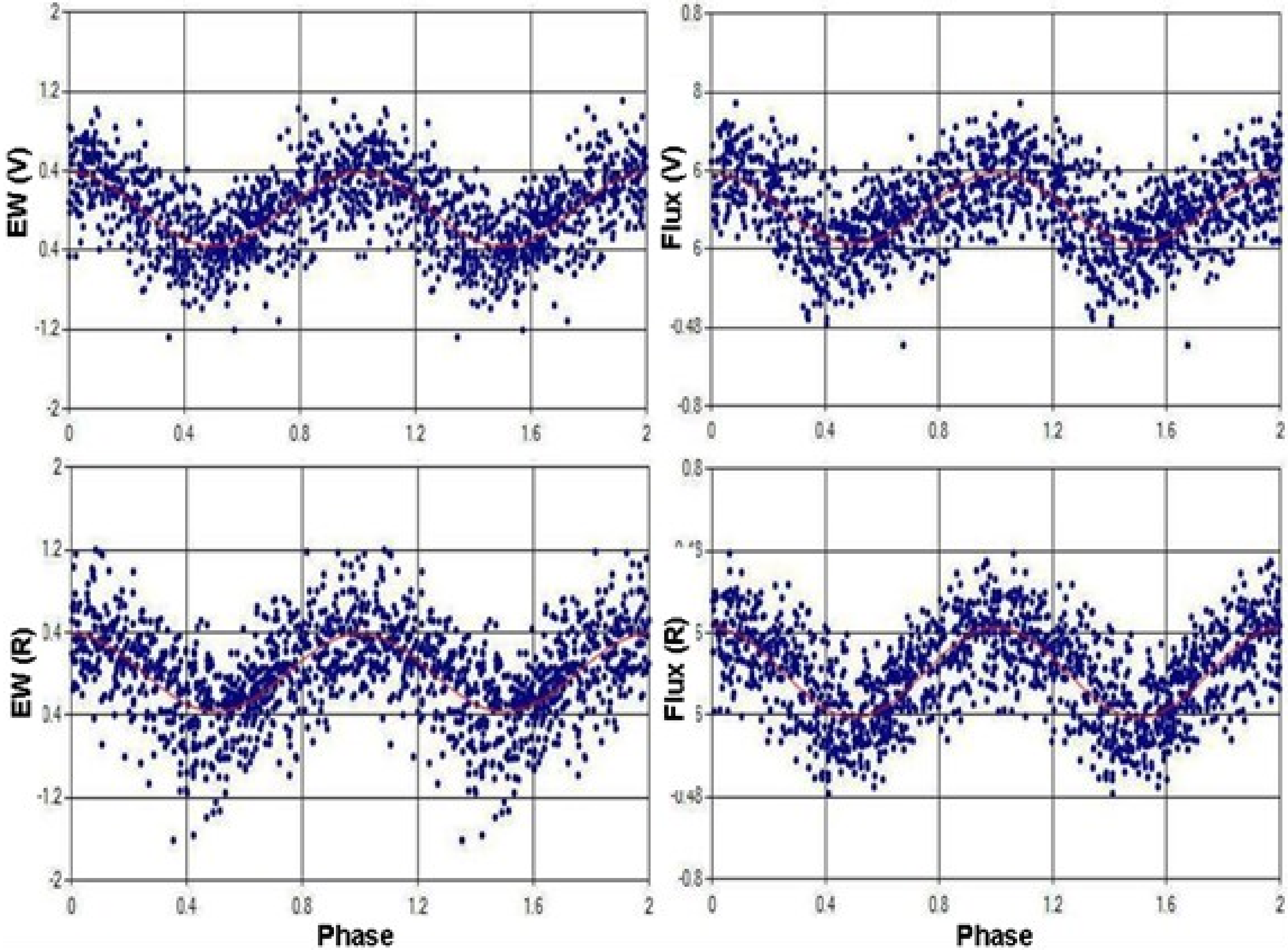

Flux measurements of the B star's upper polar axis emission, along with UV flux during eclipse, indicate that the U-band is primarily dominated by emission from the B star. During total eclipse, Umag brightness data (Braunwarth, BAV) show an almost complete disappearance of UV flux from the B star and its accretion disk, due to occultation by the M star.

Due to the coupling of the V+R emission sources with the rotation axis of the B star (extending well beyond the supergiant’s diameter along the observer’s line of sight), the observed short-period oscillations (see next figure) particularly in the upper polar jet (V-emission) suggest the following hypothesis:

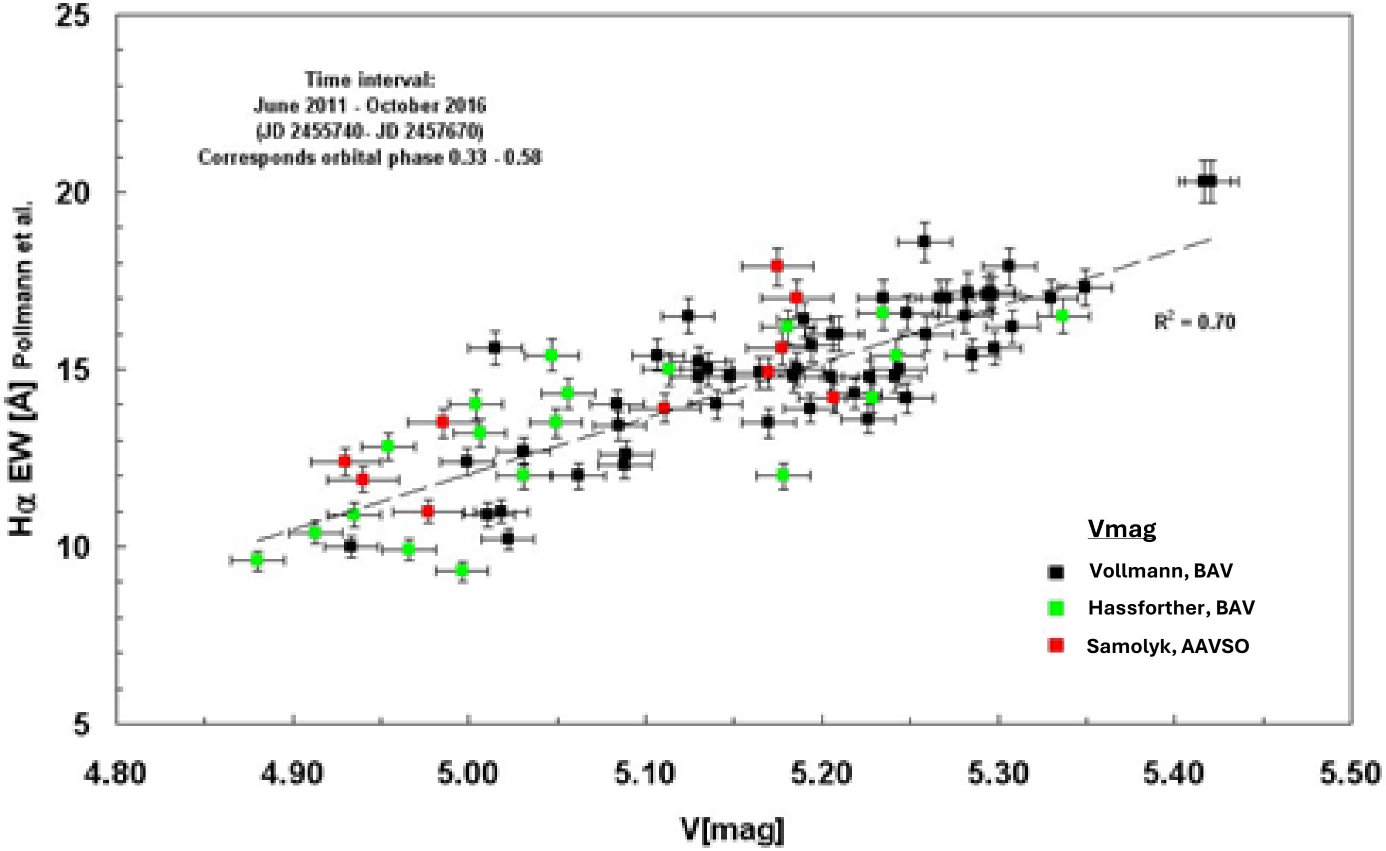
*Could these nutation-like oscillations of the rotation axis be triggered by non-radial pulsations (~50 days) of the B star, as proposed by Baldinelli (1979)?*




An observed oscillation - possibly due to nutation - in both EW and flux (R & V) indicates a short-term periodicity of approximately 43 days.




Phase plots of the 43d period of V(top) &R(bottom)
EW left, Flux right



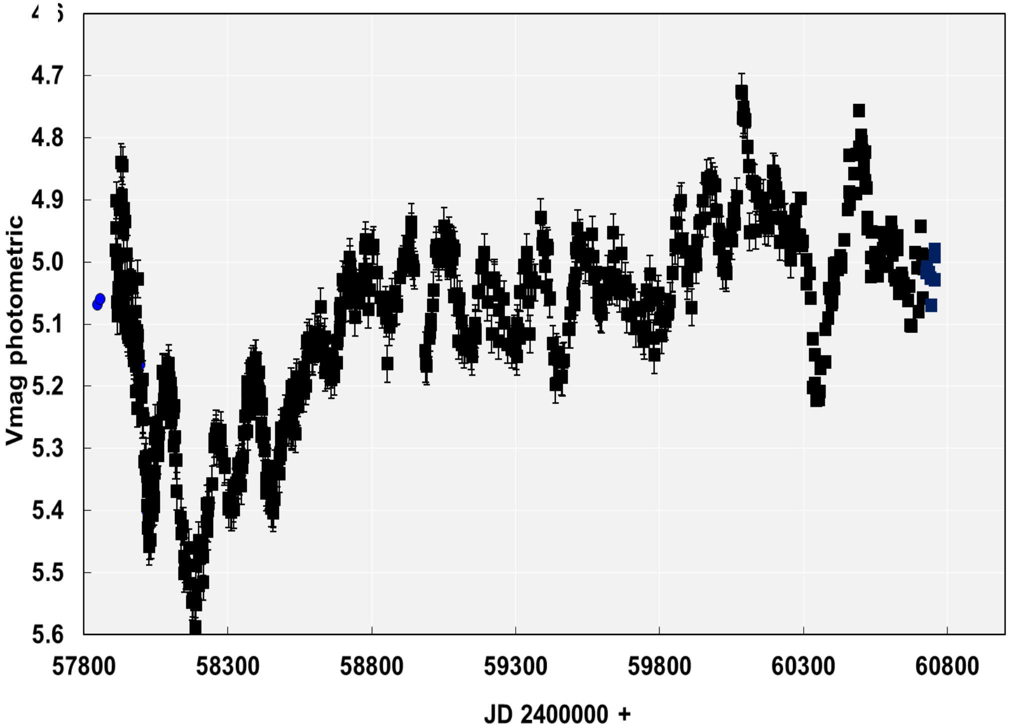

Reciprocal correlation of EW & simultaneous Vmag photometry from 01/2014 to October 10/2016.

Although this relationship is reminiscent of Be stars (Harmanec 1983), the origin of VV Cep must differ, as the majority of the continuum flux in the visual spectral range originates from the M-type supergiant (V ≈ 5.0). The B-type companion, at 7th magnitude, cannot account for the observed Hα emission

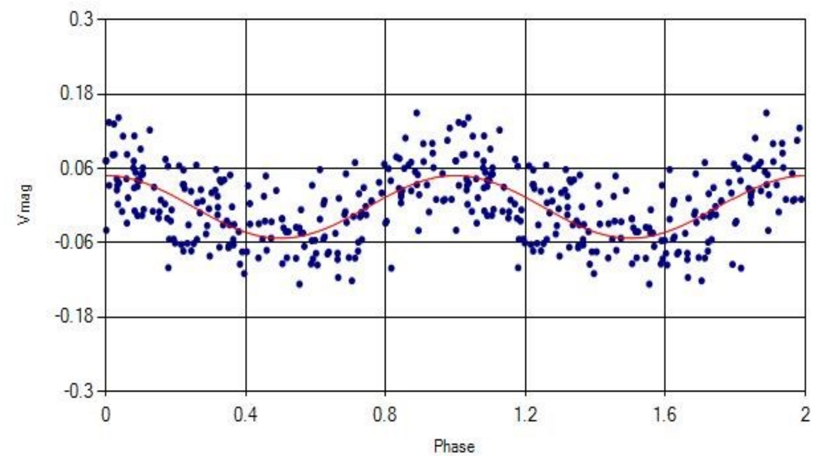
This strongly suggests that the photometric variability is intrinsic and caused by semi-regular pulsations of the M star. In this case, the variable Hα emission flux must be a consequence of the pulsations of the M star (Hayasaka et al.,Tokyo Astron. Bull., 2nd Ser., No. 247, 1977)

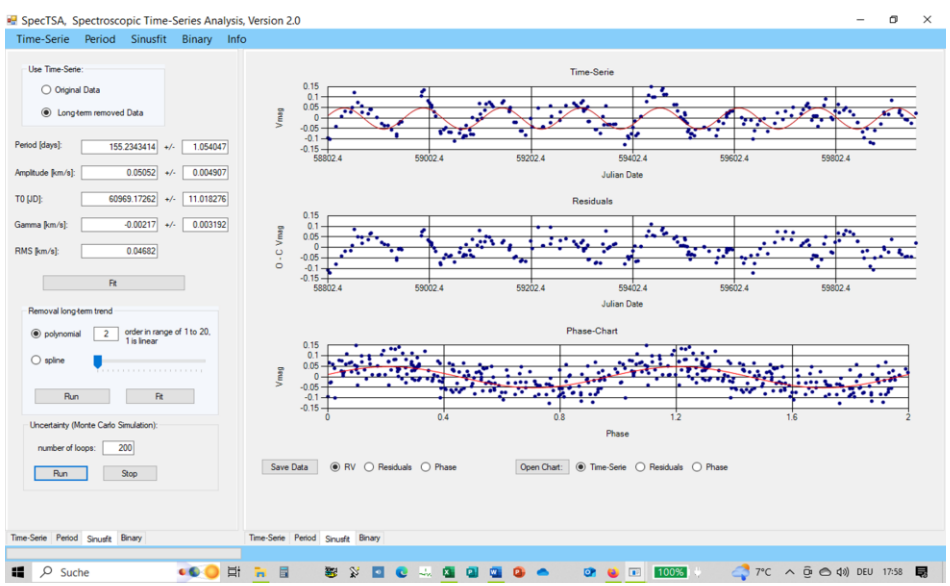
The pulsation periods and the photometric amplitudes of the variability are very similar to those of semi-regular pulsations in late supergiants. They vary on timescales of ~150 days.

A Vmag period analysis from 58800 to 59970 (next Fig.), with a Period =155 d, confirms this photometric variability in VV Cep in the next image.

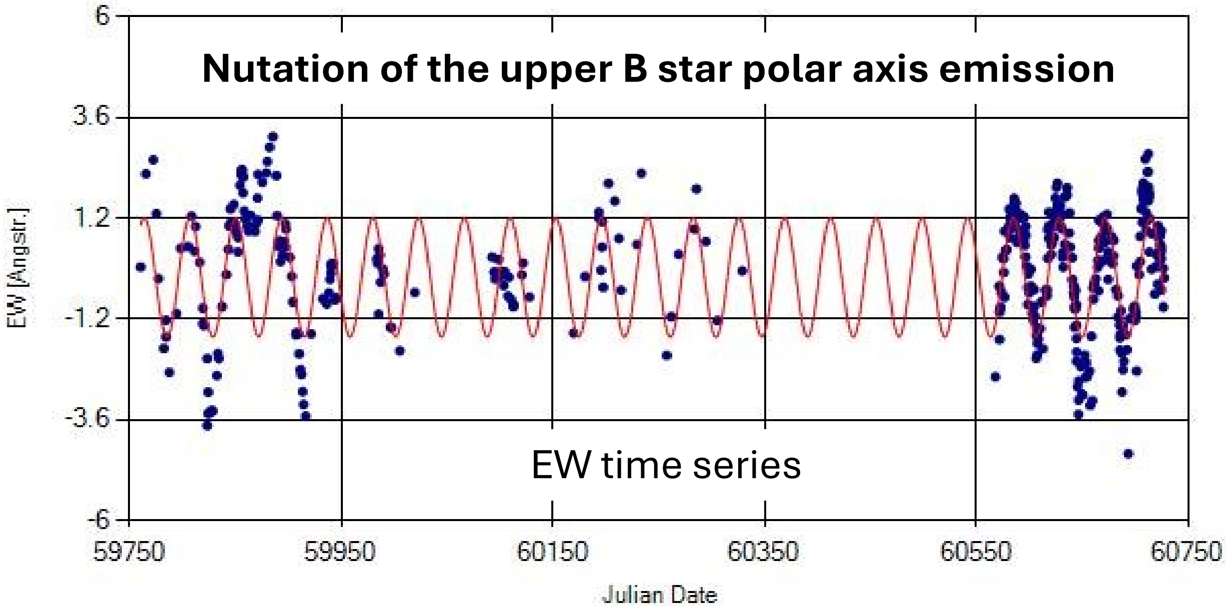


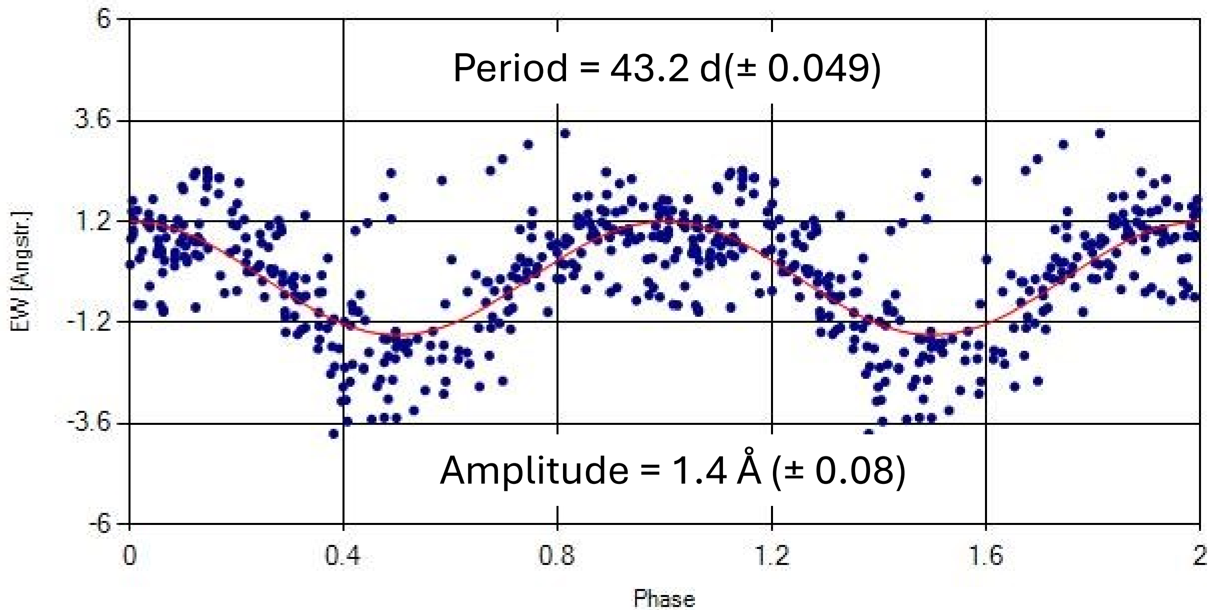

V band photometric data
by Vollmann (Vienna)
PDM Analysis of detrendet data
Period = 155 d (±1) See also David Boyd’s PERANSO analysis for additional insights.




The orbital period, based on photometric data, is approximately 7430 days (Gaposchkin 1937; Saito et al. 1980) or 7450 days (McLaughlin, ApJ. 79, 1934). Observations during the 1997/98 eclipse by Graczyk et al. (IBVS 4679) and Leedjärv et al. (A&A 349) revealed that the mid-eclipse occurred 65 and 68 days later than predicted, respectively.



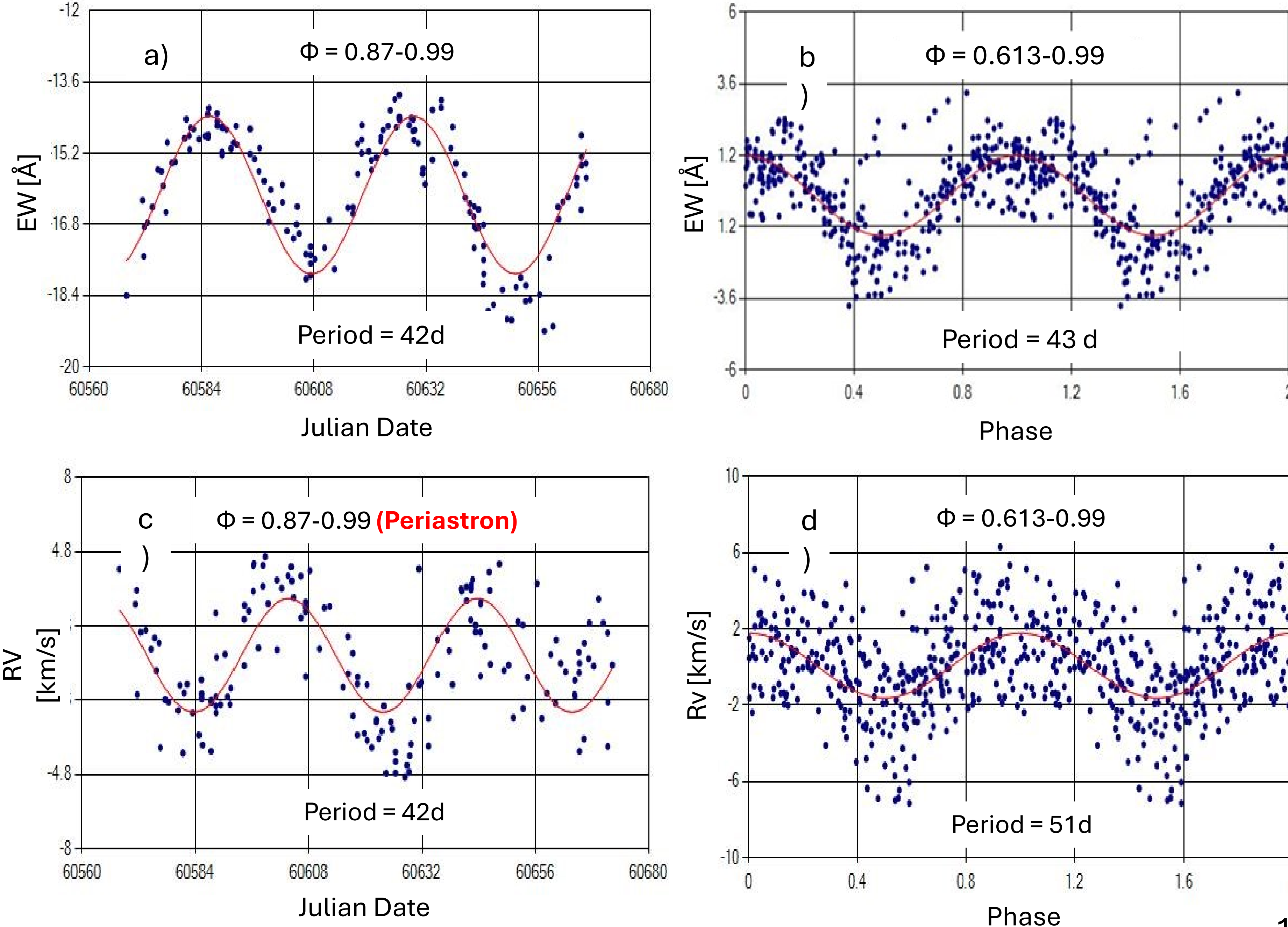

The short-term nutation oscillations shown in Figs. 4 and 5 may vary when the companion approaches periastron.
These oscillations are intended to be observed during future orbital phases.

The polar axis of the B star undergoes nutation oscillations, which are expected to produce periodic variations in radial velocity.
Actual campaign: period = 41.5d, amplitude = 3.0 km/s

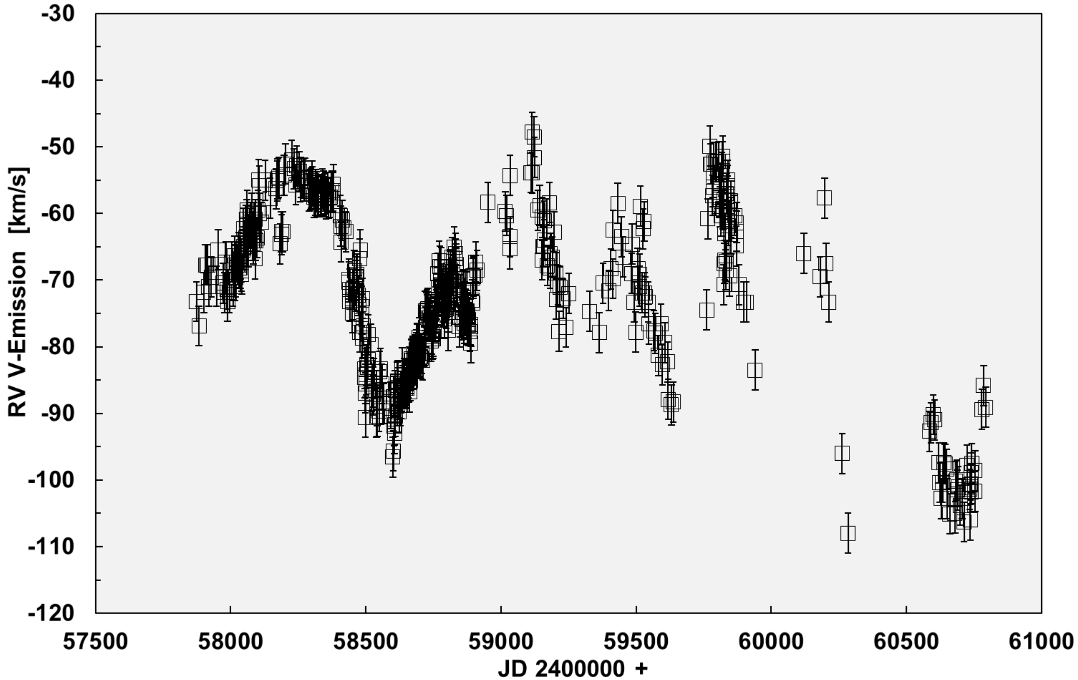
## Periodicity of Rv and EW of the upper polar axis emission before and while the periastron (next Fig.)

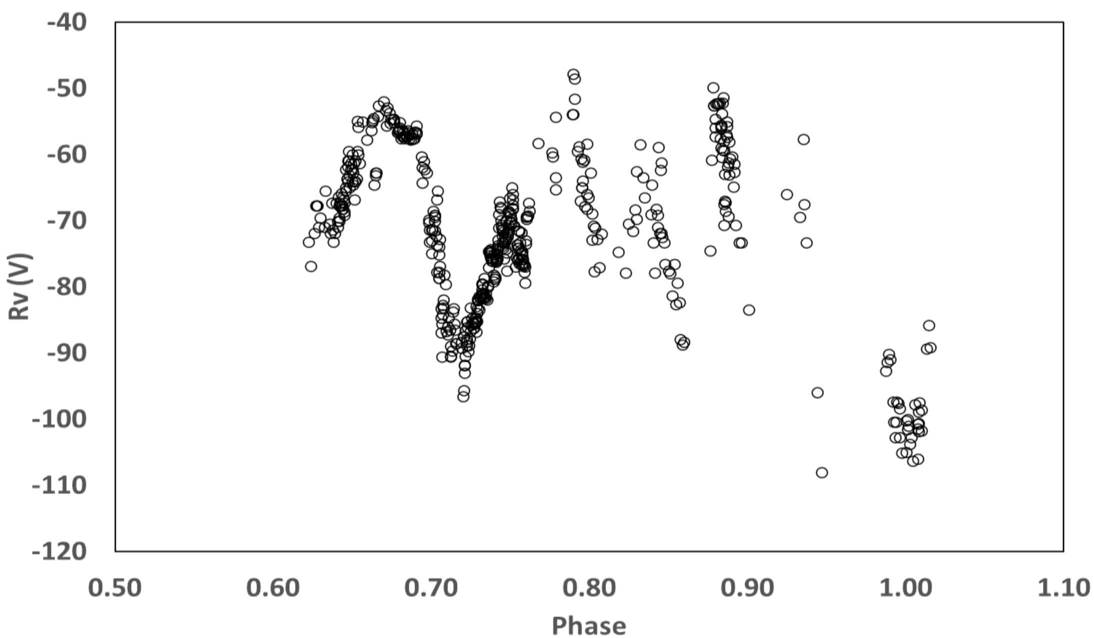
| Orbital Phase 0.6 – 0.9 | Orbital Phase 0.8 – 1.0 |
|---|---|
| EW = 42 d | EW = 42 d |
| RV = 51 d | RV = 42 d |

There is obviously, during periastron, a gravitational effect from the M star that decreases the RV period of the upper polar axis emission (i.e., increases the nutation frequency)



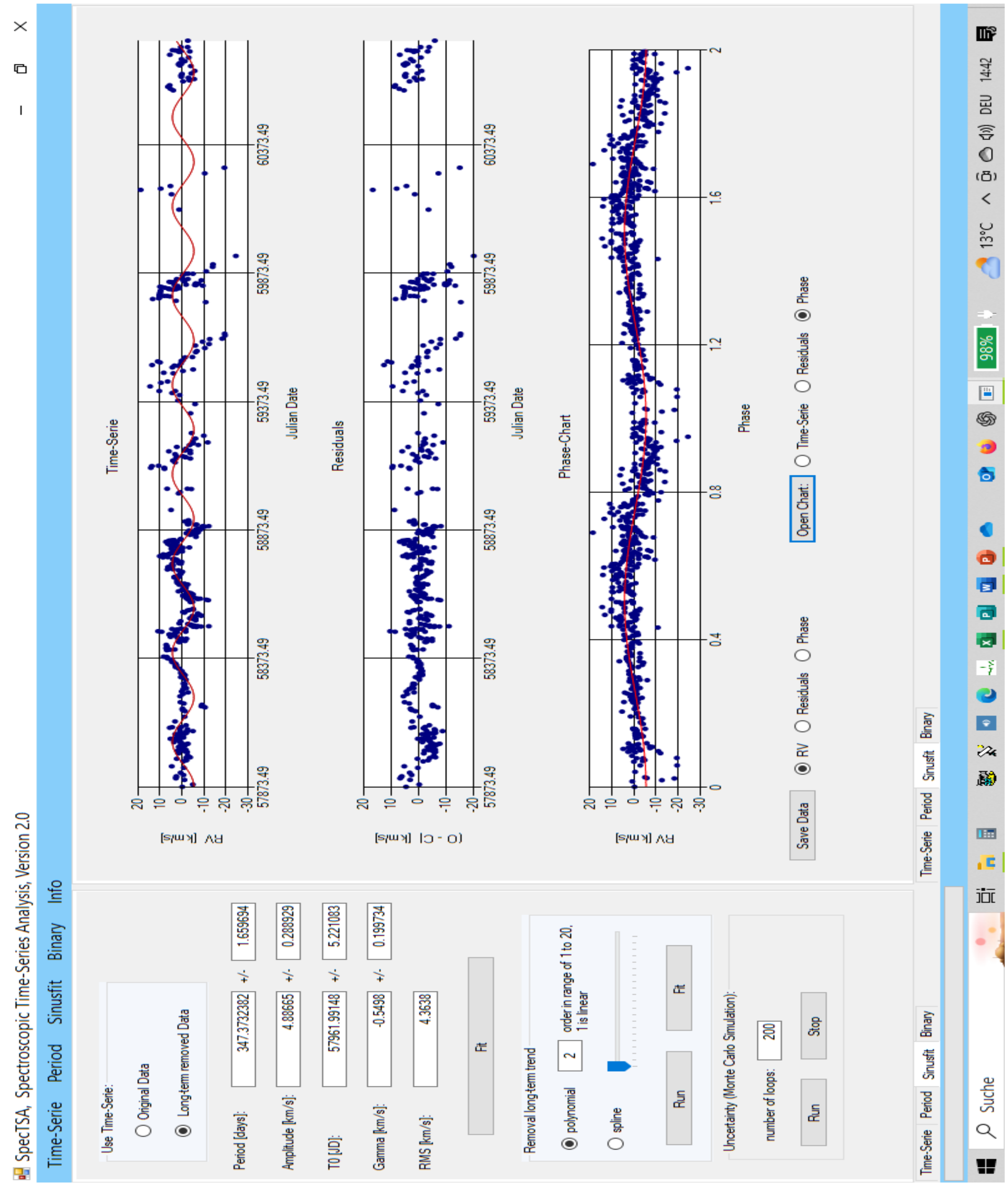
a)
Φ = 0.87-0.99
Period = 42d
EW [Å]
Julian Date
b
)
Φ = 0.613-0.99
Period = 43 d
EW [Å]
Phase
c
)
Φ = 0.87-0.99 (Periastron)
Period = 42d
RV [km/s]
Julian Date
d
)
Φ = 0.613-0.99
Period = 51d
Rv [km/s]
Phase



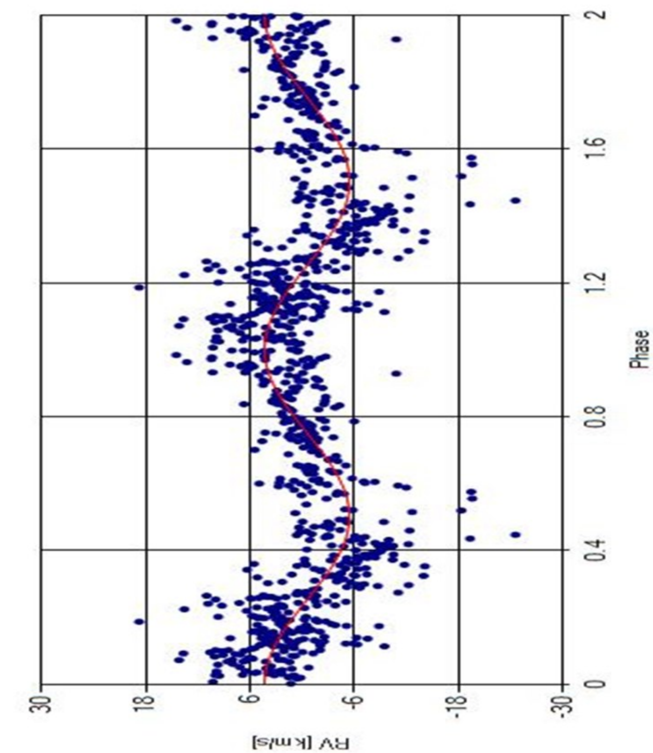




Radial velocity of the upper polar jet (V-Emission) of the B star. Wavelength calibration with metal lines of the M star.

Plot above: Time series
Plot below: Phase
[Wright 1977; P = 7430d; T = 2438389 (± 60)




# Period analysis
# Radial velocity
# of the upper polar-Jet
## (long-term removed)



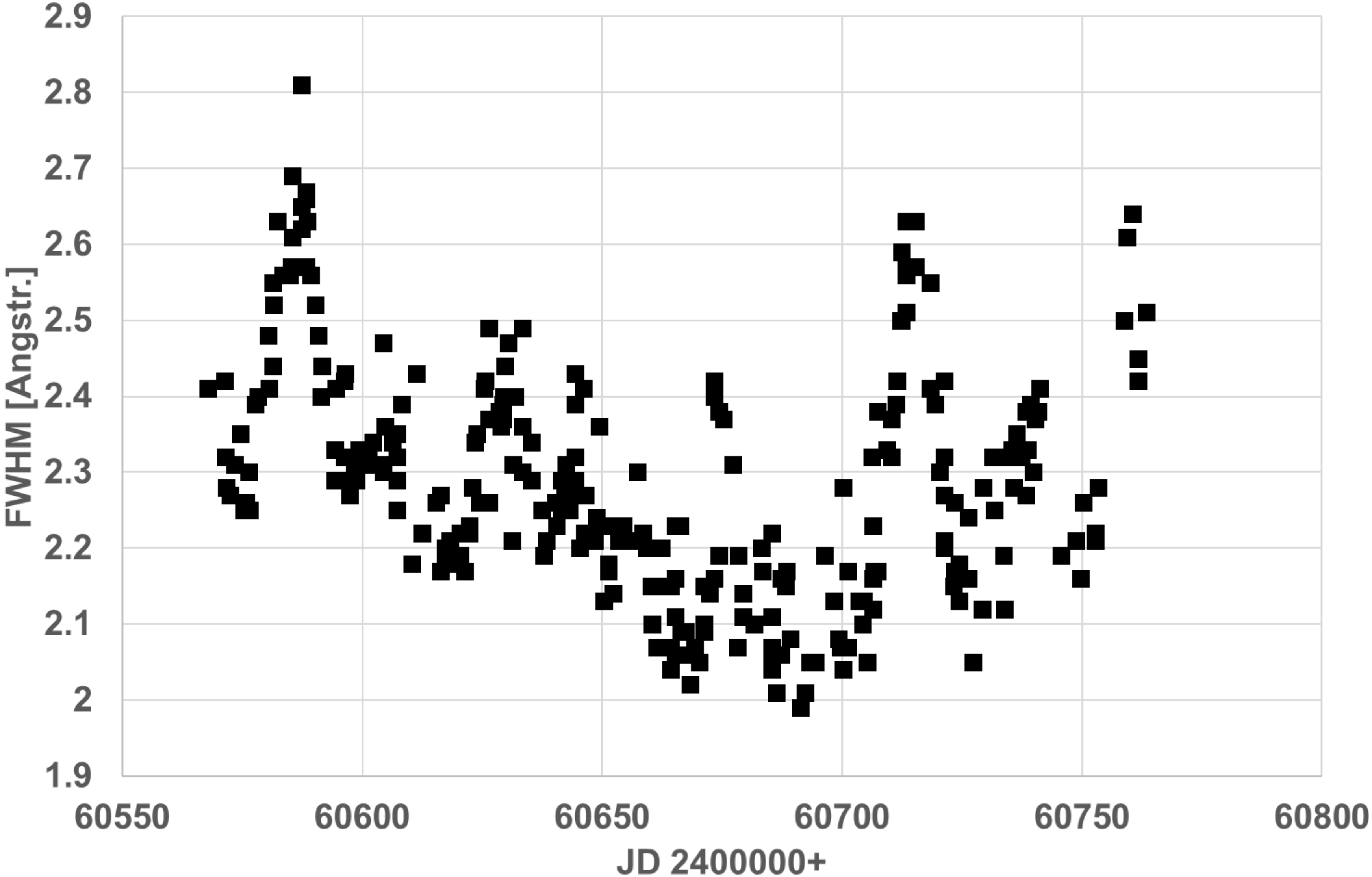

Period = 348 d (± 1.7)

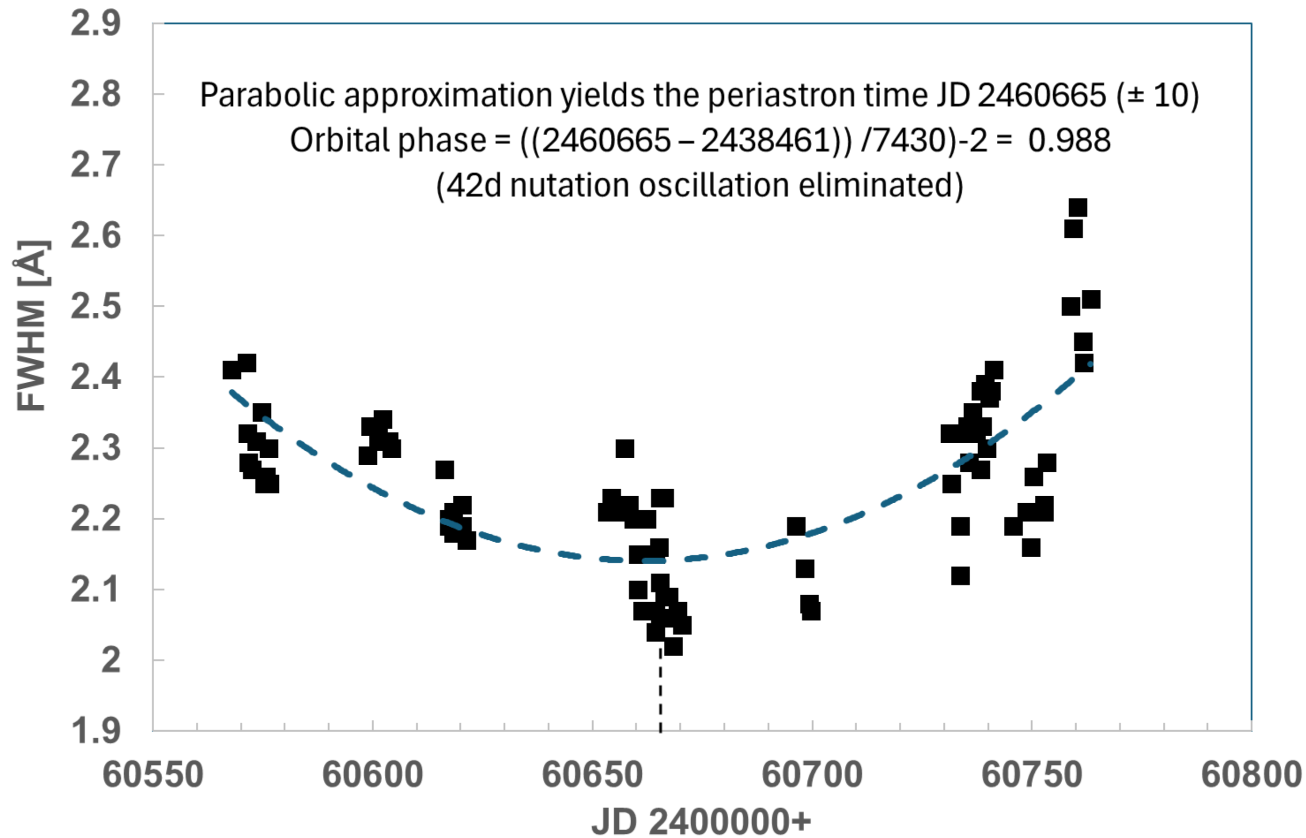
T0 = 2457962

Precession of the

rotational axis of the B star?

## Hα FWHM used to determine periastron time

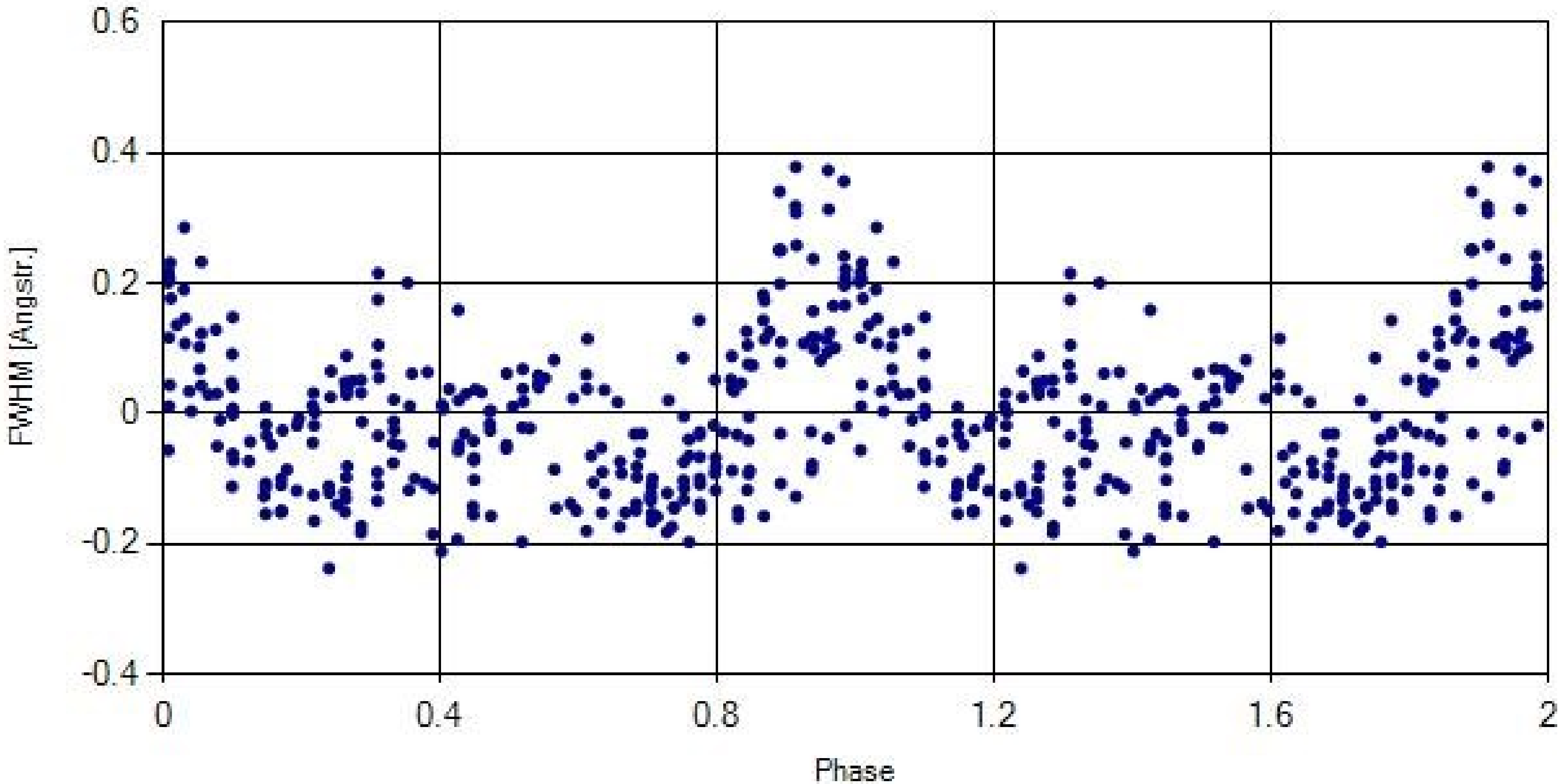





New orbital period =7430 x 0.988 = 7341(?)

As the system approaches periastron, the Doppler-induced wavelength dispersion of the blue emission (V) reaches in observers view its minimum ($\Delta\lambda_{min}$ = $FWHM_{min}$). Changes in the orbital period of binaries can result from mass transfer between the components or the ejection of mass from the system. V-band magnitude variations are not driven solely by semi-regular pulsations of the M-type supergiant but are also influenced by variable mass transfer from the M-star to the accretion disk of the B-star (Graczyk et al., IBVS 4679).

As expected, the 42-day nutation oscillation of the upper polar jet is also evident in the FWHM.




**P = 42.0d (±0.58) T0 = 58037 (±36)**