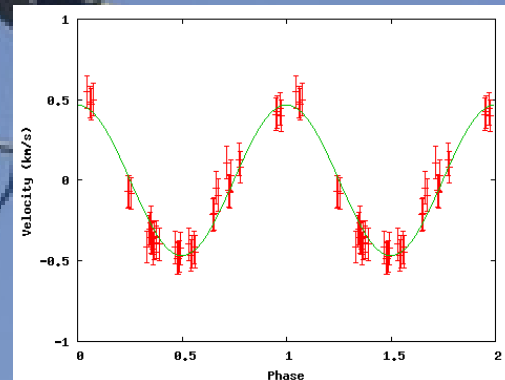


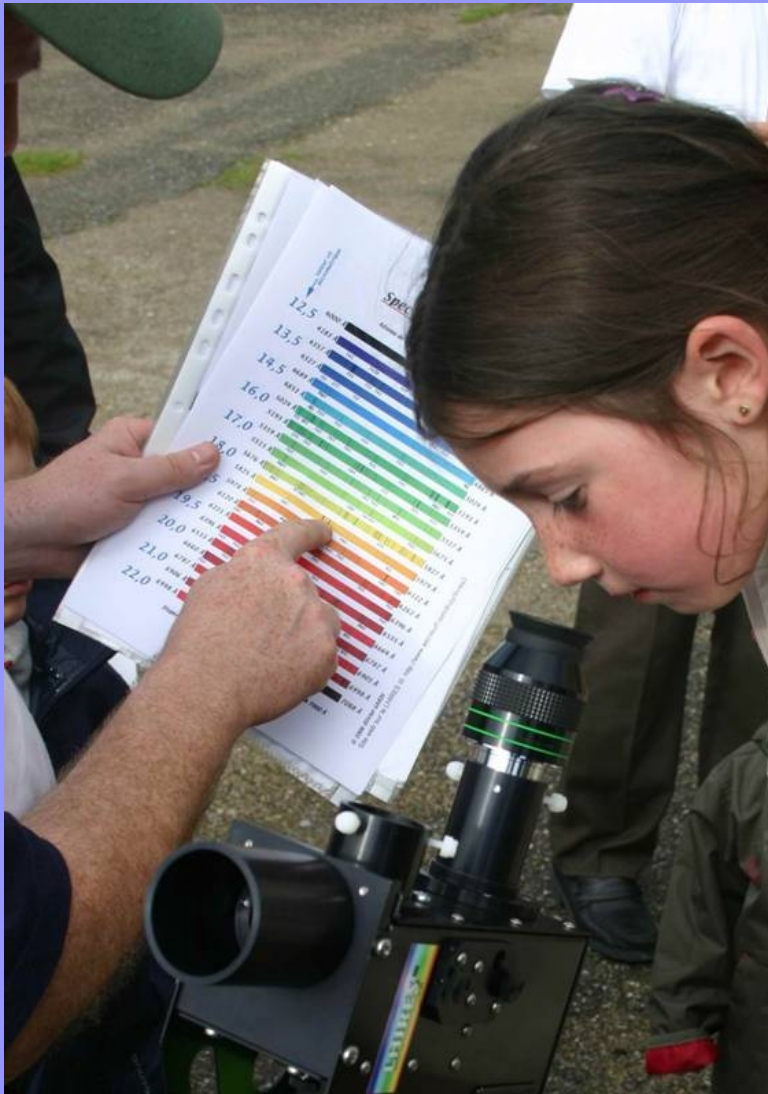
# High Resolution Spectroscopy...

## ...a quest to RV !

*Olivier Thizy*  
*[olivier.thizy@shelyak.com](mailto:olivier.thizy@shelyak.com)*



# Content

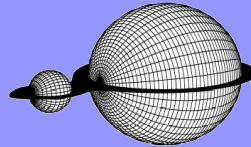


- RV as educational tool



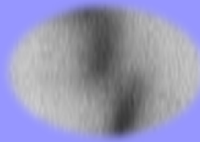
- Spectroscopic binaries
  - $\beta$  Aurigae

- Mizar



- AW Uma close binary

- Pulsating stars



- BW Vulpeculae

- $\beta$  Cephei

- Exoplanets



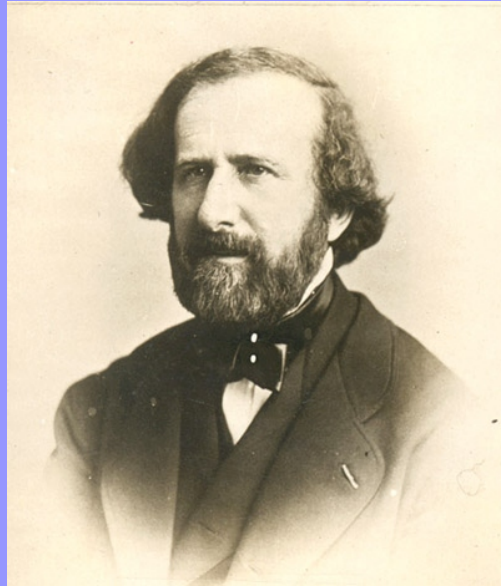
- $\tau$  Boo b

- hd189733

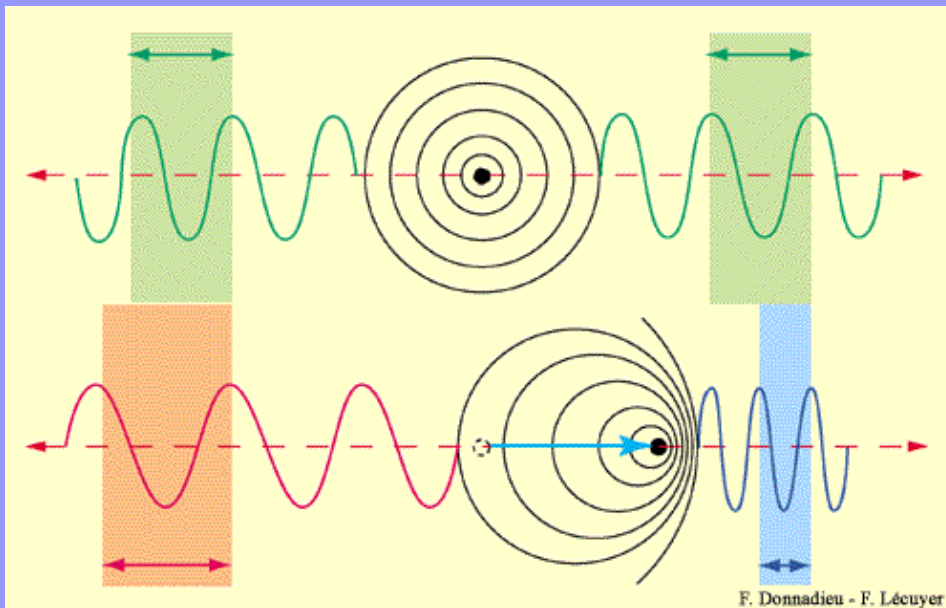
- Conclusion



# Doppler-Fizeau effect



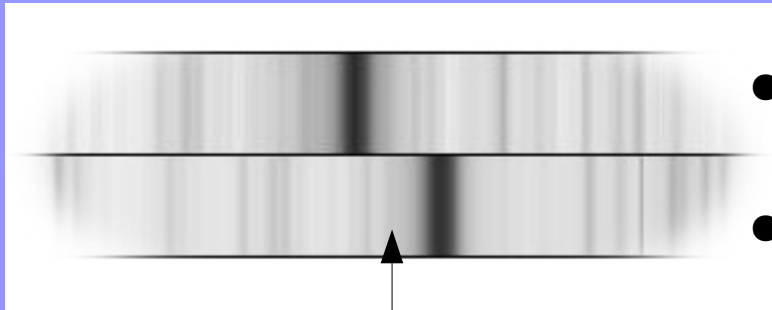
$$\frac{(\Delta \lambda)}{\lambda} = \frac{v}{c}$$





# RV = Radial Velocity

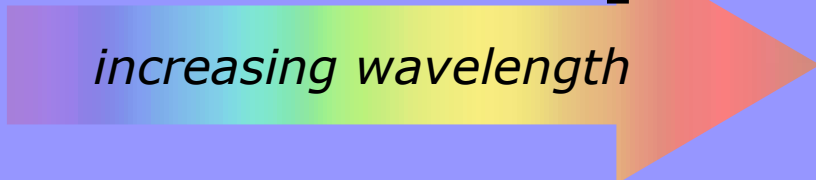
- RV (Radial Velocity) is the speed of a star projected on our line of sight
- *When a star is moving away from us, yellow light is red shifted*
- *When a star is moving toward us, yellow light is blue shifted*



- SAO104807 :  $V = -100$  km/s
- SAO112958 :  $V = +99$  km/s

•  $H\alpha$  [6563]

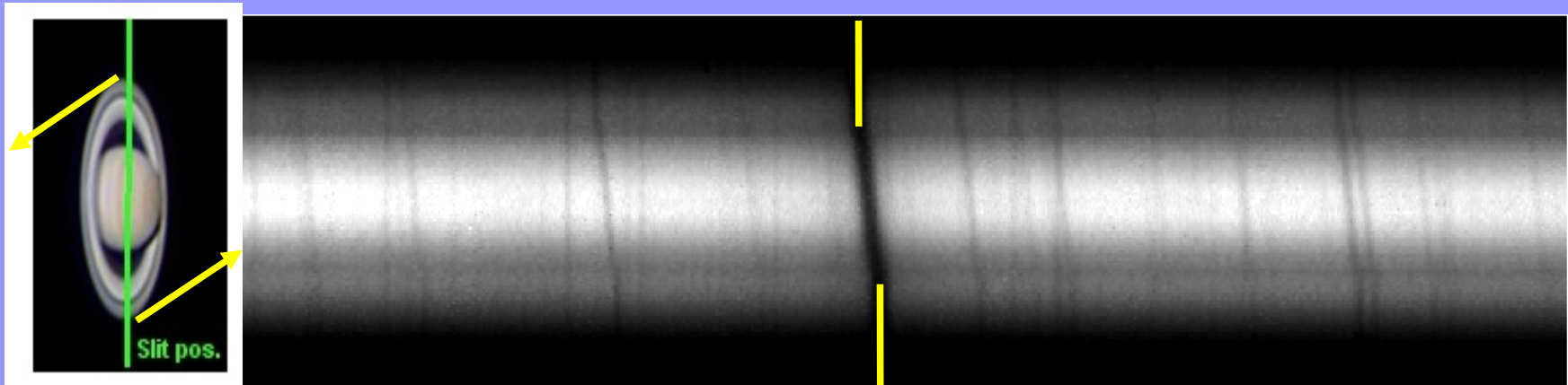
*increasing wavelength*





# RV as educational tool

- Easy math:  $V = c \cdot \Delta\lambda / \lambda$
- Single evening project: two star spectra are enough
- Even more demonstrative: Saturn's rotation



Saturn:

Shift = 7 pixels = 8,8 km/s

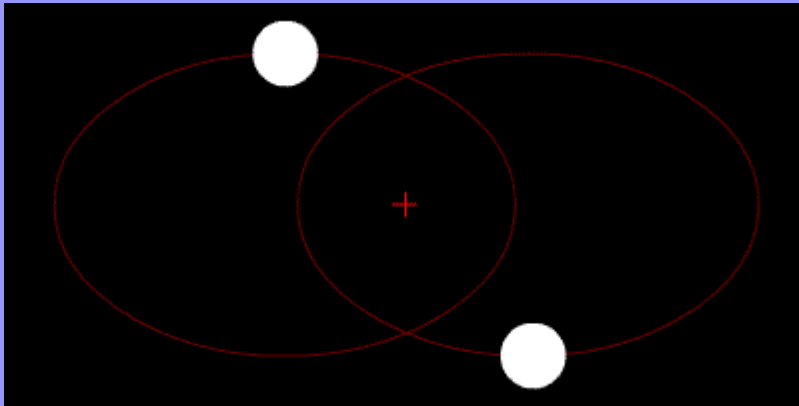
Period of 10,6 h >> R = 107511 km



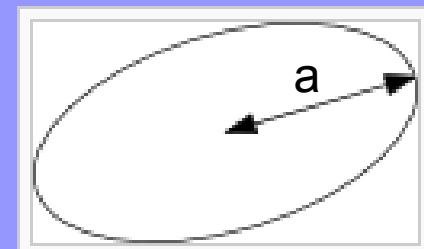
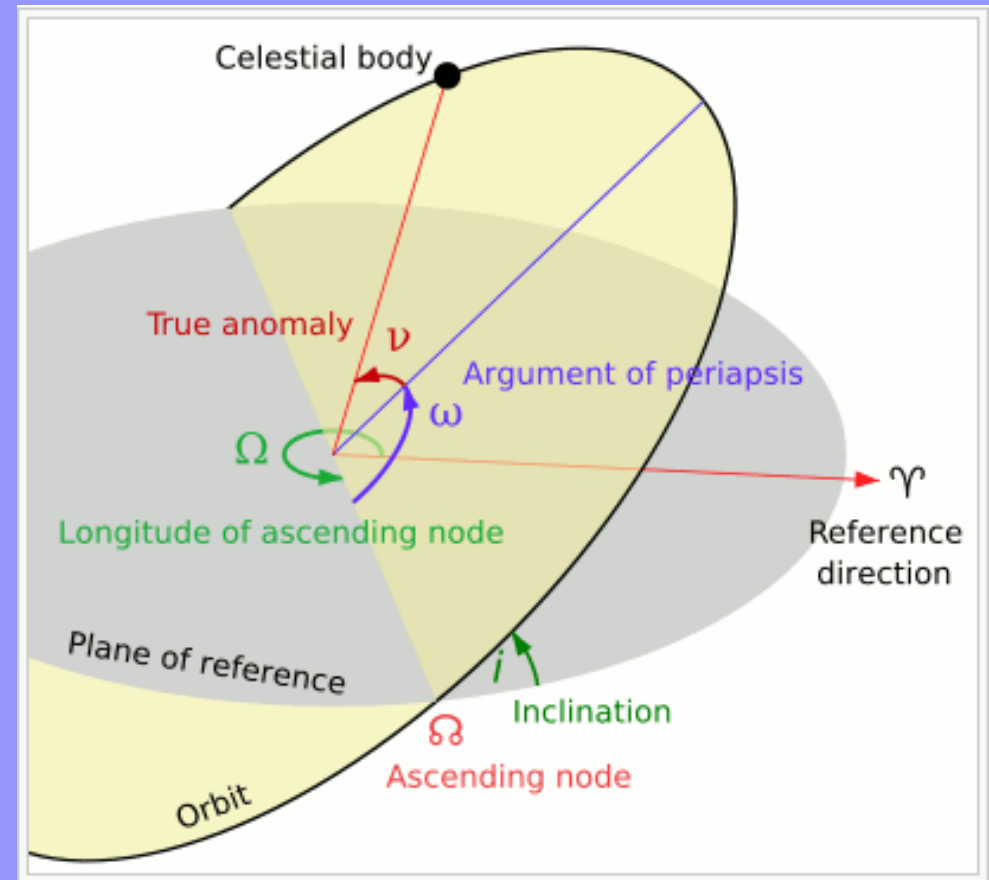
# Spectroscopic Binaries

- 50% of stars are binary (or more) systems
- Visual binaries / Spectroscopic binaries and eclipsing binaries
- John Goodricke's report on Algol in 1787
- First spectroscopic binaries discovered in 1889 (Harvard & Postdam)
- 2386 orbits listed in SB9 catalog (Pourbaix)
- Lot of information from eclipsing double line spectroscopic binaries (EB / SB2)

# Theory



➤ **1<sup>st</sup> Keplerian law:**  
**viewed from star A, star B is**  
**rotating on an ellipse with the**  
**following characteristics:**  
 *$a$  = semi-major axis,*  
 *$e$  = excentricity,*  
 *$P$  = period,*  
 *$\Omega$  = node angle,*  
 *$\omega$  = longitude of periastron from*  
*node,*  
 *$i$  = inclination of orbital plan,*  
 *$T$  = epoch of periastron*





# Some maths...

➤ **2<sup>nd</sup> Keplerian law: 'surface' speed is constant.**

*r*: distance between the stars; *v*: angle from periastron

$$\frac{r^2}{2} \frac{dv}{dt} = \frac{\pi \cdot a^2 \cdot \sqrt{1-e^2}}{P}$$

$$r = \frac{a \cdot (1-e^2)}{1+e \cos v}$$

➤ **3<sup>rd</sup> Keplerian law: Period, semi-axis & total mass  $M_1+M_2$  are linked**

$$\frac{a^3}{P^2} = M_1 + M_2$$

➤ **Half amplitude  $K$  is linked to  $V_r - V_\gamma$ ,  $e$ ,  $\omega$ ,  $v(t)$ :**

$$V_r = V_\gamma + K \cdot [e \cos \omega + \cos(\omega + v(t))]$$

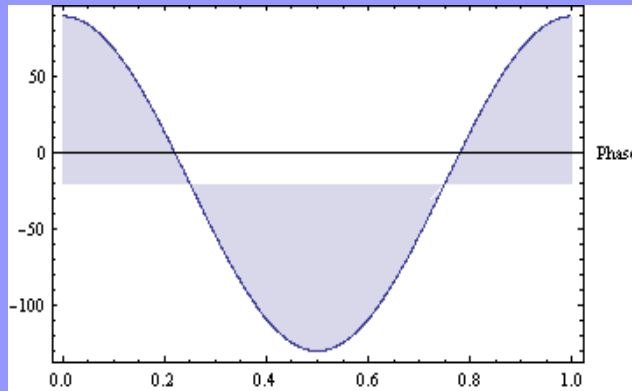
**For circular orbits:  $v(t) = 2\pi t/P$**

$$K_{1,2} = \frac{2\pi \cdot a_{1,2} \cdot \sin i}{P \sqrt{1-e^2}} \quad \text{and} \quad K_{2,1} = \frac{2\pi \cdot a_{2,1} \cdot \sin i}{P \sqrt{1-e^2}}$$

$$\frac{K_1}{K_2} = \frac{M_2}{M_1}$$



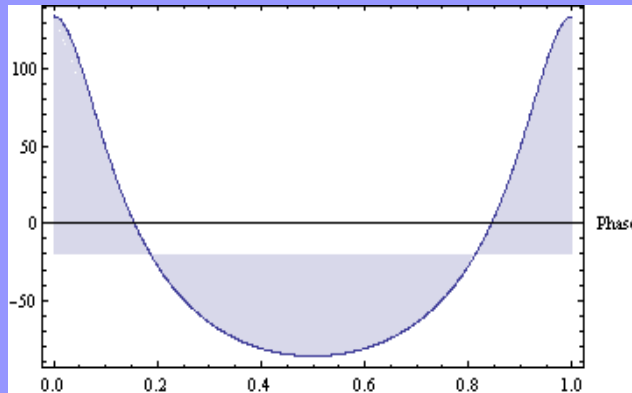
# RV curve shapes



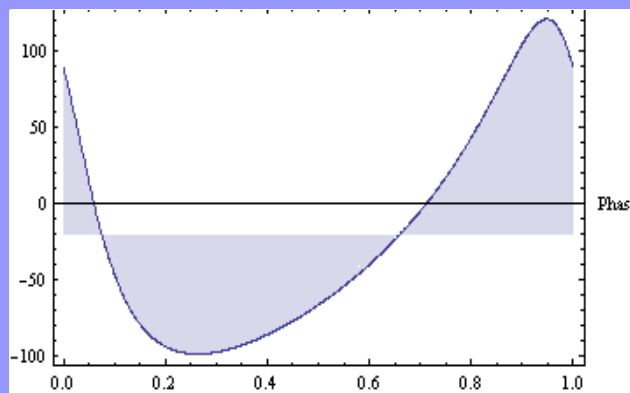
$e=0$

$$V_r = V_\gamma + K \cdot [e \cdot \cos \omega + \cos(\omega + v)]$$

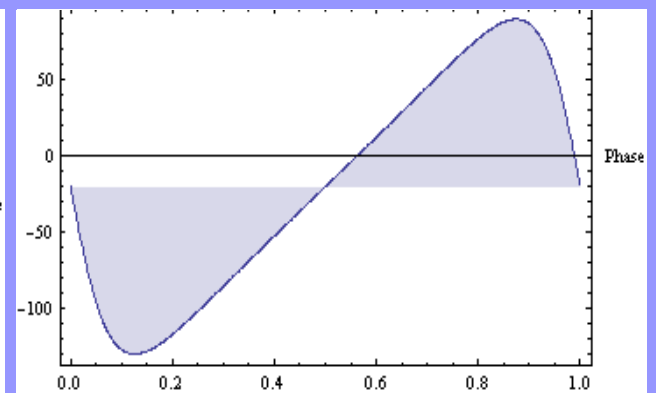
( $K = 110 \text{ km.s}^{-1}$  ;  $V_\gamma = -20 \text{ km.s}^{-1}$ )



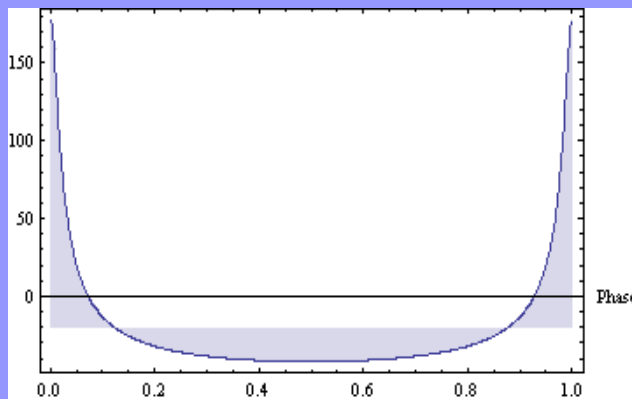
$e=0.4; \omega=0$



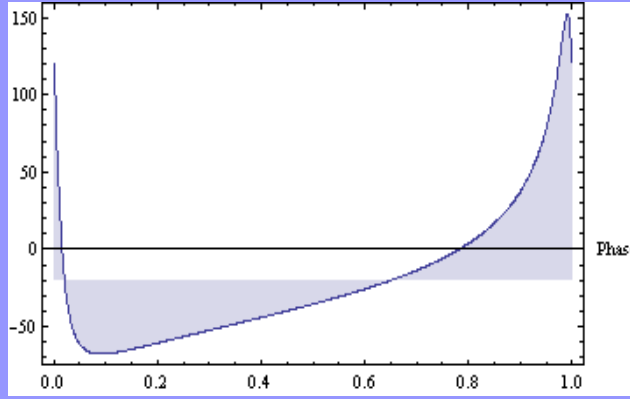
$e=0.4; \omega=45^\circ$



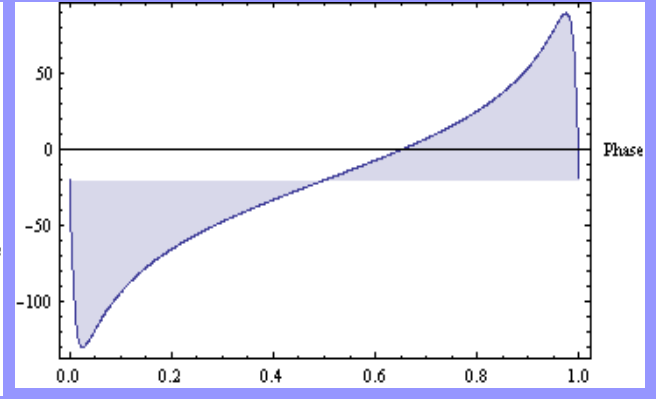
$e=0.4; \omega=90^\circ$



$e=0.8; \omega=0$

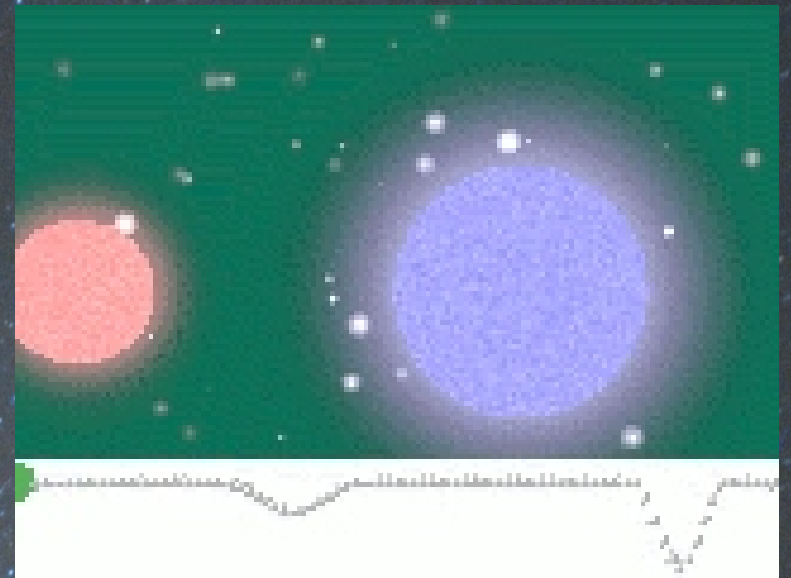


$e=0.8; \omega=45^\circ$



$e=0.8; \omega=90^\circ$

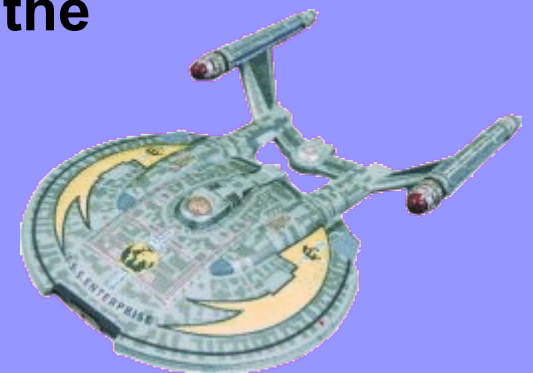
# $\beta$ Aurigae





# $\beta$ Aurigae

- Menkalinan or Menkarlina; the shoulder of the 'charioteer'
- HR 2088, HD 40183;  $\alpha_{2000} = 05^{\text{h}}59^{\text{m}}31.7^{\text{s}}$ ,  $\delta_{2000} = 44^{\circ}56'50.8''$
- $M_v = 1.90\text{-}1.97$  (variable star, eclipsing binary)
- Type A1IV star moving from hydrogen to helium burning and becoming a giant star such as Aldebaran
- Second star to have been discovered as spectroscopic binary (after Mizar); discovered by Antonia Maury – part of Pickering's women's team.
- Rotation in less than 4 days, faster than Mizar (20 & 175 days)
- Distance: 80 light years
- In one of the original Star Trek series, the crew of the Enterprise is en route to the  $\beta$  Aurigae system to study the system's two large binary components !





# Target selection

| Designation | Comp | Coord2000        | Mag1 | Mag2 | Sp1      | Sp2   | Period | Eccentricity | Periastr<br>(deg) | Periastr<br>(-2400000) | K1    | K2    | Radial<br>Vel Bibcode      |
|-------------|------|------------------|------|------|----------|-------|--------|--------------|-------------------|------------------------|-------|-------|----------------------------|
| pi Cas      |      | 00432809+4701287 | 4.94 |      | A5V      |       | 1.96   | 0            | 0                 | 27535.74               | 120.5 | 122.1 | 12.9 1955MmSAI...27...65M  |
| nu And      |      | 00494883+4104442 | 4.53 |      | B5V      | F8V   | 4.28   | 0.03         | 25                | 18155.67               | 71.7  | 101.9 | -23.5 1978ApJS...36...241A |
| gamma And   | B    | 02035392+4219475 | 4.84 |      | B9.5V    | B9.5V | 2.67   | 0.29         | 175.2             | 36122.18               | 141   | 112.5 | 2.5 1960ApJ...131...119M   |
| beta Per    | A    | 03081013+4057203 | 2.12 |      | B8V      | Am    | 2.87   | 0.02         | 62                | 28482.74               | 44    | 201   | 1971ApJ...168...443H       |
| o Per       | A    | 03441913+3217178 | 3.83 |      | B1III    |       | 4.42   | 0.05         | 344               | 27325.62               | 109.3 | 159.4 | 19.8 1960ApJ...131...122L  |
| epsilon Per | A    | 03575123+4000368 | 2.9  |      | B0.5III  |       | 2.48   | 0.22         | 118               | 48130.60               | 42    | 52    | -1 1992ApJ...393...666M    |
| lambda Tau  | Aa   | 04004082+1229254 | 3.47 |      | B3V      | A4IV  | 3.95   | 0            | 0                 | 44658.40               | 56.8  | 213.4 | 1982ApJ...263...289F       |
| 88 Tau      |      | 04353923+1009393 | 4.24 |      | Am       |       | 3.57   | 0            | 0                 | 19735.89               | 76.3  |       | 28.7 1913LicOB...7...104W  |
| 94 Tau      | A    | 04421470+2257251 | 4.28 |      | B3V      |       | 2.96   | 0.05         | 126.7             | 36425.25               | 53.6  | 179   | 12.3 1961PDAO...11...385P  |
| pi^5 Ori    |      | 04541510+0226264 | 3.69 |      | B2III    |       | 3.7    | 0            | 0                 | 17921.64               | 57.88 |       | 24.2 1913ApJ...38...175L   |
| eta Ori     | Aab  | 05242862-0223497 | 3.35 |      | B1V      |       | 7.98   | 0            | 0                 | 15839.72               | 145.2 |       | 35.9 1971AJ.....76...544L  |
| psi Ori     | A    | 05265023+0305444 | 4.59 |      | B1III    | B2V   | 2.53   | 0.04         | 285               | 37685.23               | 139.1 | 219   | 26.3 1985PASP...97...428L  |
| delta Ori   | A    | 05320040-0017567 | 2.14 | 2.26 | O9.5II   |       | 5.73   | 0.1          | 358.7             | 20024.21               | 101   |       | 20.1 1914POMic...1...118C  |
| iota Ori    | A    | 05352598-0554356 | 2.76 |      | O9III    | B1III | 29.13  | 0.76         | 123.7             | 45236.49               | 102.5 |       | 28.7 1987Obs...107...5S    |
| HD 37756    |      | 05405072-0107436 | 4.93 |      | B3III    |       | 27.15  | 0.73         | 84.6              | 29991.10               | 88.5  | 137.9 | 36.2 1953AJ.....58...46P   |
| 136 Tau     |      | 05531964+2736442 | 4.54 |      | B9.5V    |       | 5.97   | 0            | 0                 | 20147.25               | 48.9  | 71    | -17.2 1936ApJ...84...85L   |
| beta Aur    | A    | 05593177+4456508 | 1.9  | 2.83 | A2IV     | A2IV  | 3.96   | 0            | 0                 | 31075.76               | 107.5 | 111.5 | -17.1 1948ApJ...108...504S |
| 1 Gem       | A    | 06040722+2315491 | 4.16 |      | G8III-IV |       | 9.6    | 0            | 0                 | 40443.13               | 51.7  |       | 31.7 1976Obs...96...188G   |
| omicron Leo | A    | 09410912+0953326 | 3.52 |      | A5V      | F6II  | 14.5   | 0            | 0                 | 14660.30               | 63.1  | 54.1  | 27.1 1908LicOB...5...21P   |
| 55 UMa      |      | 11190794+3811086 | 4.75 |      | A2V      |       | 2.55   | 0.43         | 74.3              | 34830.88               | 80.4  |       | -4.6 1981MNRAS.195...805L  |
| zeta^1 UMa  | A    | 13235542+5455315 | 2.27 |      | A2V      |       | 20.54  | 0.54         | 104.2             | 36997.21               | 68.8  | 67.6  | -5.6 1961JO.....44...83F   |
| d Boo       |      | 14102395+2505306 | 4.82 |      | F8IV     |       | 9.6    | 0.19         | 290               | 17680.05               | 67.4  | 66.5  | 9.1 1976ApJS...30...273A   |
| delta Lib   |      | 15005839-0831082 | 4.92 | 5.9  | A0V      | G     | 2.33   | 0.07         | 115.5             | 43319.27               | 76.6  | 218.7 | -40 1978ApJ...221...608T   |
| epsilon Her |      | 17001741+3055348 | 3.92 |      | A0V      |       | 4.02   | 0.02         | 138               | 17947.24               | 70.7  | 112   | -24.2 1936ApJ...84...85L   |
| 68 Her      |      | 17171957+3306004 | 4.77 | 5.4  | B2IV     | B8III | 2.05   | 0            | 0                 | 40053.47               | 98    | 259   | -17.1 1984MNRAS.211...943H |
| HD 157950   |      | 17263794-0505114 | 4.53 |      | F3V      |       | 26.28  | 0.49         | 14.5              | 18411.52               | 47.5  | 50.7  | 0.4 1915PDO.....2...331P   |
| zeta^1 Lyr  |      | 18444634+3736182 | 4.35 |      | Am       |       | 4.3    | 0.01         | 0                 | 40000.72               | 51.6  |       | -24.9 1985ApJS...59...229A |
| beta Lyr    | A    | 18500479+3321456 | 3.38 | 4.29 | B8pe     |       | 12.93  | 0            | 0                 | 42260.92               | 184   |       | -17.8 1975PASP...87...237B |
| theta Aql   |      | 20111826-0049173 | 3.24 |      | B9III    | B9III | 17.12  | 0.61         | 34.5              | 31636.34               | 51    | 63.7  | -27.9 1946ApJ...104...282C |
| 57 Cyg      |      | 20531475+4423142 | 4.77 |      | B5V      | B5V   | 2.85   | 0.15         | 159.6             | 41571.28               | 111.9 | 126   | -21.1 1973MNRAS.164...101H |
| kappa Peg   | B    | 21443870+2538420 | 4.15 |      | F5IV     |       | 5.97   | 0.03         | 148               | 19054.96               | 41.7  |       | 1934ApJ...79...440L        |
| iota Peg    |      | 22070047+2520422 | 3.76 |      | F5V      |       | 10.21  | 0            | 0                 | 45320.00               | 48.1  | 77.9  | -5.5 1983PASP...95...1000F |
| 2 Lac       | A    | 22210153+4632116 | 4.57 |      | B6IV     | B6V   | 2.62   | 0.04         | 97.4              | 27700.80               | 79.5  | 100   | -8.9 1974MNRAS.169...323H  |
| HD 221253   | A    | 23300192+5832561 | 4.88 |      | B3V      |       | 6.07   | 0.25         | 31.4              | 40087.19               | 56.7  |       | -13.4 1971PDDO....3...99G  |

Source: The Ninth Catalogue of Spectroscopic Binary Orbits (Version September 2005). Pourbaix D., Tokovinin, A.A, Batten A.H., Fekel F.C., Hartkopf W.I., Levato H., Morell N.I., Torres G., Udry S. Astron. Astrophys. 424, 272 (2004)



# My first spectroscopic binary !

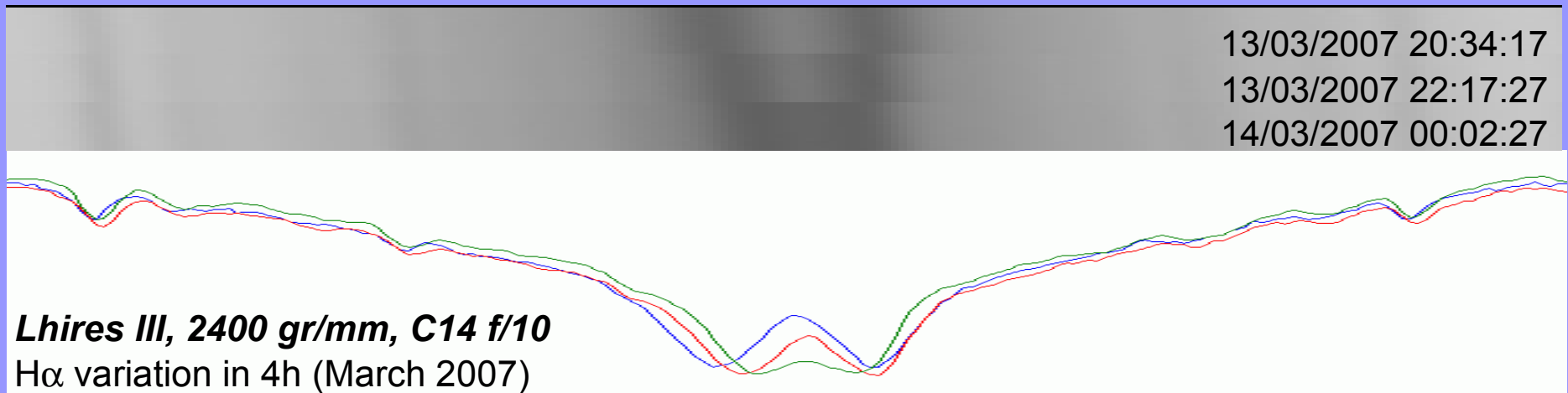
- First spectrum taken during a spectro training week: whouhaouhhhh two hydrogene lines well split !



- Another spectrum taken 3 days later: one line visible only !!



- Observations on the same night



- Definitely a star worth studying...





# Observations

- **31 spectra recorded by 5 different people**  
*(O. Thizy, JP. Masviel, J. Ribeiro, F. Cochard, E. Barbotin)*
- **All spectra recorded with Lhires III spectrographs**
- **Telescopes from 8" (Takahashi CN212) to 24" (AstroQueyras)**
- **From August 2006 to October 2007**
- **Processing:**
  - *Pre-processing*
  - *Spectra extraction*
  - *Calibration (Neon or atmospheric lines)*
  - *Heliocentric correction*
  - *Atmospheric lines removed*



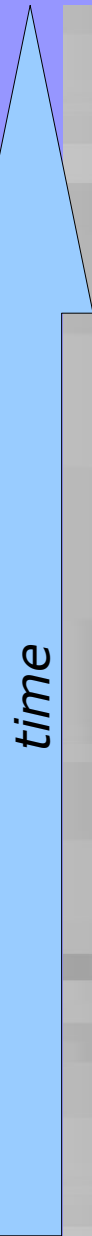


# CALA observatory





# Spectrogram



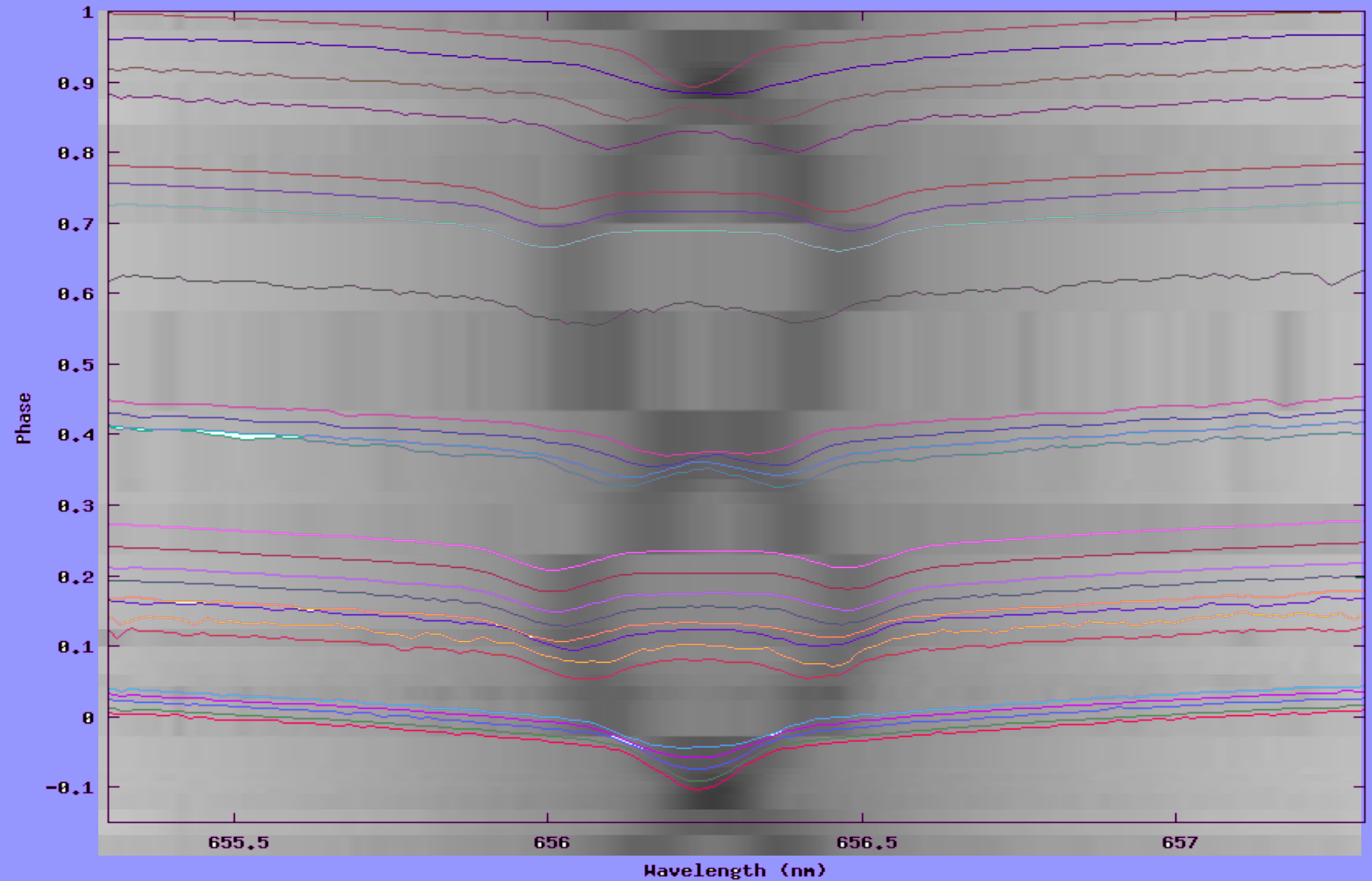
time



increasing wavelength



# Spectral profiles





$$V_r = \frac{\Delta \lambda}{\lambda_0} \cdot c$$

# Measures

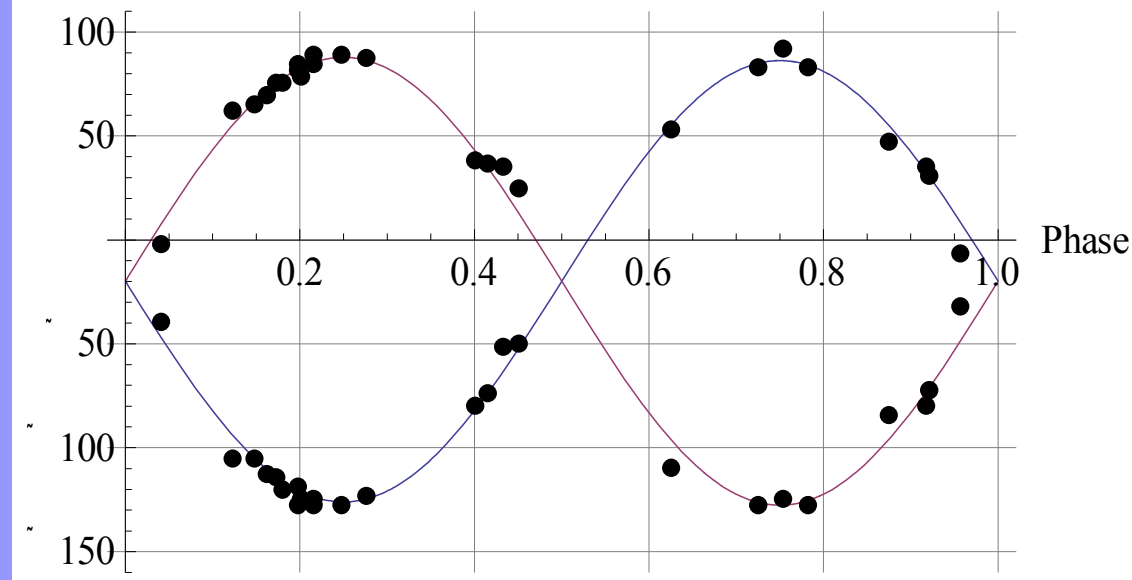
| Phase | Déterminations Vspec |        | Déterminations PeakFit |        | HJD            | Source        |
|-------|----------------------|--------|------------------------|--------|----------------|---------------|
|       | V1                   | V2     | V1                     | V2     |                |               |
| 0.040 | -1.9                 | -38.8  | 4.0                    | -49.3  | 2454393.642319 | Thizy/Masviel |
| 0.122 | -105.1               | 62.5   | -106.0                 | 63.7   | 2454338.523799 | Thizy/Cochard |
| 0.149 | -105.9               | 65.8   | -105.6                 | 68.1   | 2454358.430345 | Thizy         |
| 0.161 | -112.0               | 70.4   | -113.6                 | 69.0   | 2454172.357280 | Barbotin      |
| 0.174 | -114.6               | 75.3   | -116.4                 | 76.3   | 2454358.531744 | Thizy         |
| 0.178 | -120.3               | 75.5   | -124.8                 | 75.2   | 2454172.426093 | Thizy/Cochard |
| 0.197 | -118.2               | 81.9   | -122.3                 | 82.3   | 2454358.620222 | Thizy         |
| 0.198 | -127.2               | 84.4   | -128.5                 | 81.9   | 2454172.503476 | Thizy/Cochard |
| 0.200 | -124.0               | 79.0   | -133.1                 | 79.5   | 2453970.550290 | Thizy/Cochard |
| 0.216 | -127.3               | 89.0   | -131.5                 | 85.8   | 2454172.573610 | Thizy/Cochard |
| 0.217 | -124.7               | 84.2   | -127.7                 | 85.9   | 2454386.419786 | Thizy/Ribeiro |
| 0.246 | -127.7               | 88.4   | -130.9                 | 88.7   | 2454386.537857 | Thizy/Ribeiro |
| 0.276 | -123.1               | 87.9   | -129.5                 | 87.7   | 2454386.656107 | Thizy/Ribeiro |
| 0.399 | -79.4                | 37.9   | -78.0                  | 38.8   | 2454169.340206 | Barbotin      |
| 0.414 | -73.3                | 36.9   | -74.4                  | 37.3   | 2454173.357798 | Thizy/Cochard |
| 0.432 | -50.9                | 36.0   | -57.2                  | 34.4   | 2454173.429431 | Thizy/Cochard |
| 0.450 | -49.9                | 25.3   | -47.1                  | 20.7   | 2454173.502344 | Thizy/Cochard |
| 0.627 | 53.4                 | -110.1 | 53.9                   | -111.2 | 2454154.401586 | Thizy/Cochard |
| 0.727 | 83.3                 | -128.0 | 82.8                   | -135.0 | 2454384.479687 | Thizy/Ribeiro |
| 0.755 | 92.5                 | -124.4 | 90.3                   | -130.5 | 2454384.592097 | Thizy/Ribeiro |
| 0.782 | 82.5                 | -127.8 | 81.9                   | -134.2 | 2454384.697696 | Thizy/Ribeiro |
| 0.873 | 47.0                 | -84.0  | 47.2                   | -87.7  | 2454337.540339 | Thizy/Cochard |
| 0.917 | 35.7                 | -79.1  | 33.0                   | -76.7  | 2454171.390028 | Barbotin      |
| 0.920 | 30.8                 | -72.4  | 31.3                   | -75.5  | 2454353.564205 | Thizy/Cochard |
| 0.958 | -5.9                 | -32.5  | 12.8                   | -42.6  | 2453973.552152 | Thizy/Cochard |

Note: data around phase 0/1 are excluded  
VisualSpec: <http://astrosurf.com/vdesnoux/>  
PeakFit: <http://www.systat.com/>



# RV graphs

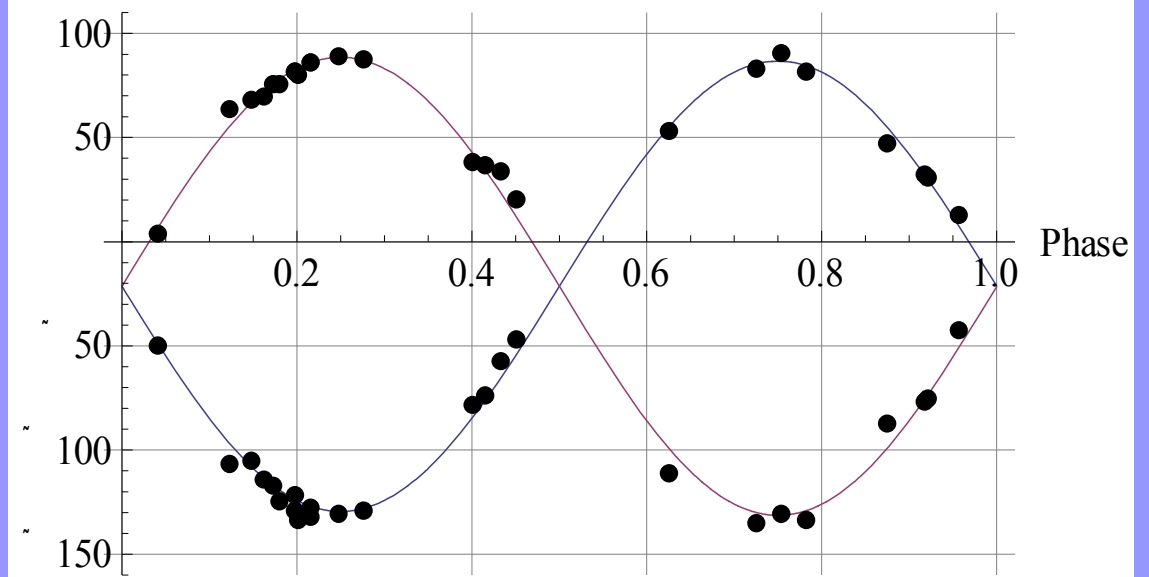
Vitesse Radiale



Measures with visualSpec



Vitesse Radiale

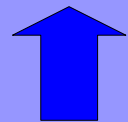
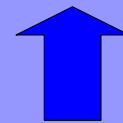


Measures with PeakFit



# Results on $\beta$ Aurigae

| Paramètres orbitaux                 | Cette étude (VSpec) | Cette étude (PeakFit) | Nordström (1994)  |
|-------------------------------------|---------------------|-----------------------|-------------------|
| $K_1$ (km.s <sup>-1</sup> )         | 106 $\pm$ 3         | 108 $\pm$ 3           | 107.75 $\pm$ 0.40 |
| $K_2$ (km.s <sup>-1</sup> )         | 108 $\pm$ 3         | 110 $\pm$ 3           | 111.25 $\pm$ 0.40 |
| $M_1/M_2$                           | 0.98 $\pm$ 0.06     | 0.98 $\pm$ 0.06       | 0.97 $\pm$ 0.01   |
| $V_\gamma$ (km.s <sup>-1</sup> )    | -20 $\pm$ 2         | -21 $\pm$ 2           | -17.0 $\pm$ 0.4   |
| $a.\sin(i)$ (R <sub>sol</sub> )     | 16.7 $\pm$ 0.5      | 17.1 $\pm$ 0.6        | 17.13 $\pm$ 0.04  |
| $m_1.\sin^3(i)$ (M <sub>sol</sub> ) | 2.02 $\pm$ 0.06     | 2.15 $\pm$ 0.06       | 2.19 $\pm$ 0.02   |
| $m_2.\sin^3(i)$ (M <sub>sol</sub> ) | 1.99 $\pm$ 0.06     | 2.11 $\pm$ 0.06       | 2.12 $\pm$ 0.02   |



*Note: study done by Pierre Noyrez based on recorded/processed spectra and SBS tool (Spectroscopy Binary Solver): [http://www.vub.ac.be/STER/JAD/JAD10/jad10\\_3/jad10\\_3.htm](http://www.vub.ac.be/STER/JAD/JAD10/jad10_3/jad10_3.htm)*

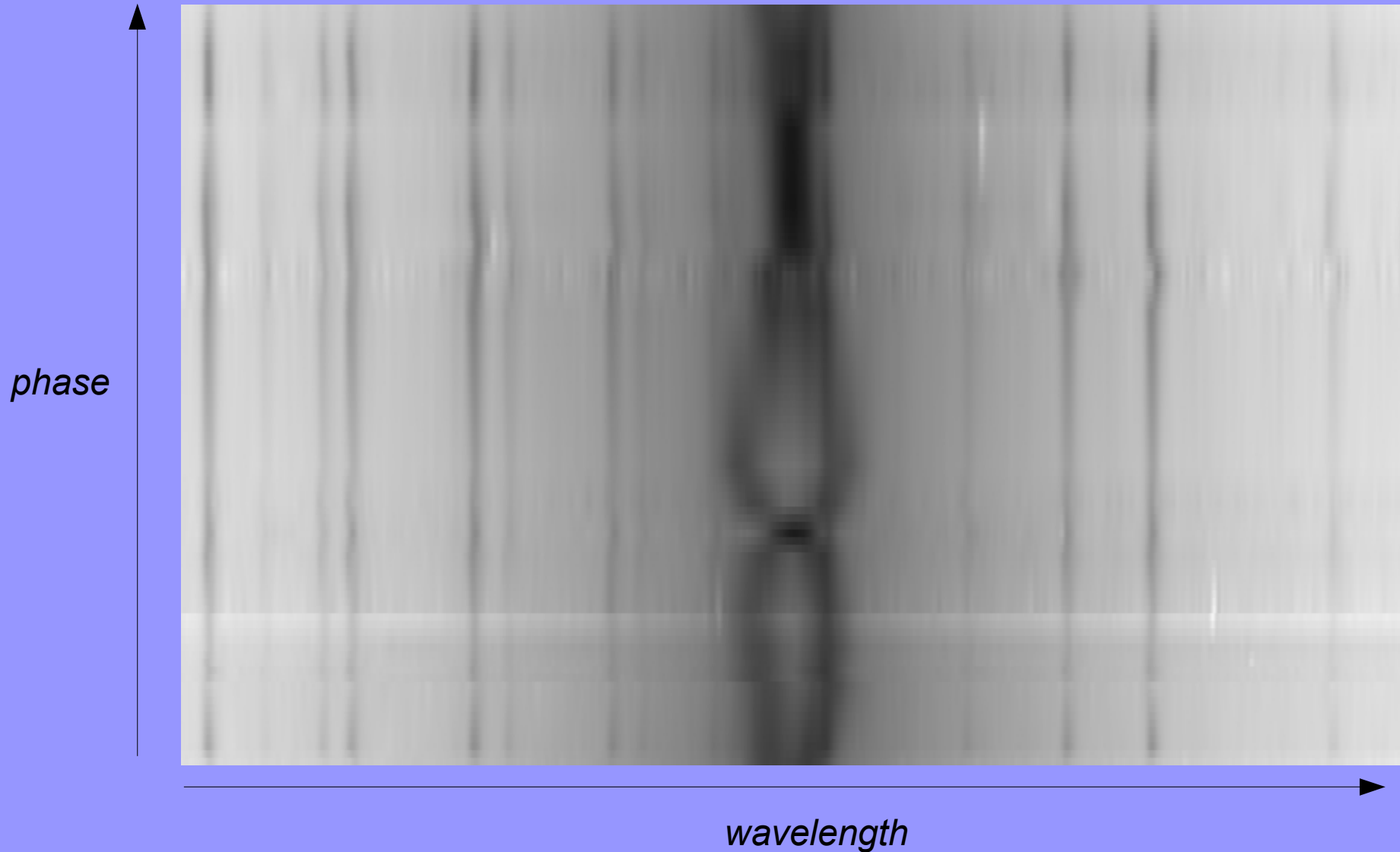
*Nordström 1994: “Radii and masses for  $\beta$  Aurigae”, B. Nordström and K.T. Johansen, *Astron. Astrophys.*, 291, 777-785 (1994).*

A photograph of a sunset or sunrise. The sun is a bright, glowing orb positioned centrally behind a dark, jagged silhouette of a mountain range. The sky is filled with layers of clouds, some of which are illuminated from below by the sun, creating a warm, orange and yellow glow. The overall scene is dramatic and atmospheric.

Mizar

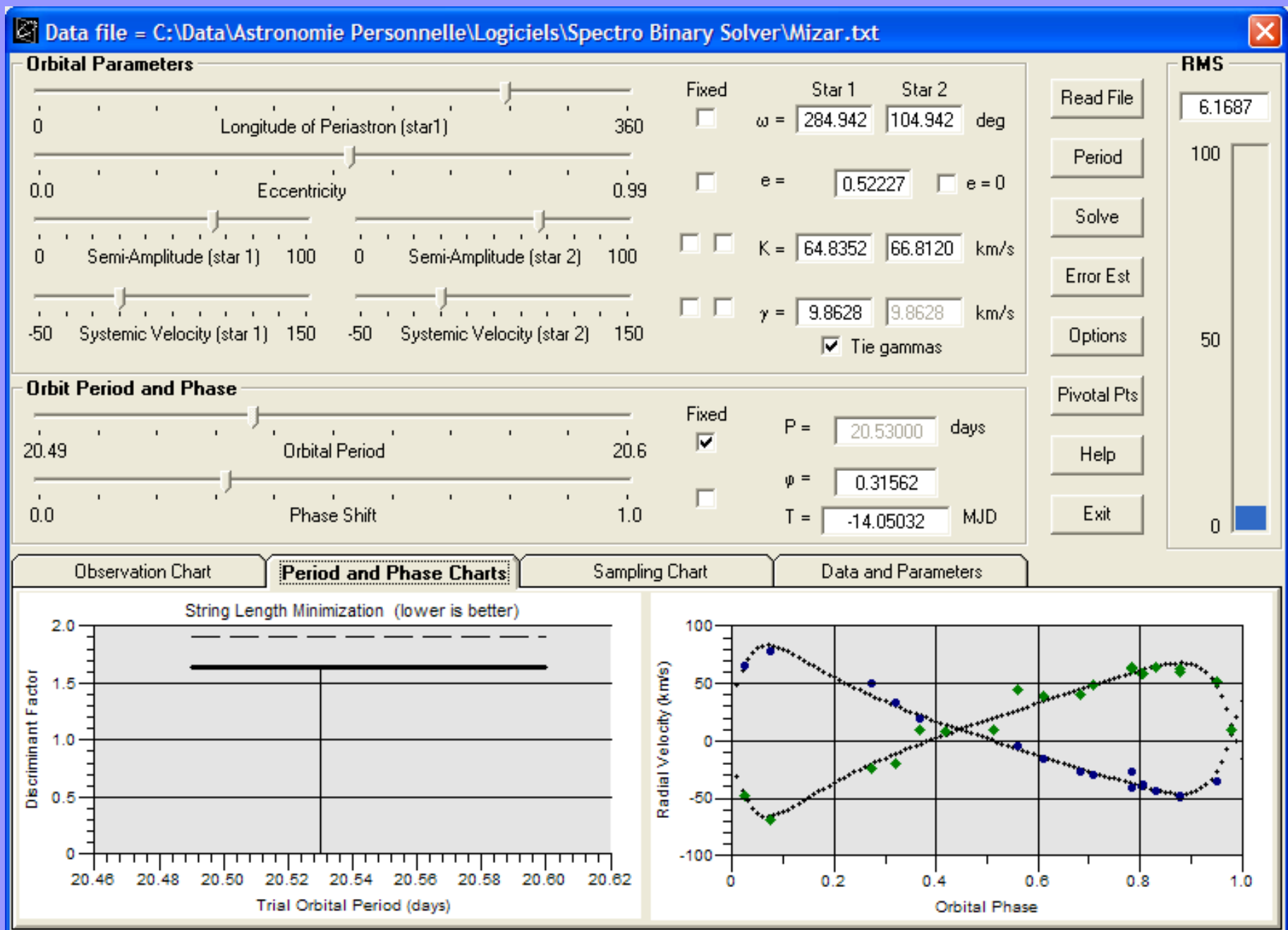


# Observations



*All data recorded by John Cordiale with Lhires III spectrograph and ST402xme ccd camera.  
Processing & data analysis by Olivier Thizy*

# Spectroscopic Binary solver





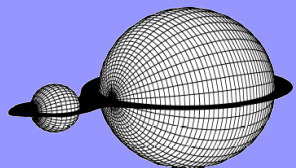
# Results

|  | This study | Vogel<br>(1901) | Hummel<br>(1998) | Budovicova<br>(2004) |
|--|------------|-----------------|------------------|----------------------|
|--|------------|-----------------|------------------|----------------------|

|                         |                           |               |                      |                   |
|-------------------------|---------------------------|---------------|----------------------|-------------------|
| Long. of Periastron (1) | 285 $\pm$ 3 deg.          |               |                      |                   |
| Long. of Periastron (2) | 105 $\pm$ 3 deg.          | 101.3 deg.    | 104.3 $\pm$ 0.3 deg. | 104.16 $\pm$ 0.05 |
| Eccentricity            | 0.52 $\pm$ 0.02           | 0.502         | 0.5354 $\pm$ 0.0025  | 0.542 $\pm$ 0.004 |
| Semi-Amplitude (1)      | 64.8 $\pm$ 2.5 km/s       | 64 km/s       | 67.2 km/s            | 65.51 $\pm$ 0.4   |
| Semi-Amplitude (2)      | 66.8 $\pm$ 2.5 km/s       | 78 km/s       | 69.1 km/s            | 68.85 $\pm$ 0.02  |
| Systemic Velocity       | 9.9 $\pm$ 1 km/s          |               |                      |                   |
| Orbital Period          | 20.53 days                | 20.6 days     | 20.53835 days        | 20.53835 days     |
| a1 sin(i)               | 15.6 $\pm$ 0.7 million km | 35 million km |                      |                   |
| a2 sin(i)               | 16.1 $\pm$ 0.7 million km |               |                      |                   |
| m1/m2                   | 1.03                      |               | 1.03 $\pm$ 0.07      | 1.051 $\pm$ 0.006 |
| m1 sin <sup>3</sup> (i) | 1.53 $\pm$ 0.16 Msol      | 4 Msol        |                      |                   |
| m2 sin <sup>3</sup> (i) | 1.48 $\pm$ 0.15 Msol      |               |                      |                   |

AW UMa





# AW UMa = SAO 62579

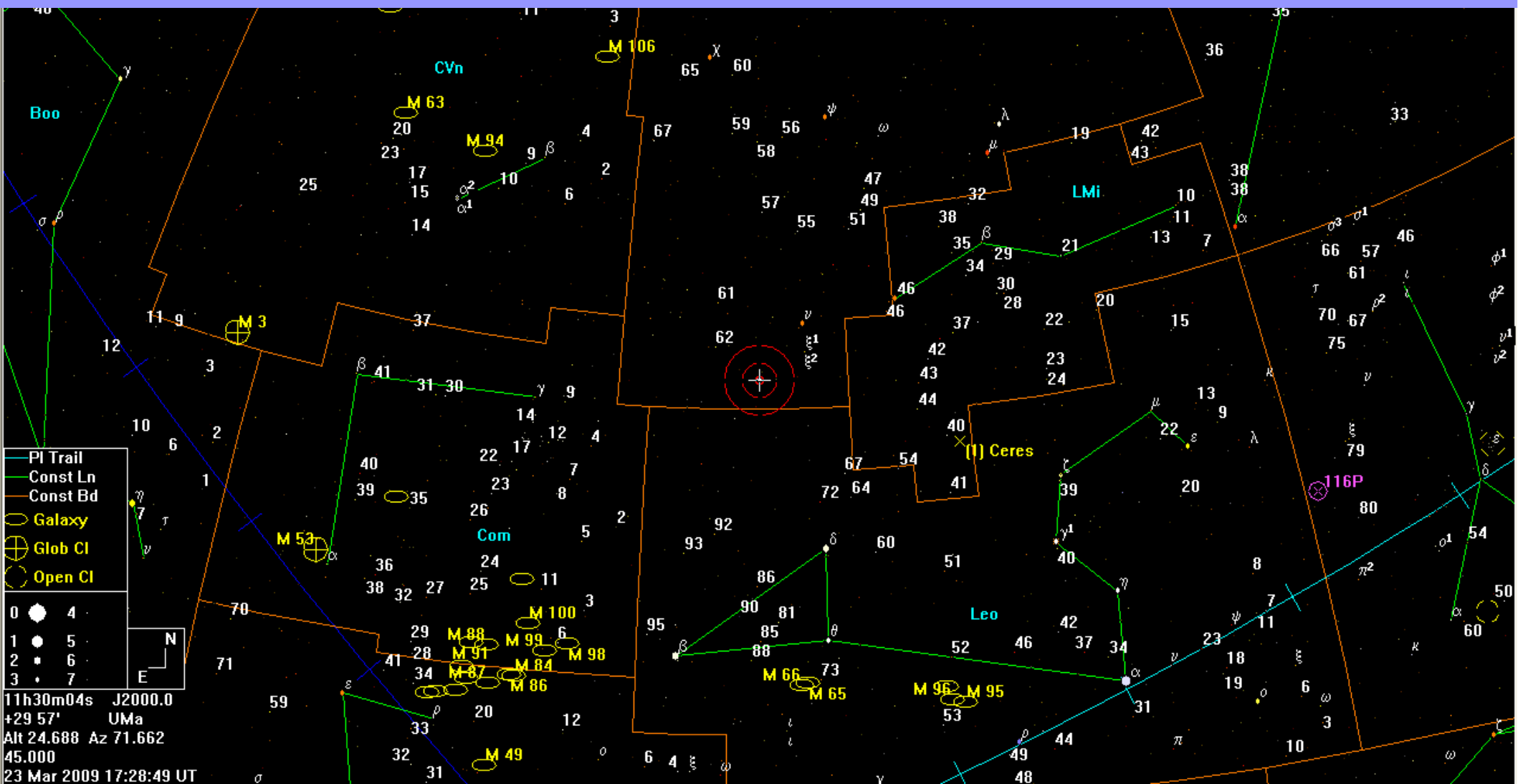
Magnitude: 6.83-7.13

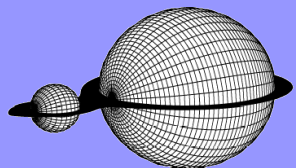
Period of variation: 0.4387299 days

Spectral type: F0-F2

Right ascension: 11h30m04.170s

Declination: +29 57' 52.50"





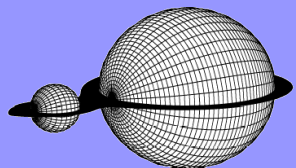
# Equipment



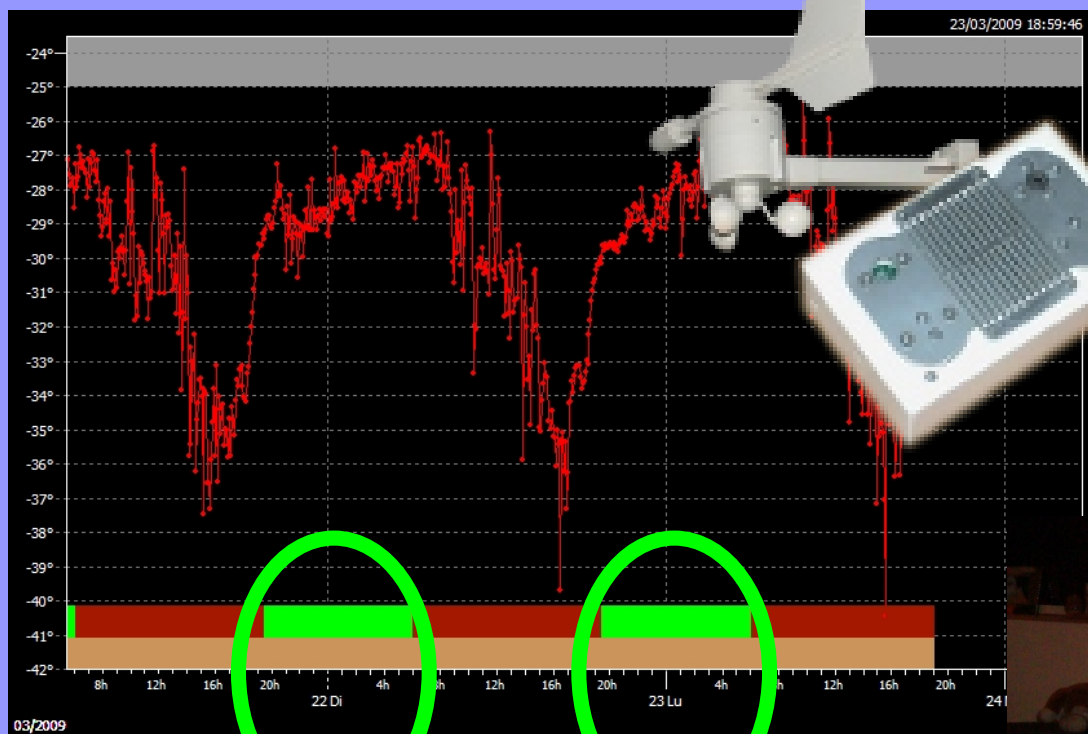
Shelyak Instruments eShel:  
Thorium-Argon calibration + echelle spectrograph



Fiber Injection  
& Guiding Unit on C11



# Observations

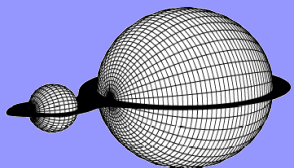


Night of march 22nd, 2009  
...after a long serie of clear nights!  
(graph from Sentinel weather station)

Total: 34 spectra, 15min exp. each

Operating remotely  
by the fireplace... :-)

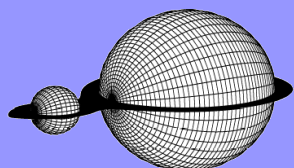




# Echelle spectrum

**Order #34: H $\alpha$**

**Order #46: H $\beta$**

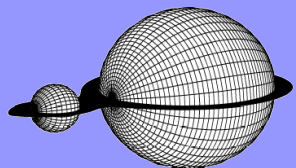


# Calibration

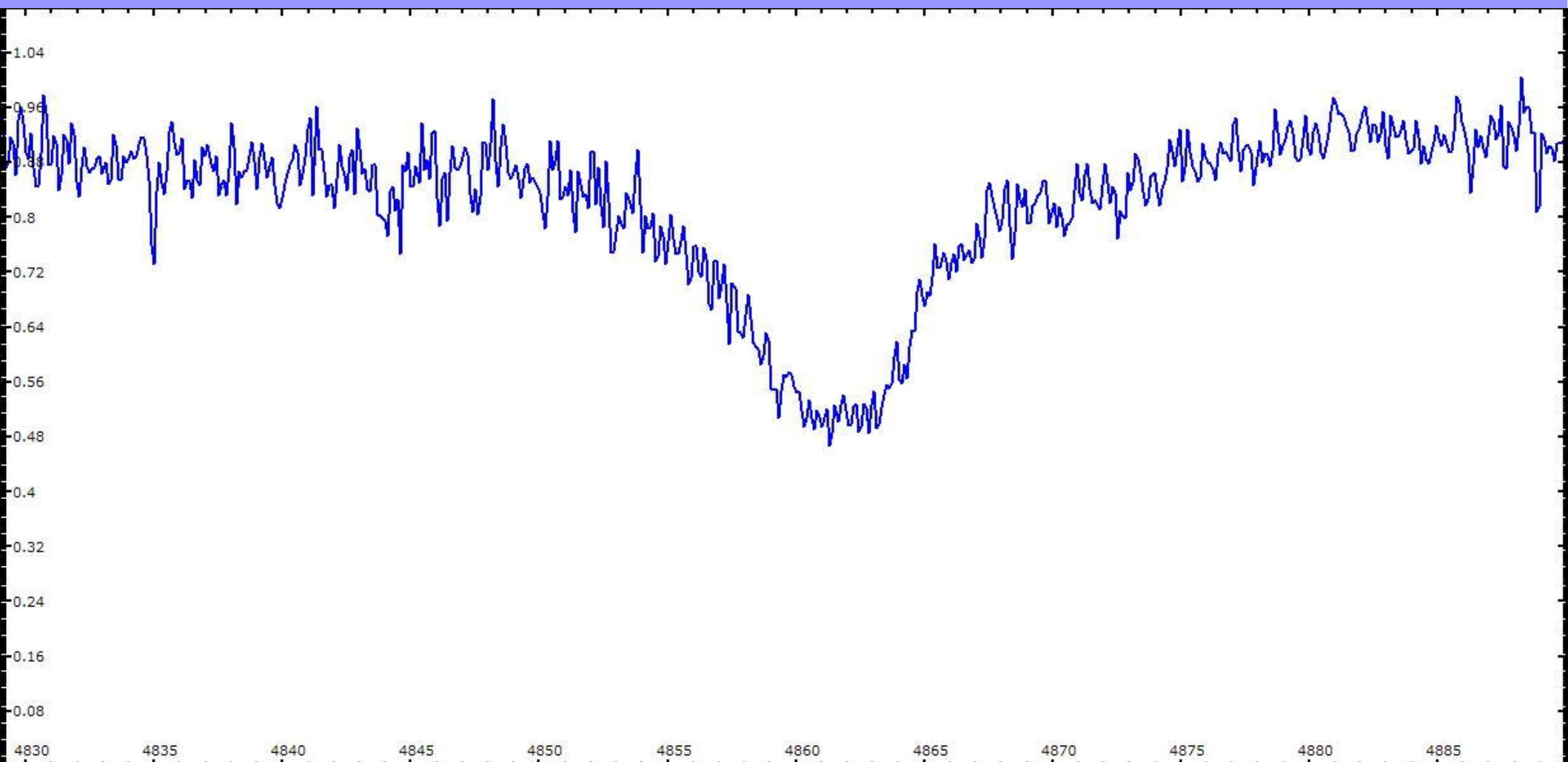


| order | rms_order | central  | . | . | .. | rms_cal | fwhm | disp  | resolution | nb_lines |
|-------|-----------|----------|---|---|----|---------|------|-------|------------|----------|
| 33    | 0.0292    | 6810.985 | . | . | .. | 0.0028  | 4.02 | 0.187 | 9037.7     | 5        |
| 34    | 0.0184    | 6610.662 | . | . | .. | 0.0074  | 3.41 | 0.181 | 10724.3    | 8        |
| 35    | 0.0169    | 6421.786 | . | . | .. | 0.0031  | 3.41 | 0.171 | 11028.1    | 7        |
| 36    | 0.0173    | 6243.403 | . | . | .. | 0.0036  | 3.07 | 0.163 | 12494.3    | 10       |
| 37    | 0.0162    | 6074.662 | . | . | .. | 0.0045  | 3.35 | 0.159 | 11433.6    | 7        |
| 38    | 0.0150    | 5914.803 | . | . | .. | 0.0023  | 3.17 | 0.156 | 11946.6    | 5        |
| 39    | 0.0133    | 5763.141 | . | . | .. | 0.0034  | 3.42 | 0.156 | 10799.2    | 5        |
| 40    | 0.0155    | 5619.062 | . | . | .. | 0.0083  | 3.38 | 0.149 | 11179.9    | 7        |
| 41    | 0.0145    | 5482.012 | . | . | .. | 0.0073  | 3.40 | 0.147 | 10943.2    | 7        |
| 42    | 0.0147    | 5351.488 | . | . | .. | 0.0021  | 3.66 | 0.143 | 10209.0    | 6        |
| 43    | 0.0134    | 5227.035 | . | . | .. | 0.0022  | 3.28 | 0.142 | 11203.7    | 7        |
| 44    | 0.0139    | 5108.239 | . | . | .. | 0.0070  | 3.30 | 0.137 | 11251.1    | 7        |
| 45    | 0.0162    | 4994.722 | . | . | .. | 0.0055  | 3.36 | 0.134 | 11125.5    | 8        |
| 46    | 0.0225    | 4886.141 | . | . | .. | 0.0062  | 3.29 | 0.128 | 11586.9    | 6        |
| 47    | 0.0262    | 4782.181 | . | . | .. | 0.0003  | 3.24 | 0.128 | 11551.5    | 5        |
| 48    | 0.0249    | 4682.552 | . | . | .. | 0.0011  | 3.39 | 0.124 | 11113.0    | 6        |
| 49    | 0.0233    | 4586.990 | . | . | .. | 0.0009  | 3.34 | 0.121 | 11327.1    | 5        |
| 50    | 0.0295    | 4495.250 | . | . | .. | 0.0012  | 3.75 | 0.119 | 10085.3    | 5        |
| 51    | 0.0627    | 4407.108 | . | . | .. | 0.0102  | 4.30 | 0.115 | 8921.6     | 6        |

Power of resolution  $R \sim 10000$  to  $12000$

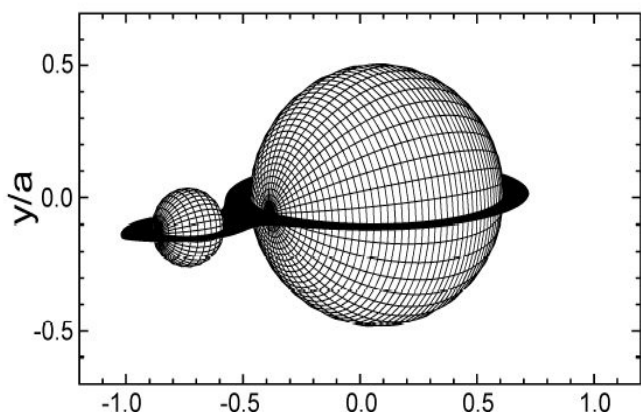


# H $\beta$ line profile

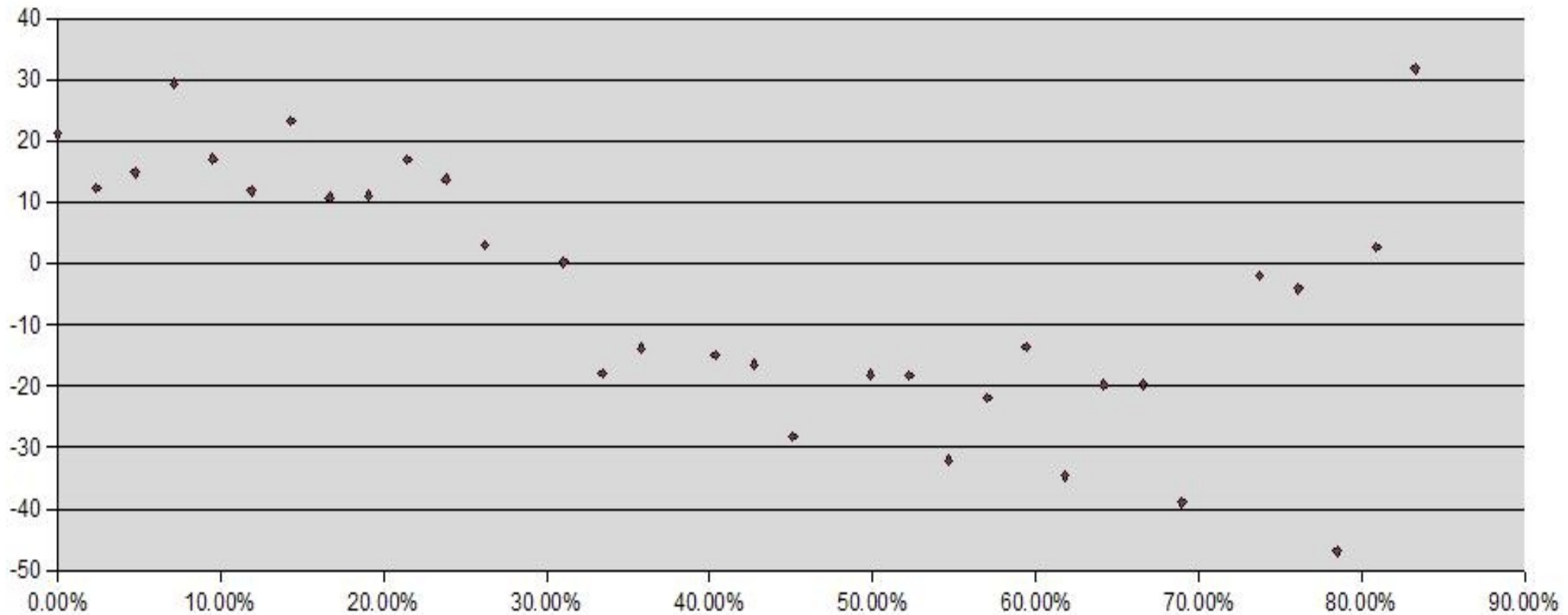


T0.28m telescope; 15min exposures

# Preliminary Results



AW UMa / H-beta

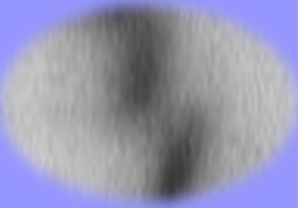


Measured (from H $\beta$ ):  
 **$V_0 \sim -17.9$  km/s**  
 **$K_1 \sim 23$  km/s**

Article (Pribulla & Rucinski, 2008):  
 **$V_0 = -17 \pm 7$  km/s**  
 **$K_1 = 29 \pm 8$  km/s**

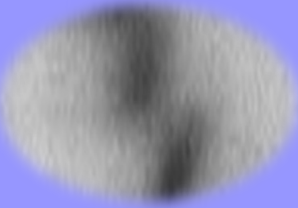
# Pulsating Stars





# beta Cep stars

- Pulsating variable stars
- Period 0.1 to 0.3 days (*single night project !*)
- Very small visual light amplitude  
(*beta Cep detected spectroscopically  
and first identified as binary system*)
- Hot stars (spectral type B0-B2)
- On or slightly above main sequence



# BW Vul : a strange beast !

- $P=0.20$  days
- $V=6.52-6.76$
- B2III star, 10 times the size of our Sun
- Largest amplitude known: 200km/s !
- It is nearing exhaustion of the hydrogen fuel in its core and preparing to use the hydrogen around the core

# Observations



The team:

- Michel Pujol*
- Olivier Thizy*
- Valérie Desnoux*
- Christian Buil*



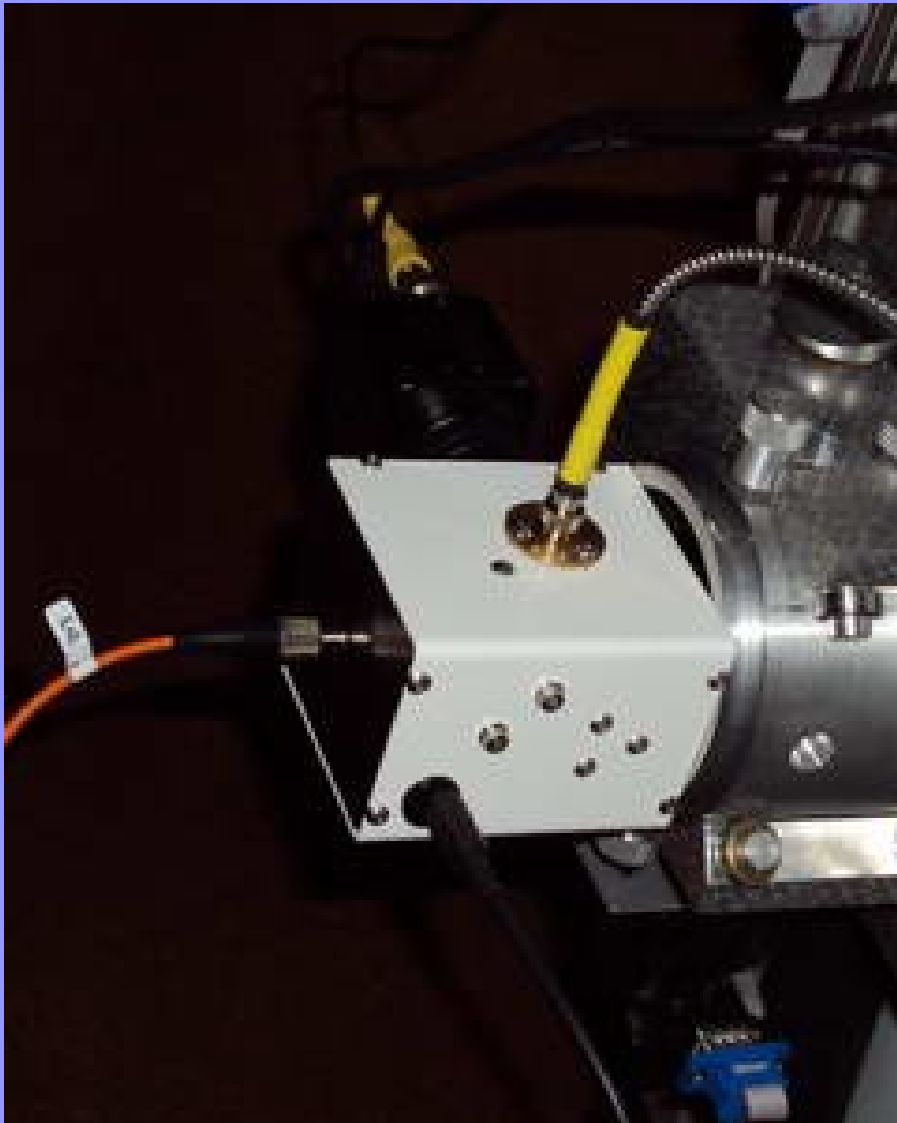
The place: Pic du Midi



The telescope:

- T60, 60cm diameter
- f/3.5

# Observations



**Shelyak Instruments  
-Fiber Injection Unit**



**Shelyak Instruments  
-eShel spectrograph  
-Calibration unit**

# Line identification

O-type: H, He I, He II, C III, C IV, N IV, O V, Si III  
 B0-B2: H, He I, C II, C III, N II, N III, O II, Si III, Si IV  
 B2-B5: H, He I, C II, Mg II, Si II  
 B5-A0 : H, He I, Mg II, (Si II)  
 A0: H, Mg II

*Source: Jaschek & Jaschek, Classification of Stars, 1990*

Table 2. Summary of Atomic Data for Lines  
 in McDonald Spectra

| Wavelength | Ion    | (eV)  | log gf |
|------------|--------|-------|--------|
| 5606.09    | S II   | 13.8  | 0.16   |
| 5639.980   | S II   | 14.1  | 0.33   |
| 5640.314   | S II   | 13.8  | 0.15   |
| 5646.979   | S II   | 14.1  | 0.11   |
| 5648.070   | C II   | 20.8  | -0.45  |
| 5639.980   | S II   | 14.1  | 0.33   |
| 5640.314   | S II   | 13.8  | 0.15   |
| 5659.956   | S II   | 13.7  | -0.07  |
| 5662.460   | C II   | 20.8  | -0.27  |
| 5666.629   | N II   | 18.5  | 0.01   |
| 5676.017   | N II   | 18.5  | -0.34  |
| 5679.558   | N II   | 18.6  | 0.28   |
| 5686.213   | N II   | 18.6  | -0.47  |
| 5696.603   | Al III | 15.7  | 0.23   |
| 5710.766   | N II   | 18.6  | -0.47  |
| 5722.730   | Al III | 15.7  | -0.07  |
| 5739.734   | Si III | 19.8  | -0.160 |
| 5747.300   | N II   | 18.6  | -1.020 |
| 5833.938   | Fe III | 18.6  | 0.616  |
| 5875.615   | He I   | 21.0  | 0.41   |
| 6247.178   | Al II  | 16.6  | -0.20  |
| 6346.859   | N II   | 23.3  | -0.86  |
| 6371.371   | Si II  | 8.2   | 0.00   |
| 6379.617   | N II   | 18.5  | -0.92  |
| 6562.801   | H I    | 10.20 | -0.69  |
| 6578.052   | C II   | 14.5  | 0.12   |
| 6582.882   | C II   | 14.5  | -0.18  |
| 6678.154   | He I   | 21.3  | 0.33   |

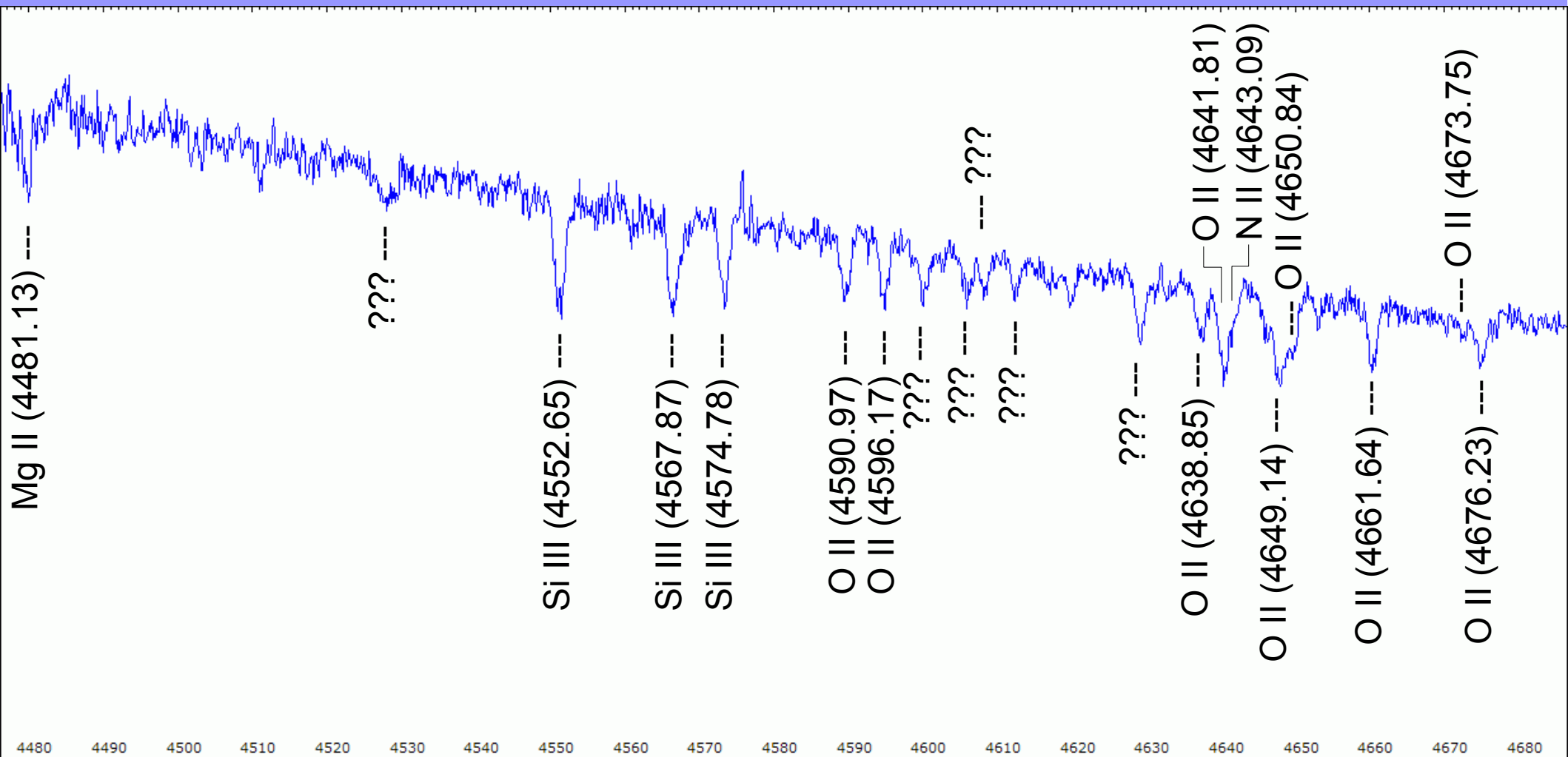
*Mon. Not. R. Astron. Soc. 000, 1–12 (2002)*

| $\lambda$ | Elem. | N  | $\lambda$ | Elem. | N  |
|-----------|-------|----|-----------|-------|----|
| 3613.64   | HeI   | 6  | 4552.65   | SiIII | 2  |
| 3673.76   | H     | 5  | 4567.87   | SiIII | 2  |
| 3711.97   | H     | 3  | 4574.78   | SiIII | 2  |
| 3721.94   | H     | 3  | 4590.97   | OII   | 15 |
| 3734.37   | H     | 3  | 4638.85   | OII   | 1  |
| 3750.15   | H     | 2  | 4641.81   | OII   | 1  |
| 3797.90   | H     | 2  | 4643.09   | NII   | 5  |
| 3806.56   | SiIII | 5  | 4649.14   | OII   | 1  |
| 3864.68   | OII   | 12 | 4650.84   | OII   | 1  |
| 3867.48   | HeI   | 20 | 4661.64   | OII   | 1  |
| 3871.82   | HeI   | 60 | 4673.75   | OII   | 1  |
| 3876.05   | CII   | 33 | 4676.23   | OII   | 1  |
| 3882.20   | OII   | 12 | 4861.33   | H     | 1  |
| 3911.96   | OII   | 17 | 4222.15   | PIII  | 3  |
| 3918.98   | CH    | 4  | 4227.75   | NII   | 33 |
| 3920.68   | CH    | 4  | 4236.93   | NII   | 48 |
| 3923.48   | HeII  | 4  | 4241.79   | NII   | 47 |
| 3926.53   | HeI   | 58 | 4317.14   | OII   | 2  |
| 3933.66   | CaII  | 1  | 4319.63   | OII   | 2  |
| 3936.07   | ZrII  | 42 | 4411.20   | CH    | 39 |
| 3941.92   | ZrII  | 55 | 4414.91   | OII   | 5  |
| 3945.08   | FeIII | 69 | 4596.17   | OII   | 15 |
| 3995.00   | NII   | 12 | 4779.71   | NII   | 20 |
| 4009.27   | HeI   | 55 | 4788.13   | NII   | 20 |
| 4128.05   | SiII  | 3  | 5001.47   | NII   | 19 |
| 4130.88   | SiII  | 3  | 5005.14   | NII   | 19 |
| 4132.81   | OII   | 19 | 5453.81   | SII   | 6  |
| 4143.76   | HeI   | 53 | 5710.76   | NII   | 3  |
| 4149.90   | AlIII | 5  | 5722.65   | AlIII | 2  |
| 4153.10   | SII   | 44 | 5739.76   | SiIII | 4  |
| 4162.70   | SII   | 44 | 5875.62   | HeI   | 11 |
| 4168.41   | SII   | 44 | 5889.95   | NaI   | 1  |
| 4366.90   | OII   | 2  | 5895.92   | NaI   | 1  |
| 4387.93   | HeI   | 51 | 6562.82   | H     | 1  |
| 4395.95   | OII   | 26 | 6578.03   | CII   | 2  |
| 4471.48   | HeI   | 14 | 6582.85   | CII   | 2  |
| 4481.13   | MgII  | 4  |           |       |    |

Liu Zong-Li; 1998 JAD 4 1:  
 High Res spectro BW Vul & gam Peg

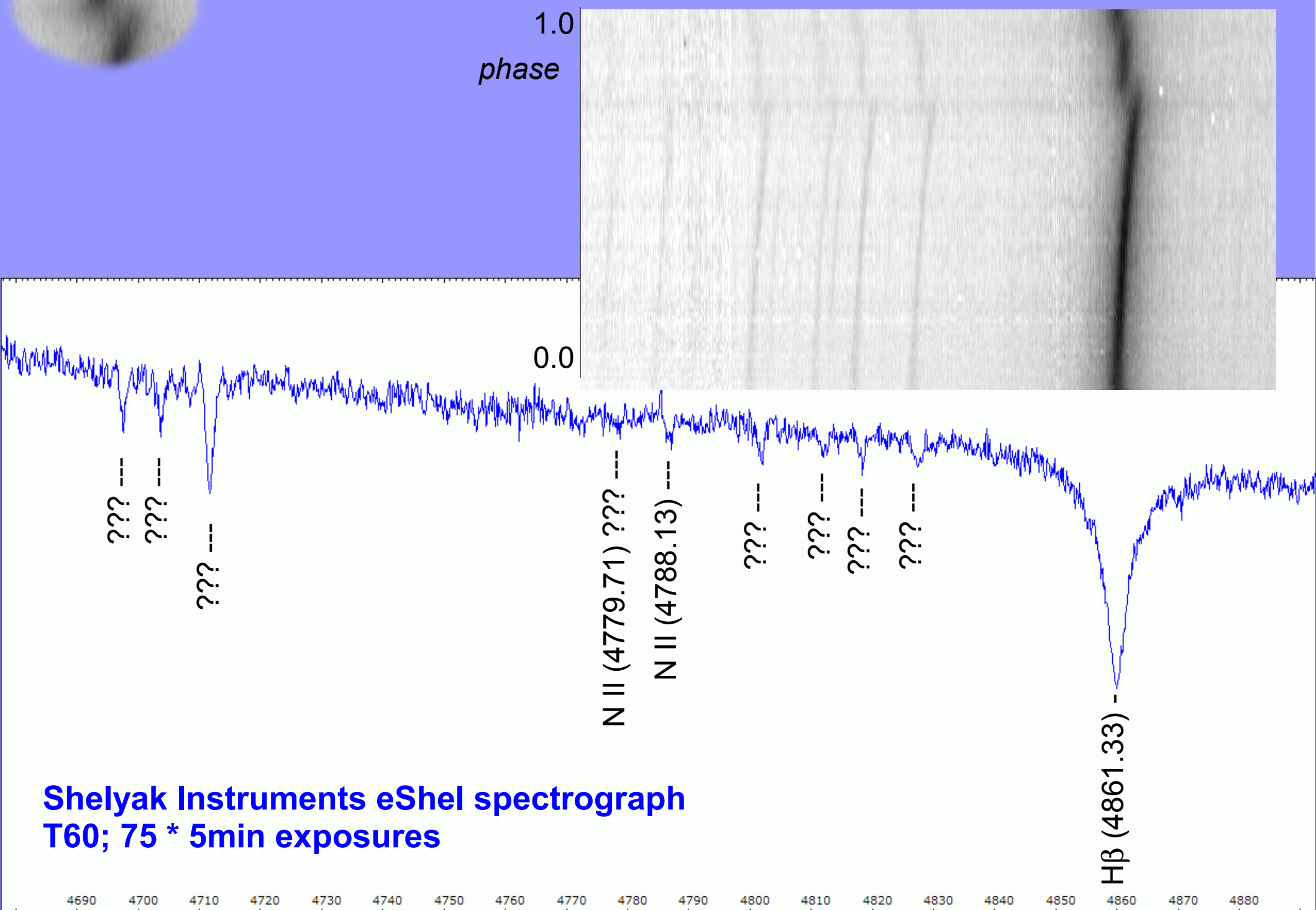
Table 4: Spectroscopic line list of BW Vul  
 with element and multiplet number N

# Line identification

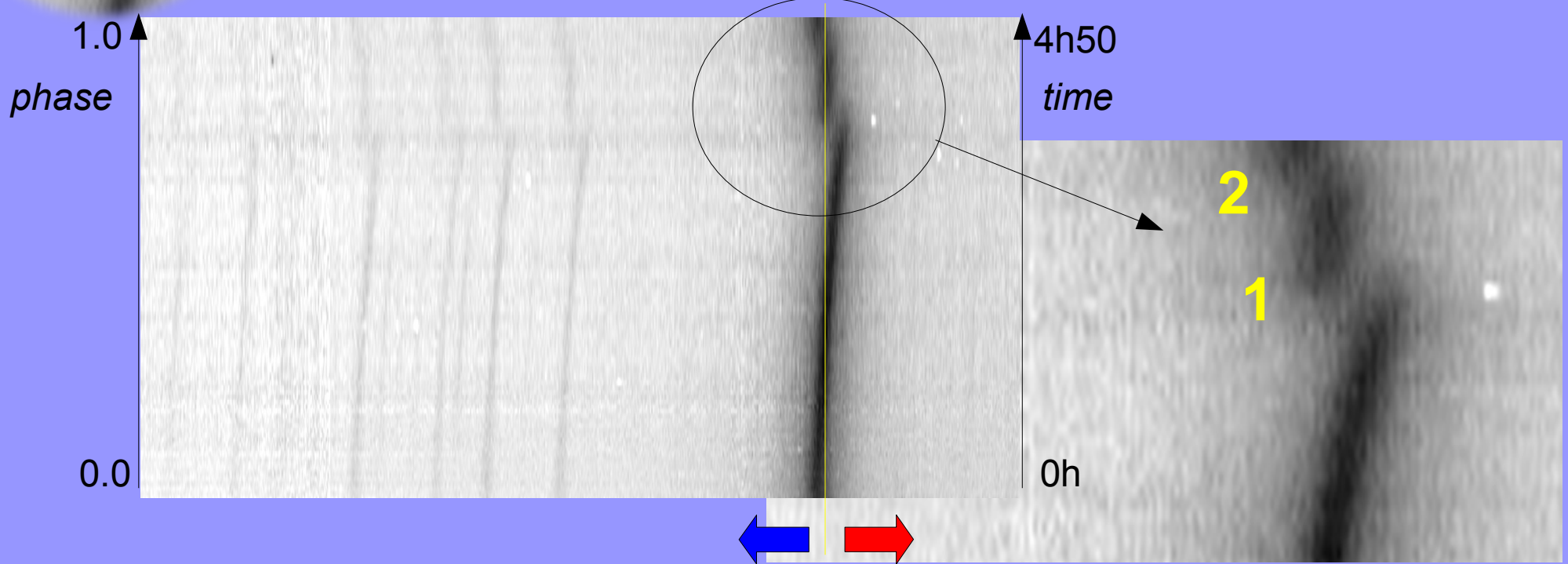


Shelyak Instruments eShel spectrograph  
T60; 75 \* 5min exposures

# Time evolution



# How does it work ?

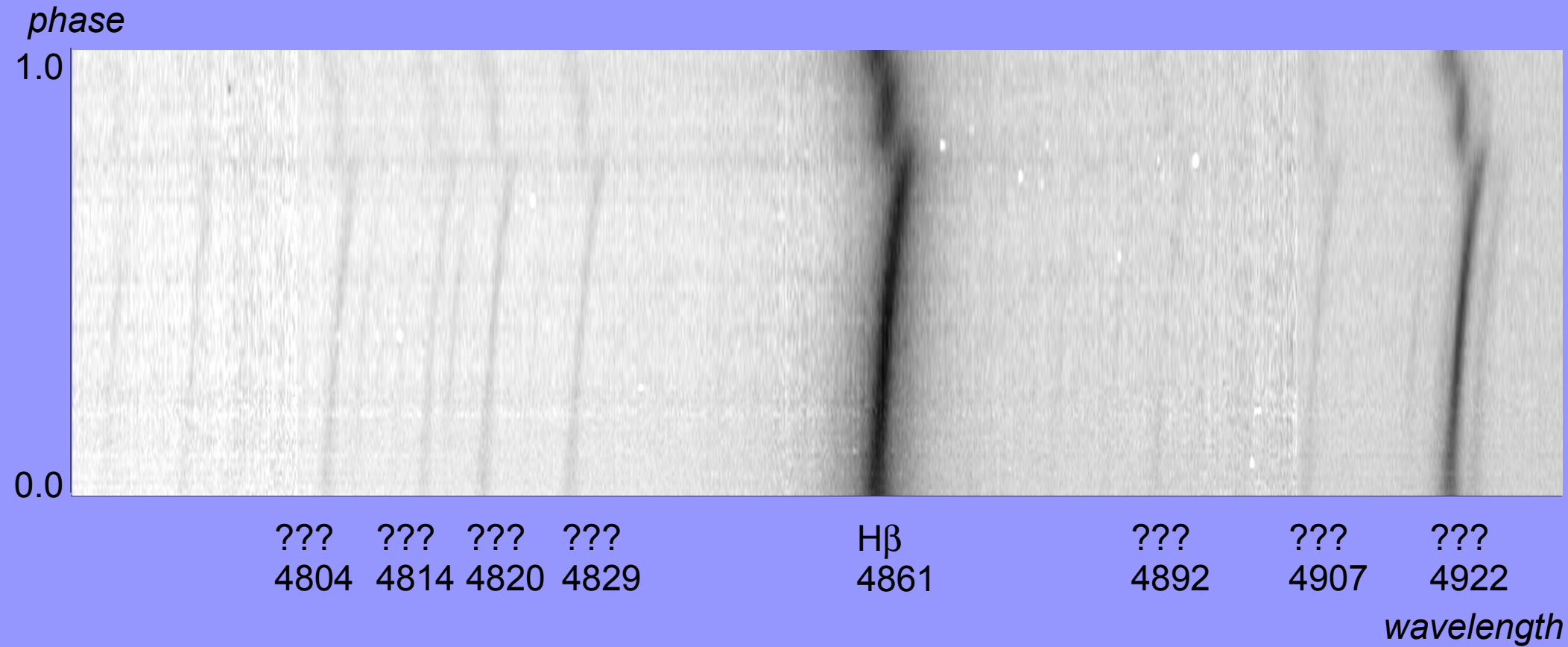


- Absorption line is **red shifted** when star is contracting
- Absorption line is **blue shifted** when star is expanding
- The line doubling phase (1 & 2) are interpreted as shock waves
- Shock 1: supersonic infalling motion of the atmosphere
- Shock 2: new shock wave probably initiated by iron (Fe)  $\kappa$ -mechanism, sweeps the layers upward

**Data: Shelyak Instruments eShel spectrograph; Pic du Midi T60; 75 \* 5min**

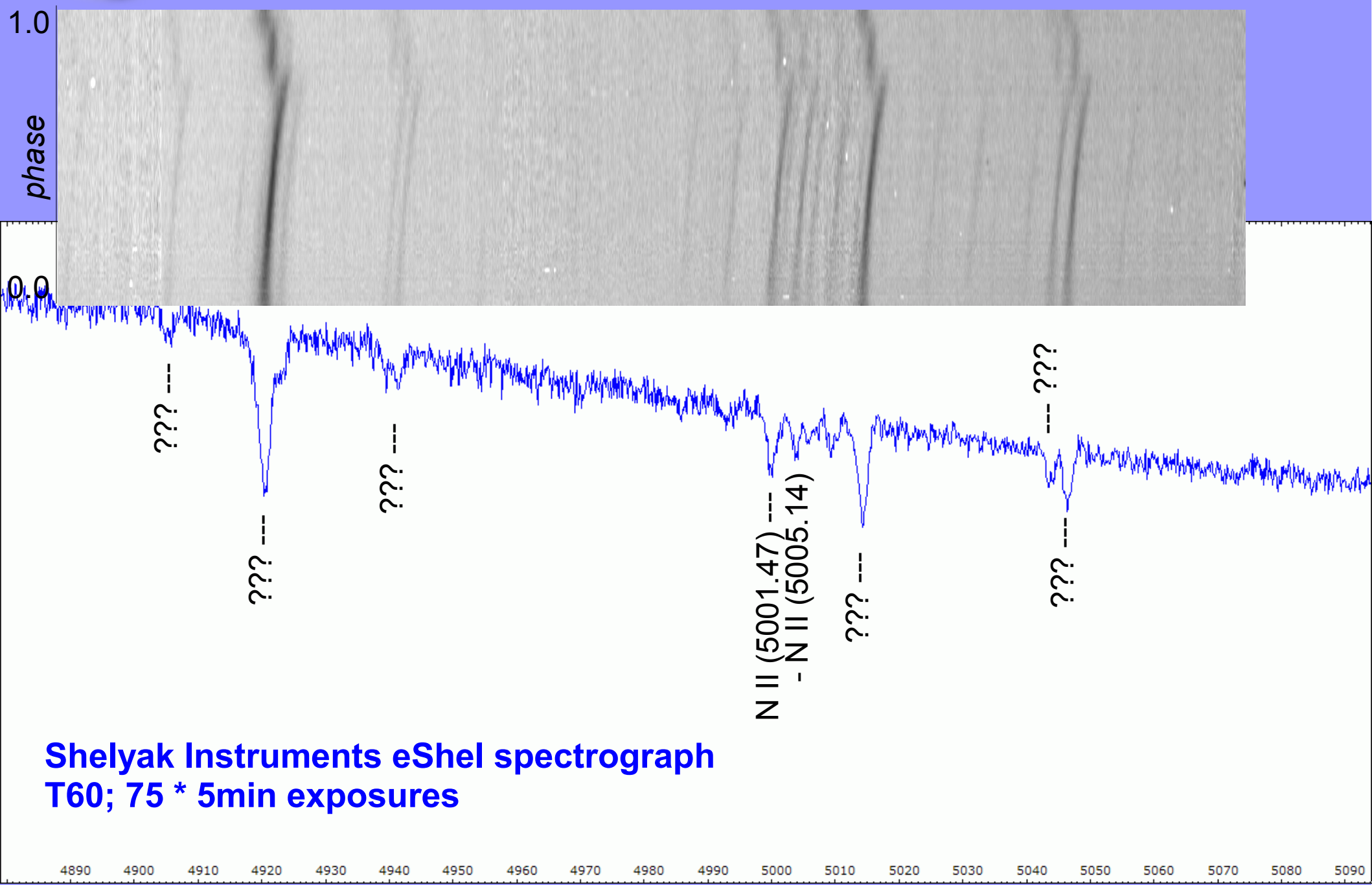
**Reference: P. Mathias et al. A&A 339, 525-520, 1998**

# Larger view on spectrogram

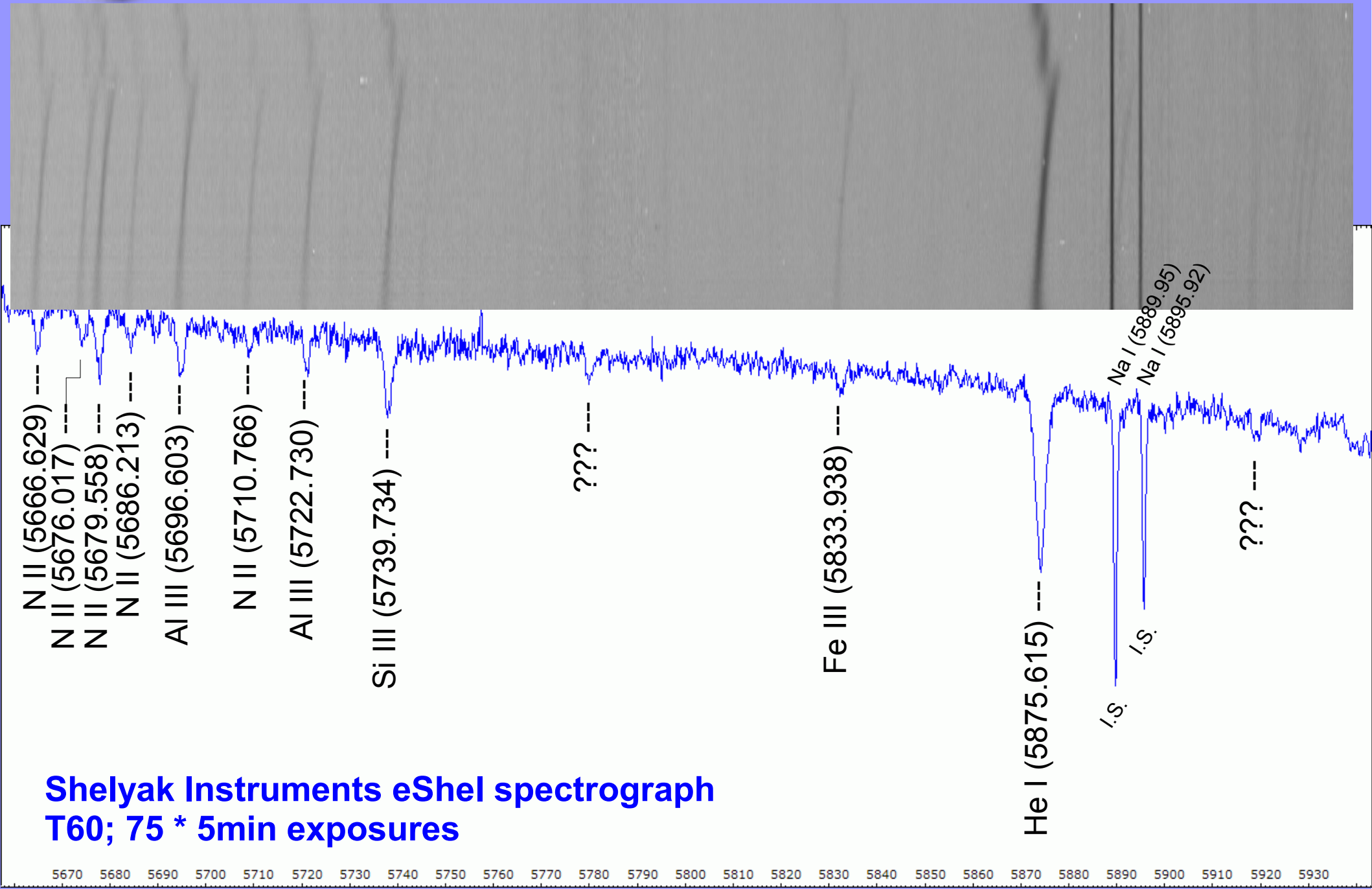


**Shelyak Instruments eShel spectrograph**  
**T60; 75 \* 5min exposures**

# Line identification



# Near Sodium doublet



# He I / Sodium doublet

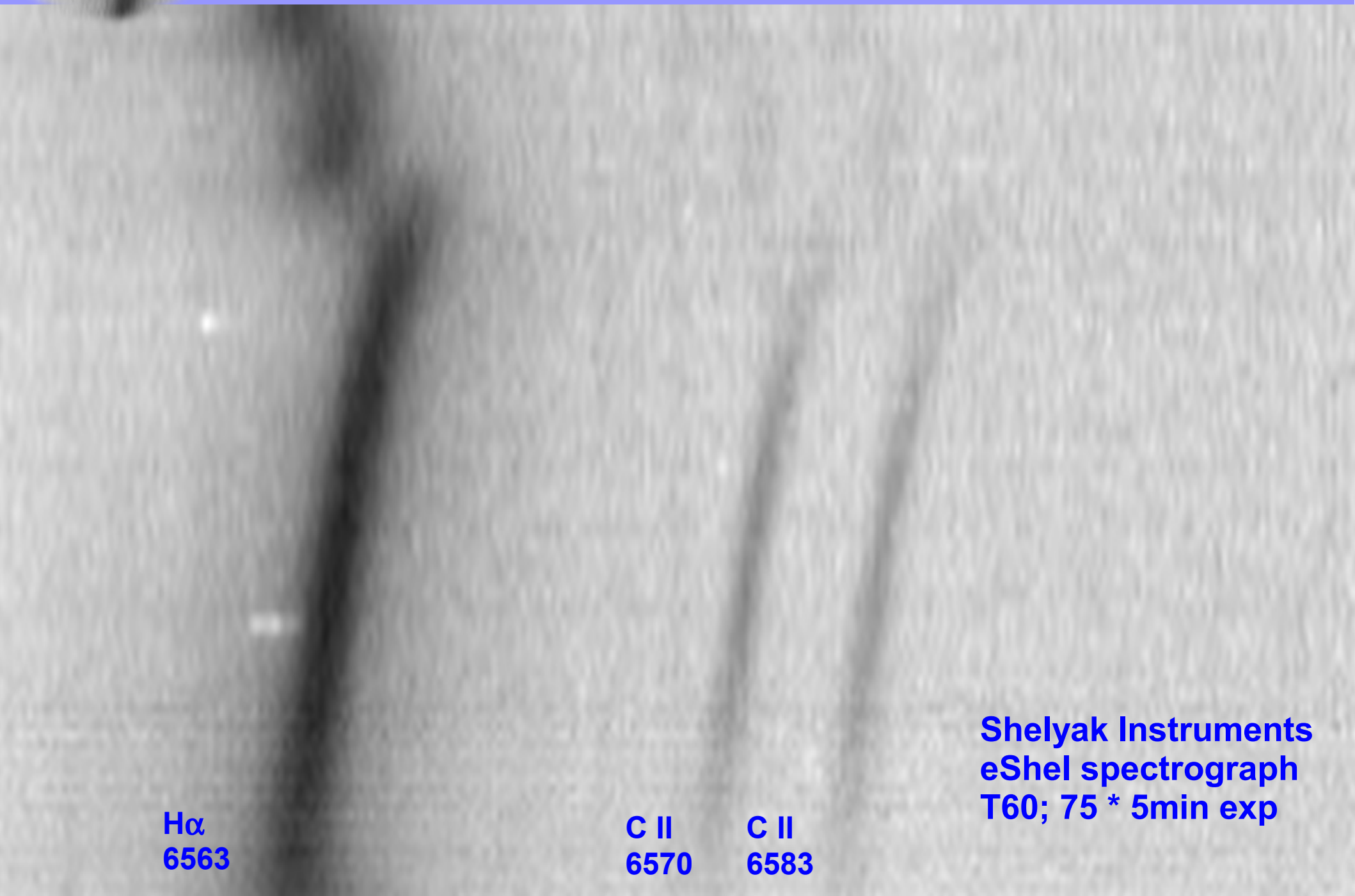
Shelyak Instruments  
eShel spectrograph  
T60; 75 \* 5min exp

He I  
5876

Na  
5890

Na  
5896

# Near H $\alpha$

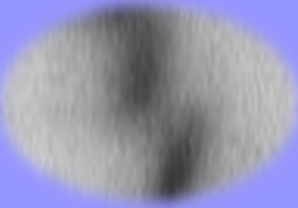


H $\alpha$   
6563

C II  
6570

C II  
6583

Shelyak Instruments  
eShel spectrograph  
T60; 75 \* 5min exp



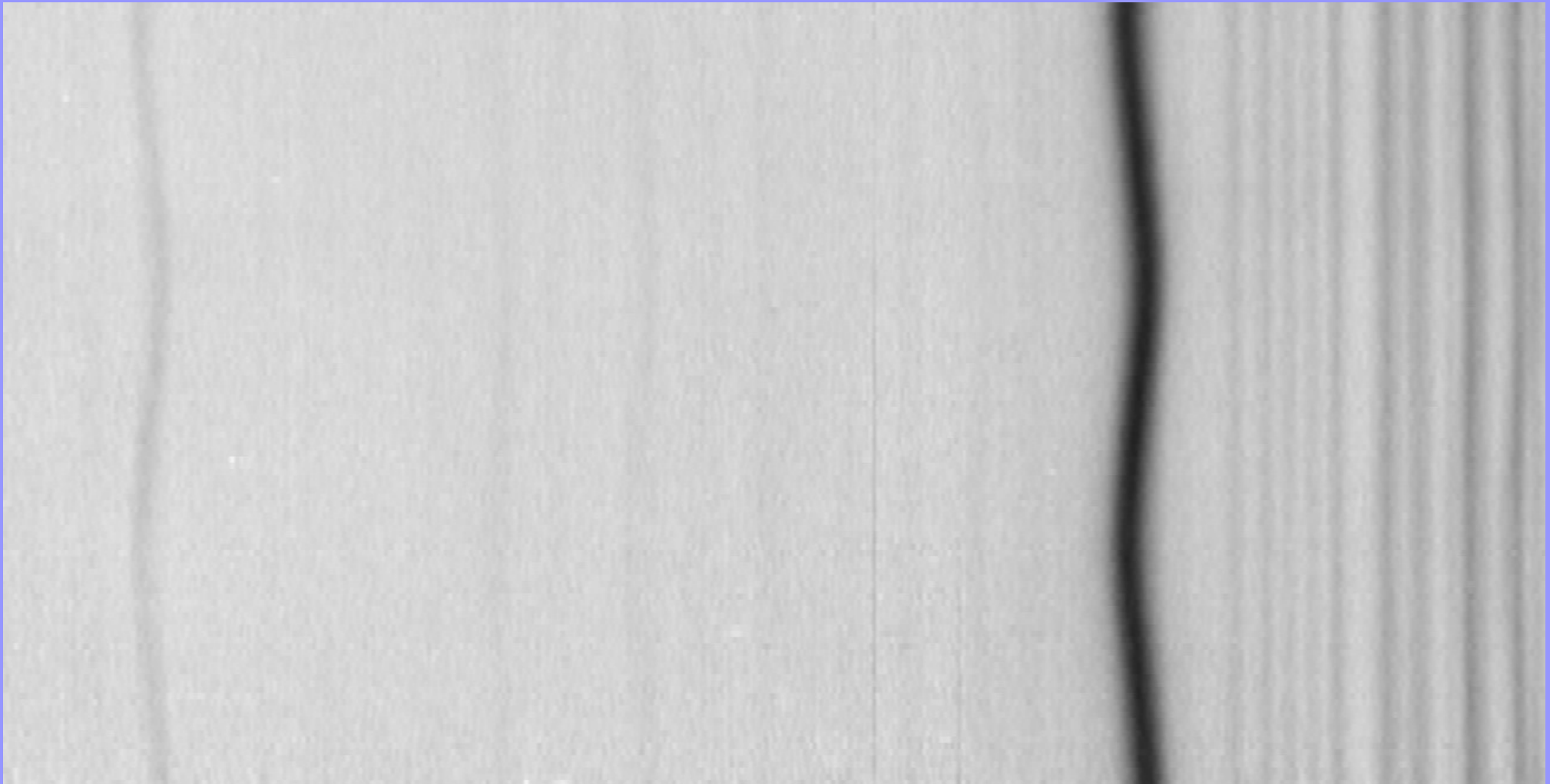
# BW Vul: next steps

- Very easy project
  - Lhires III / 1200 gr/mm or eShel
  - One night continuous observation
- Pursue line identification
- Line measurement (center, FWHM...) and correlation between elements
- Monitor long term changes in spectrum including shock wave timing

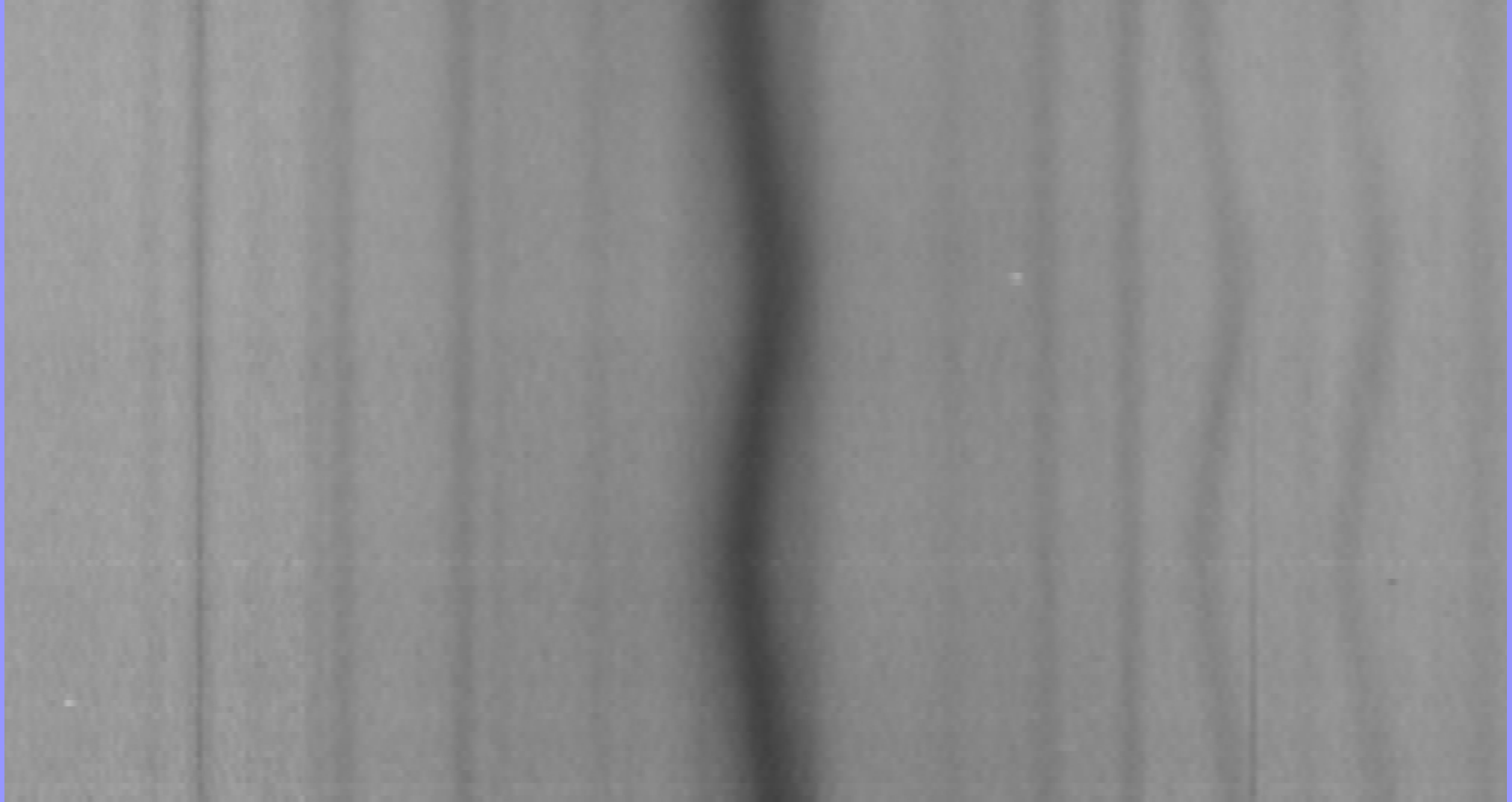
# beta Cep : the prototype

- $P=0.19$  days
- $V=3.16-3.27$

He I



# beta Cep : the prototype

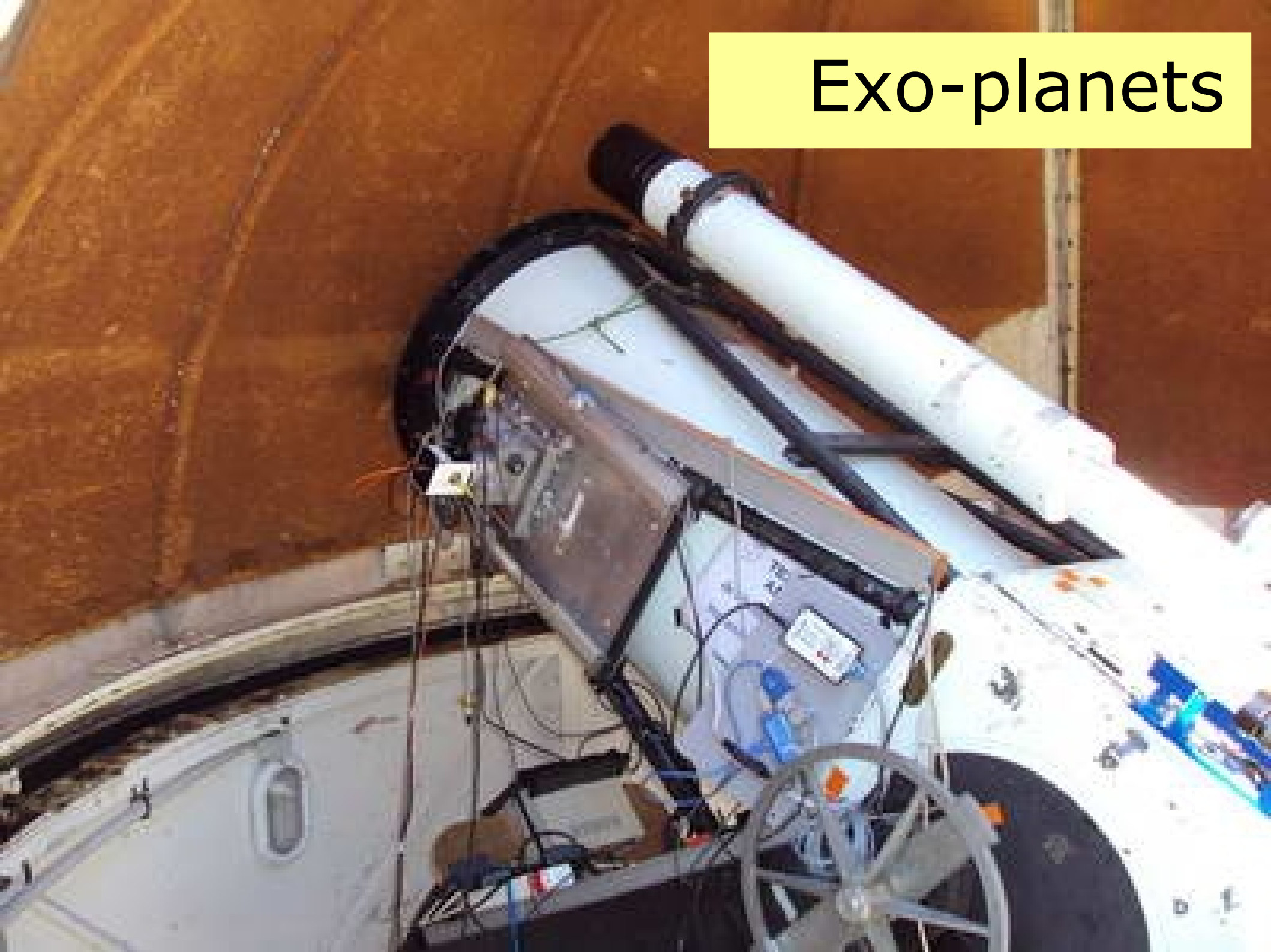


H $\alpha$

C II

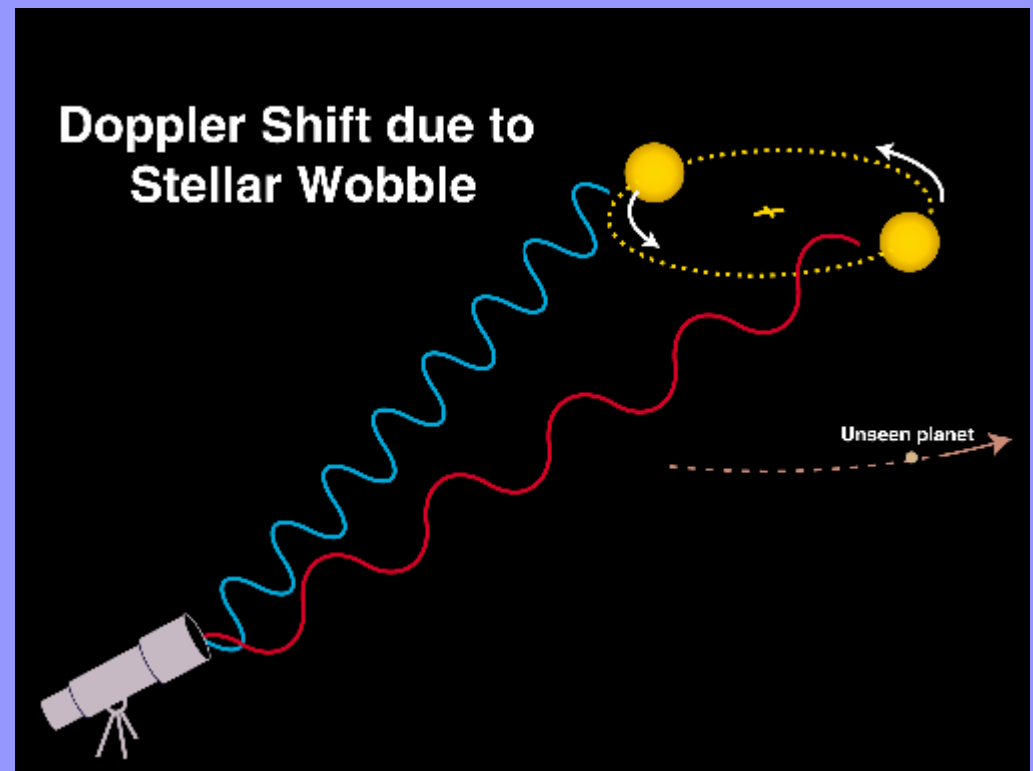
C II

# Exo-planets

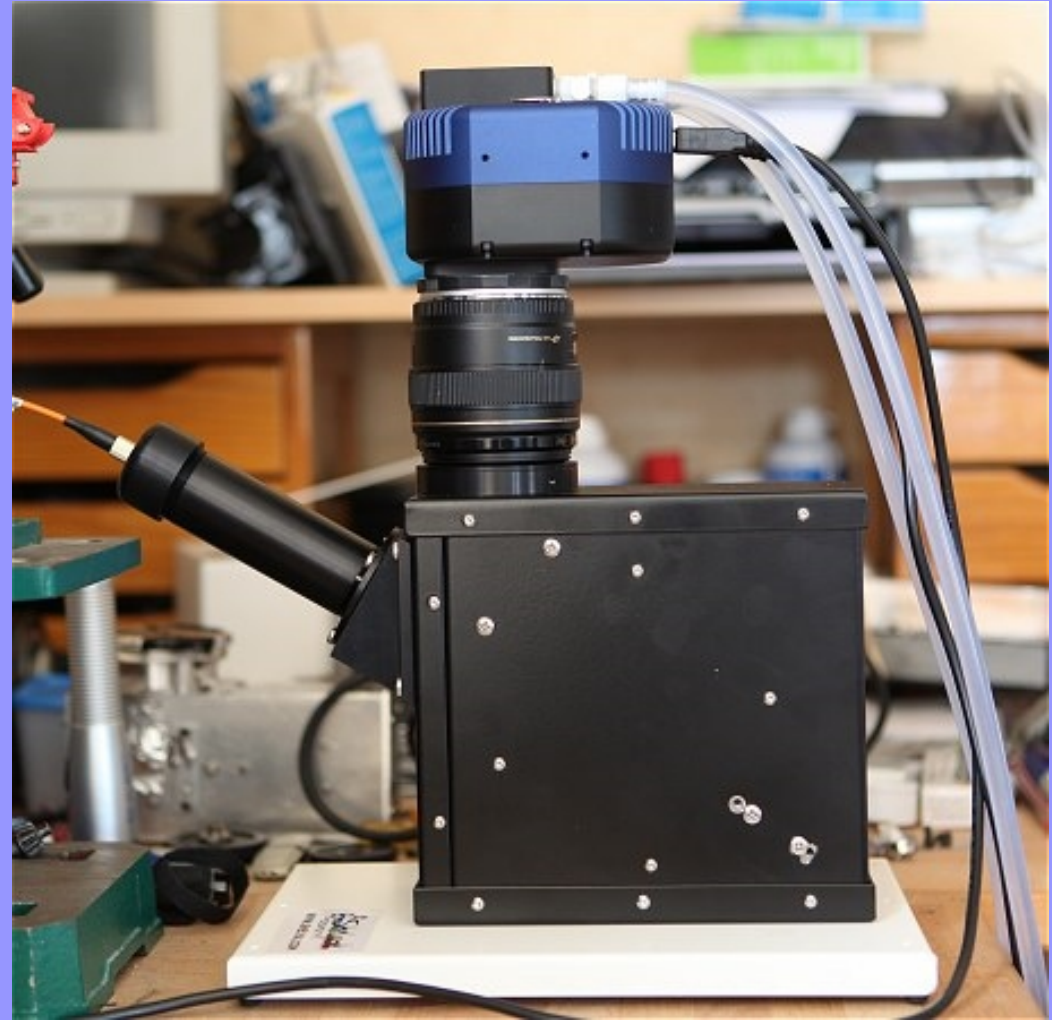
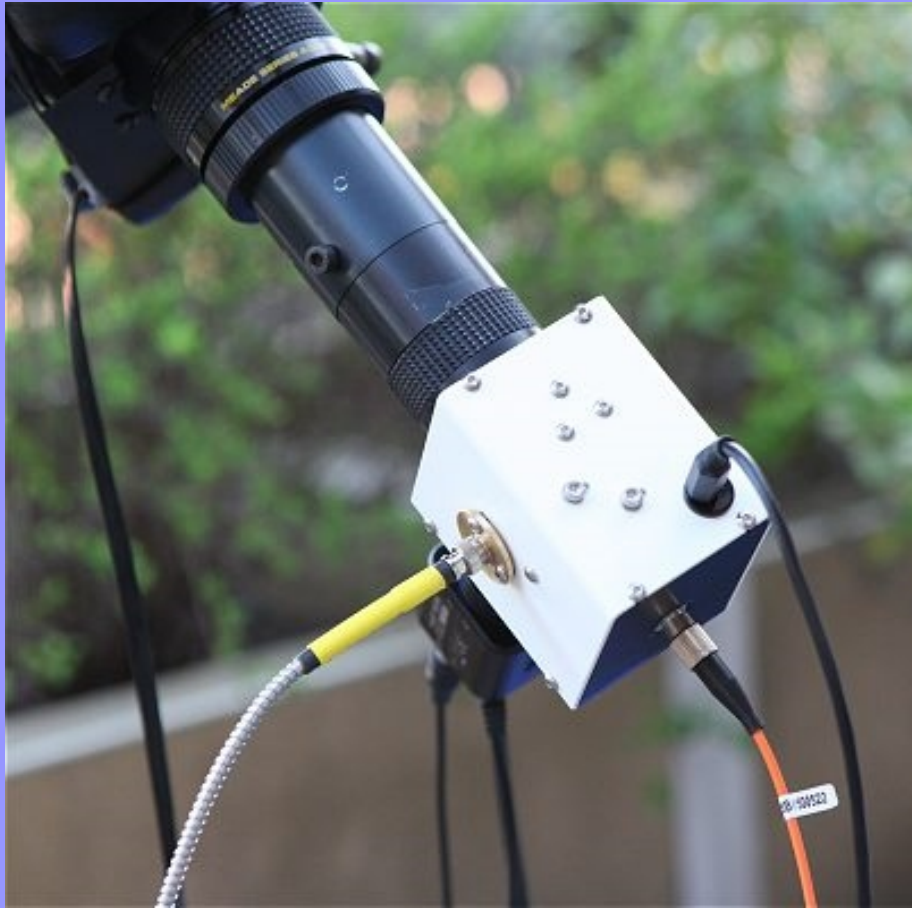


# Extrasolar planets

- First one (51 Peg) discovered in 1995
- Michel Mayor & Didier Queloz at OHP
- RV spectroscopic technic is the best method so far
- Transit possible



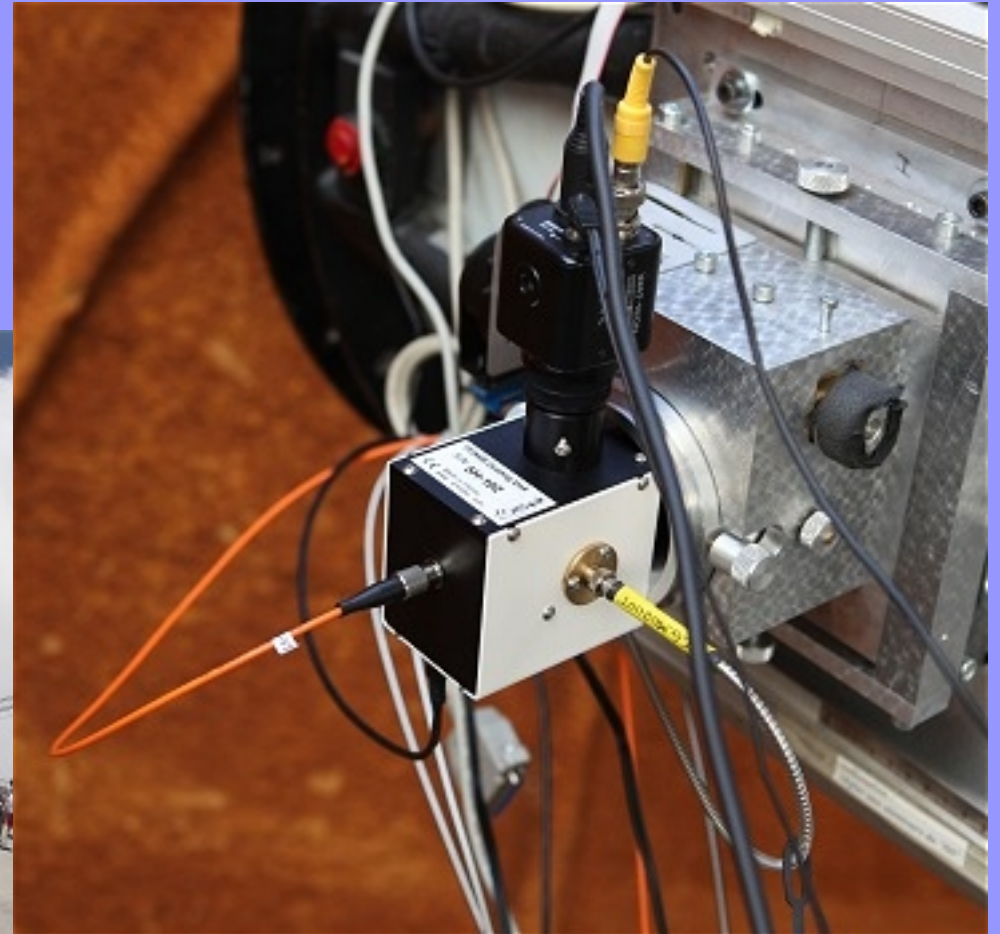
# Equipment #1



# Setup



# Equipment #2



# Control room

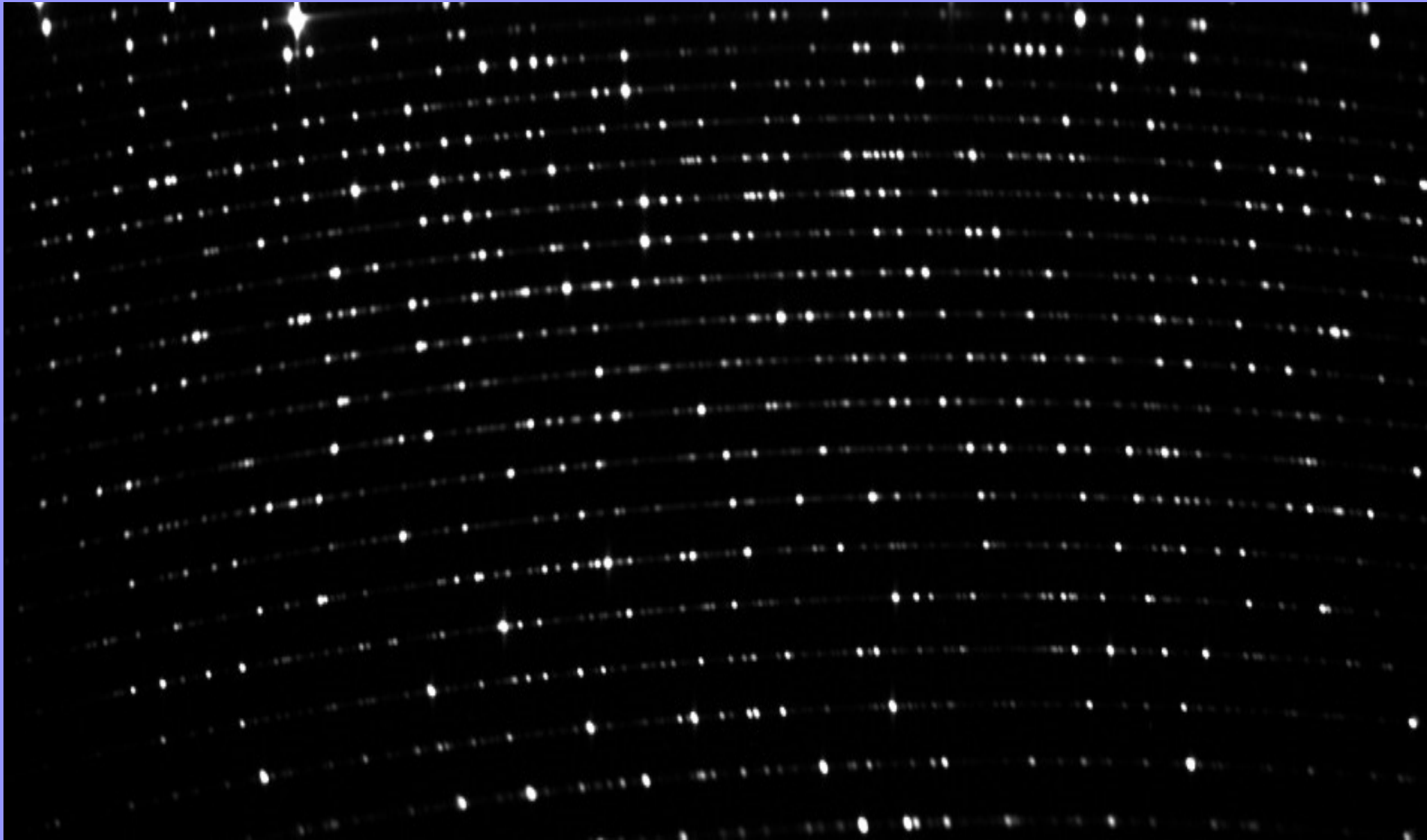


# Star spectrum

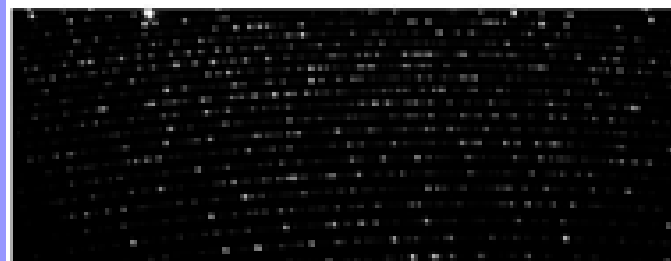


*HD120136;  $M_v=3.18$ ; F7V spectral type; 15min exposure*

# Thorium-Argon spectrum



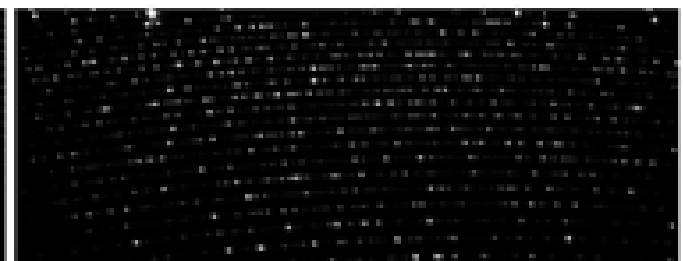
# Processing (1)



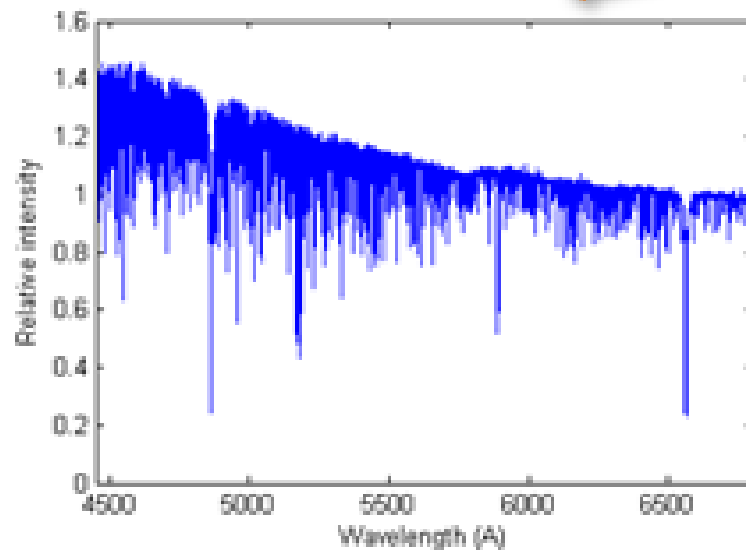
Calibration exposure: 30 sec.



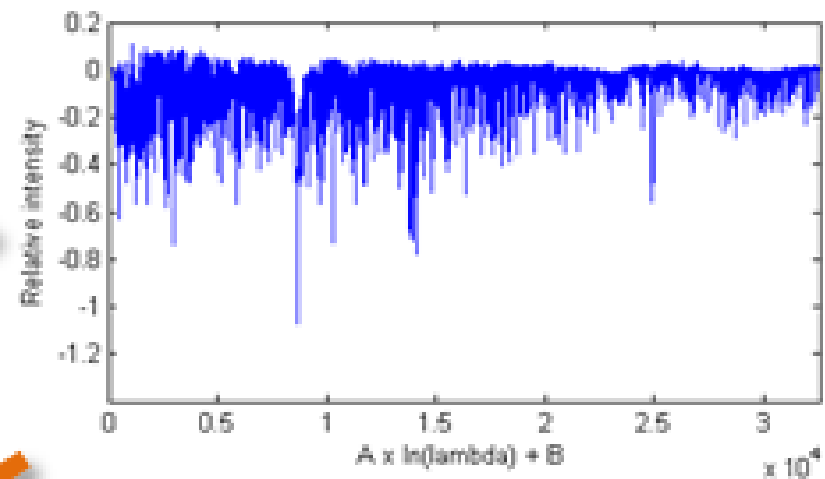
Star exposure: 300 sec.



Calibration exposure: 30 sec.

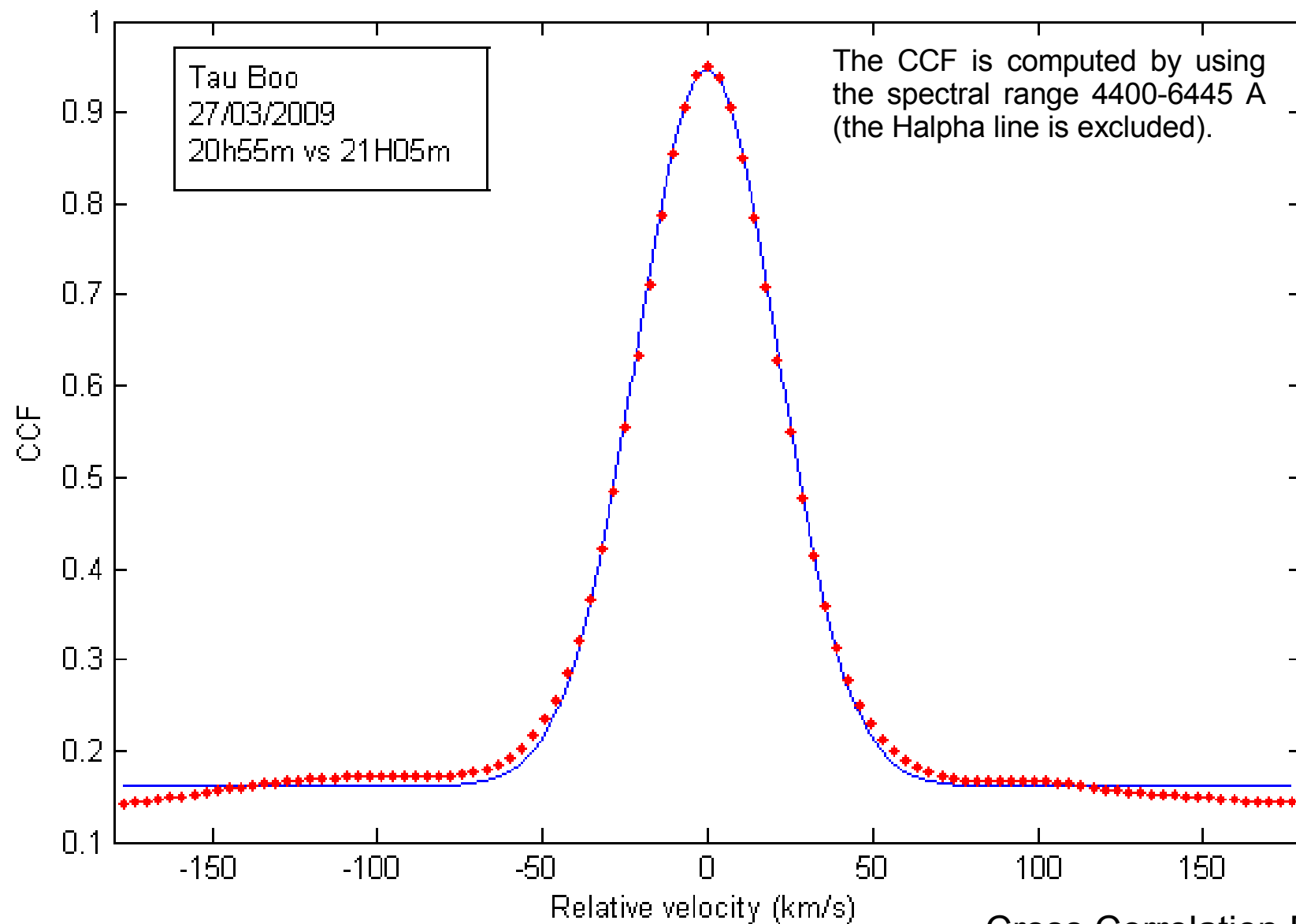


Calibrated spectrum



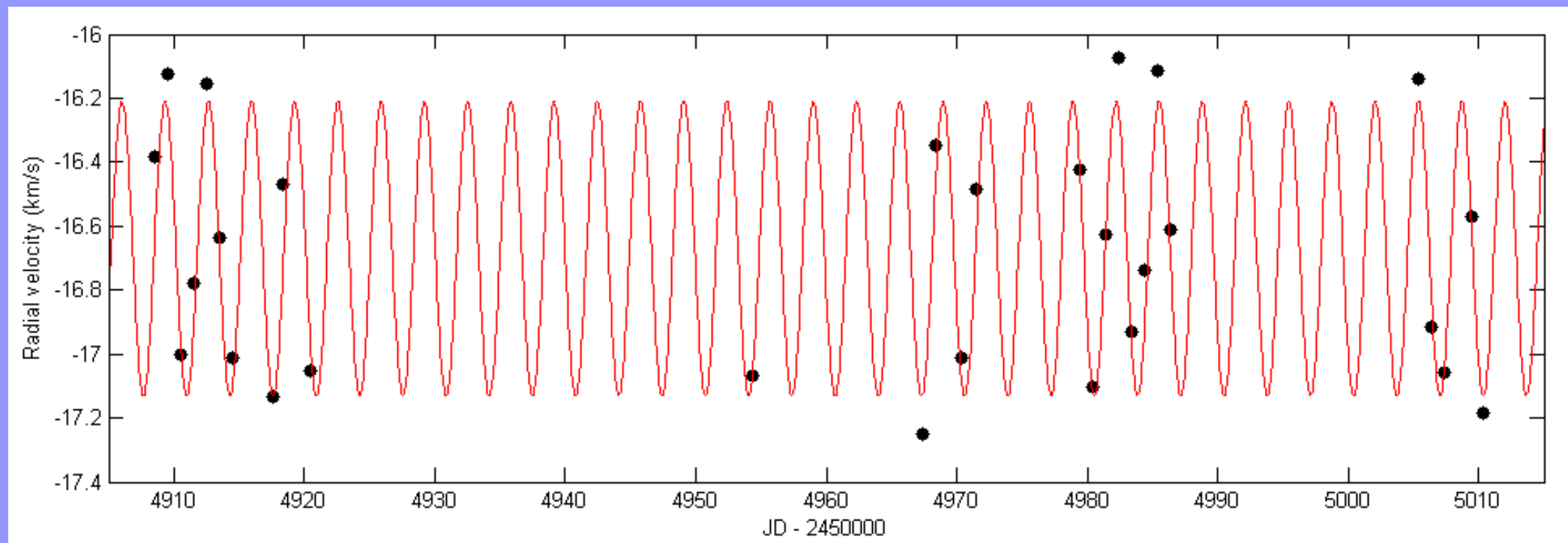
Constant velocity projection

# Processing (2)



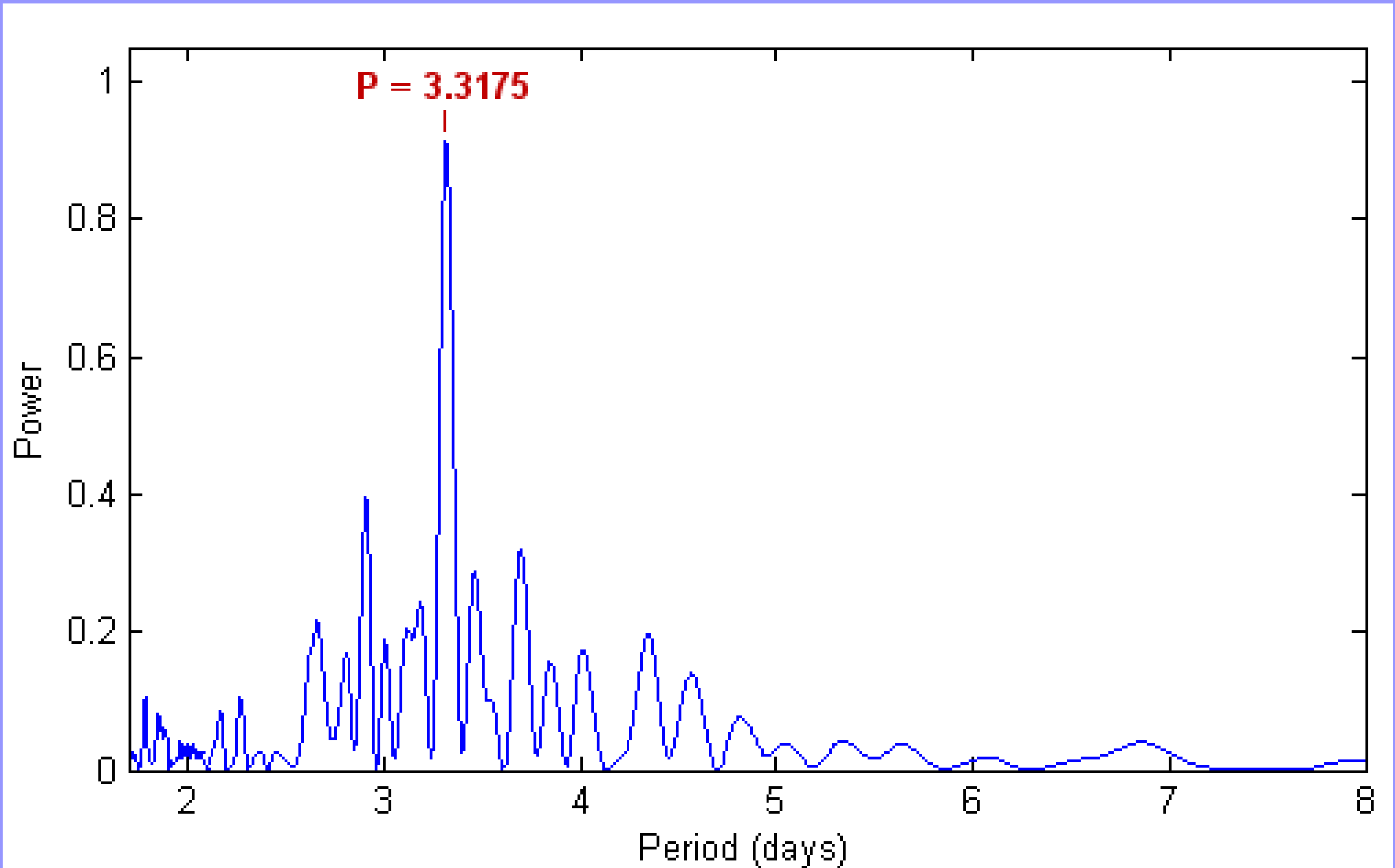
Cross Correlation Function

# Processing (3)

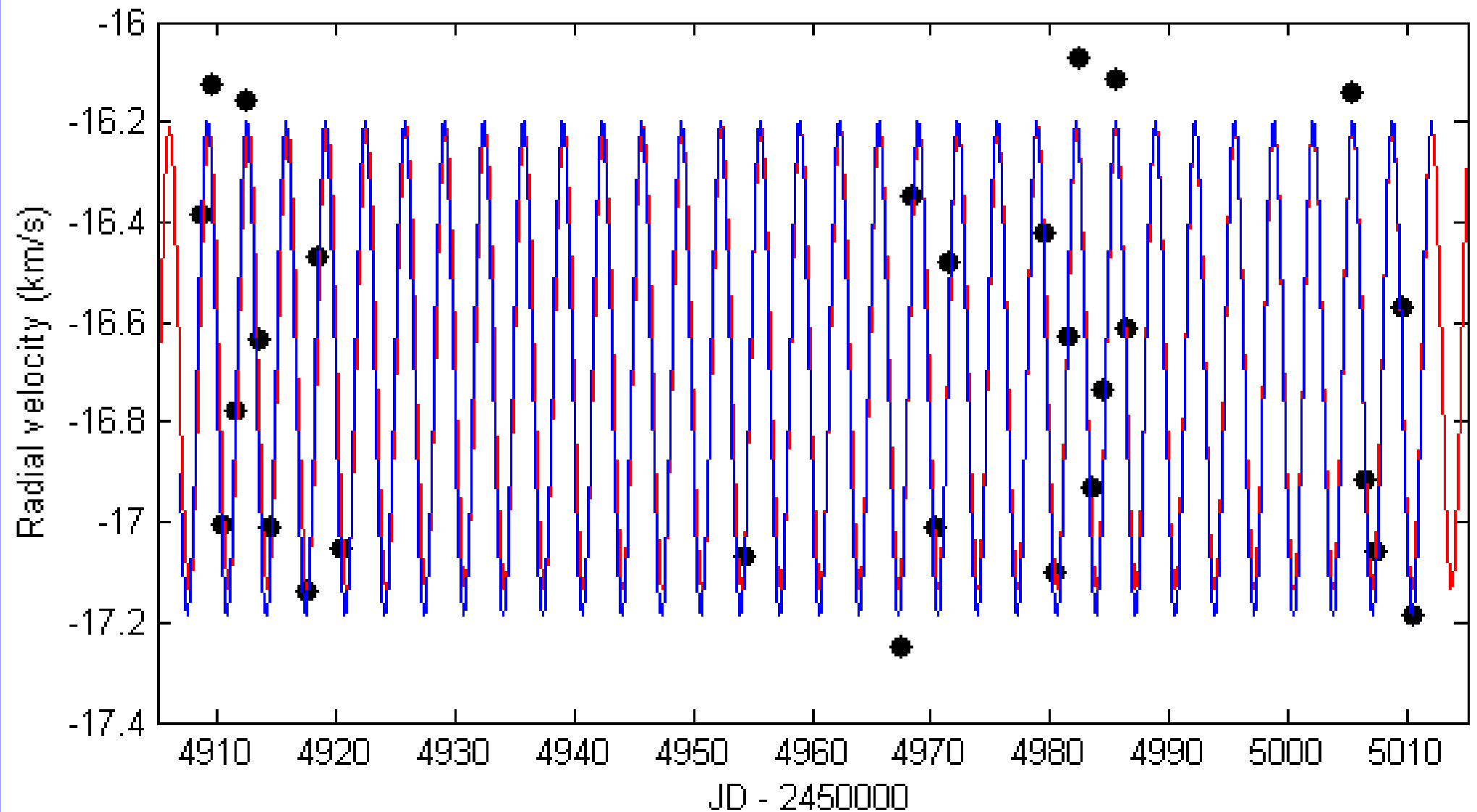


The total velocity Doppler spectral amplitude shift represents only 1/25th part of the spectrograph resolution. The data are collected between March-July, 2009.

# Periodogram on tau Boo



# Result on tau Boo

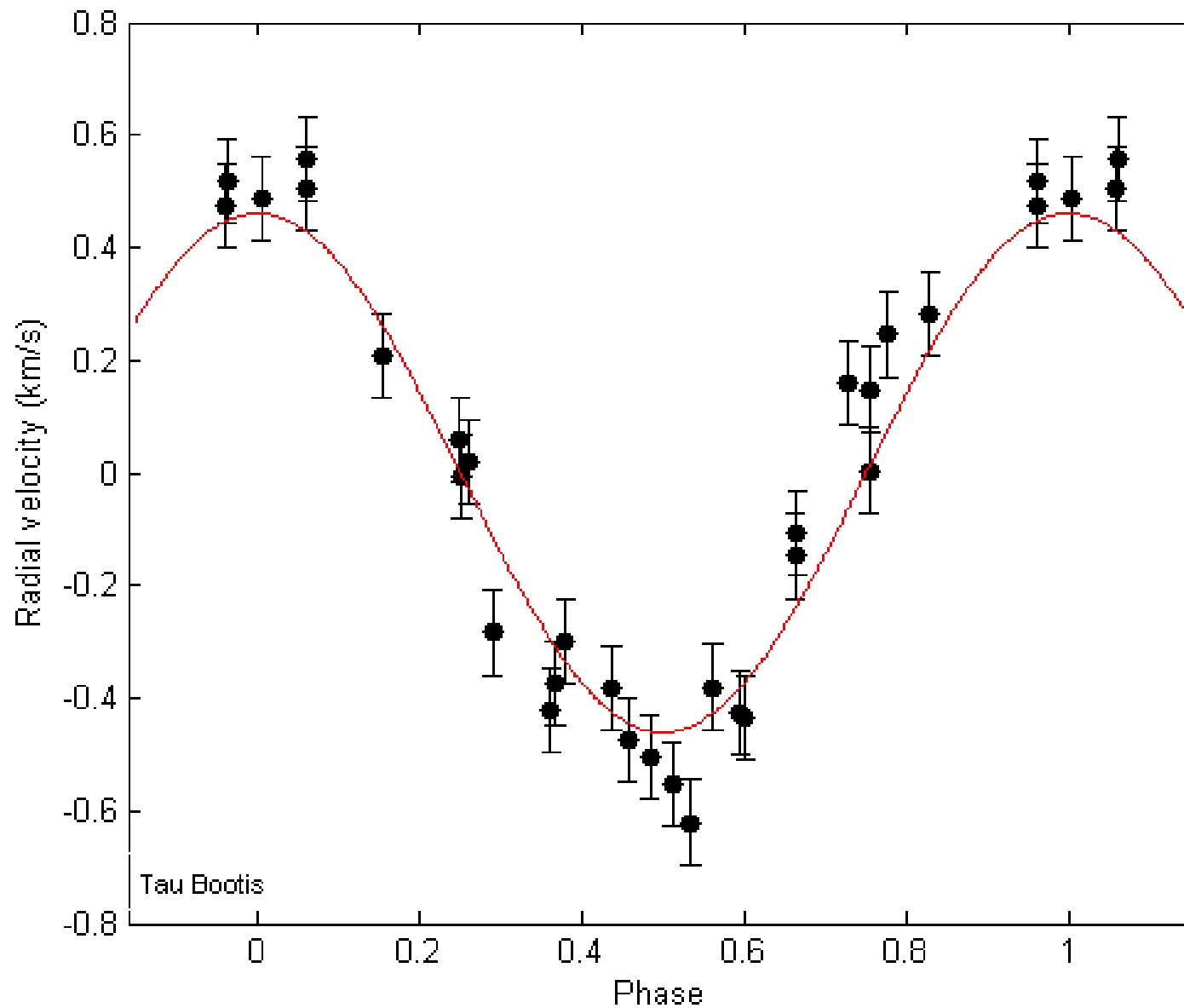


Blue = ephemeris (3.312 d) / Red = observed (3.17 d)

# Results on tau Boo

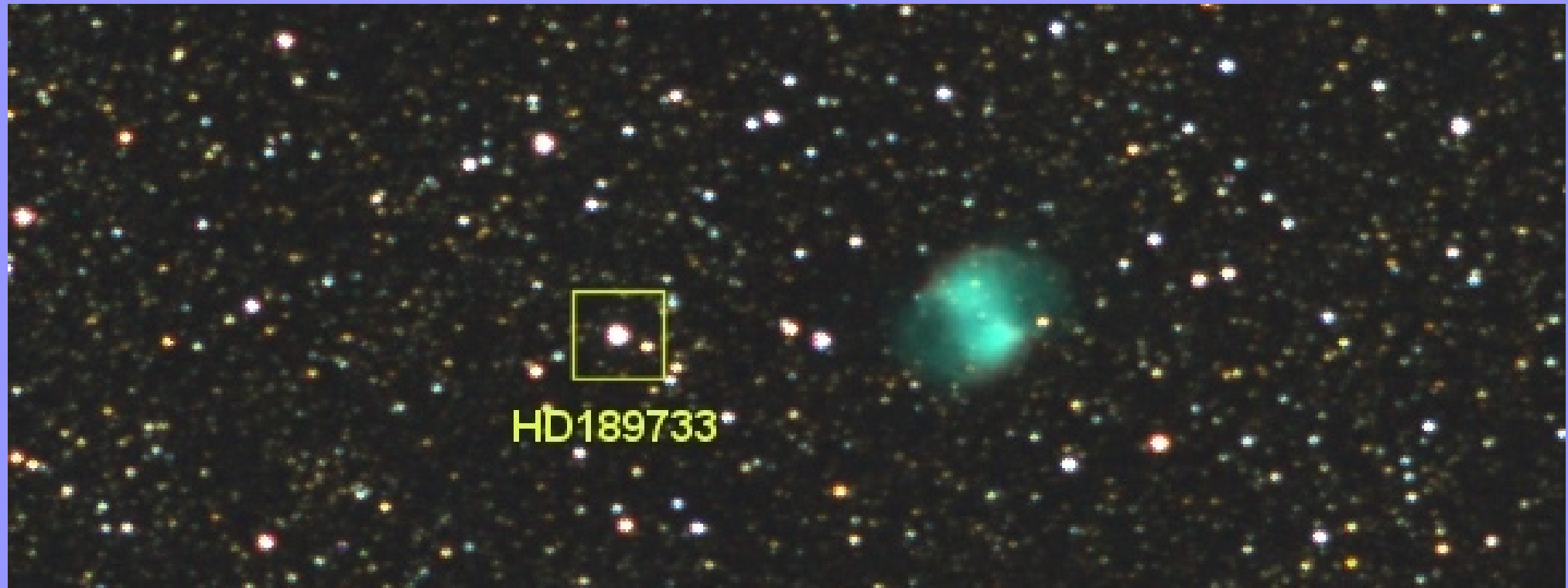
M.sini: **4.13** MJ

Orbital period: **3.317** (*Vs 3.312*)



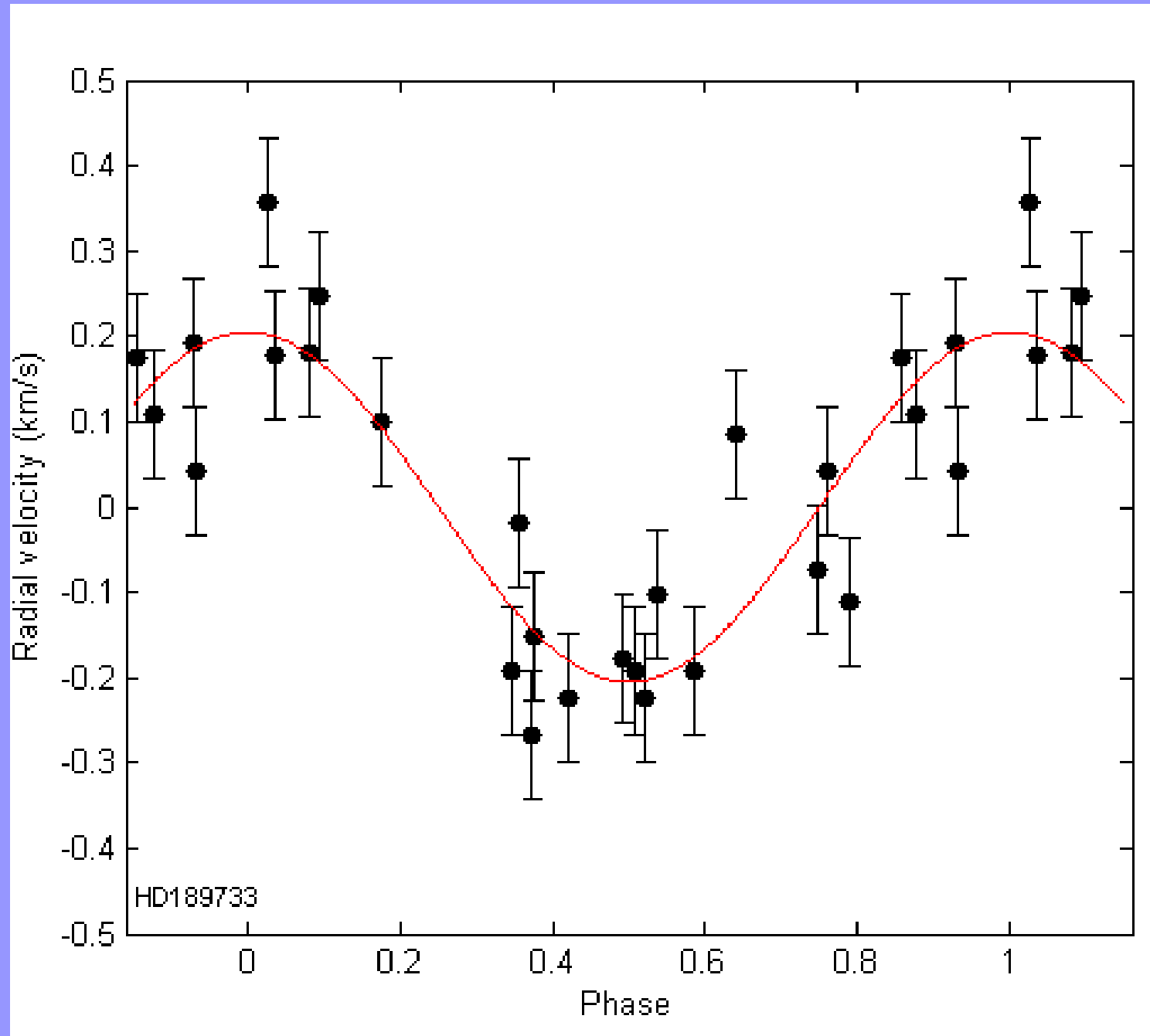
Tau Bootis

# HD 189733



**P = 2.223 d (vs 2.219)**

# HD 189733

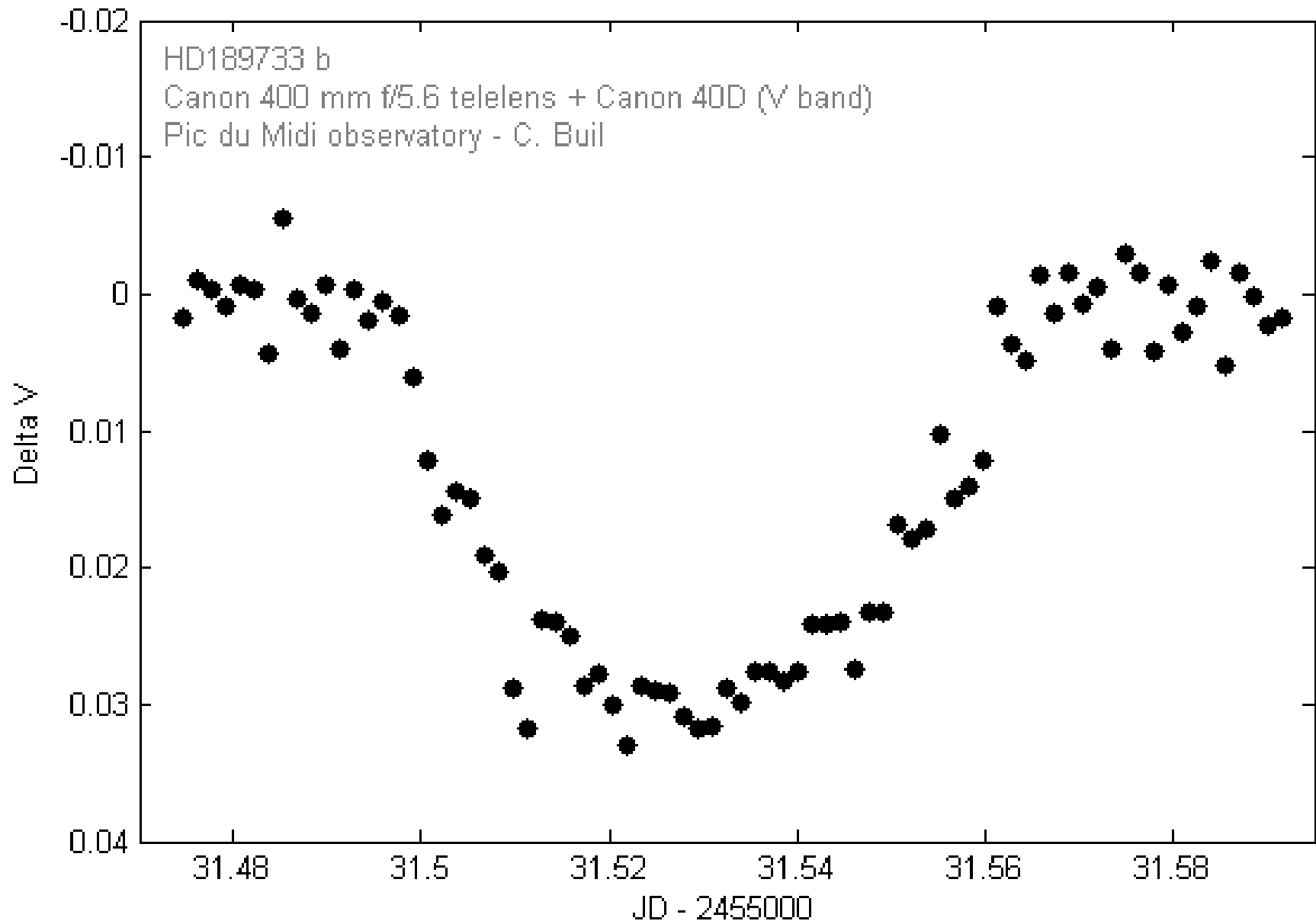


# Also a transiting exoplanet !

***Simple equipment used for photometrical observations...  
Canon 400mm f/5.6 + 40D***

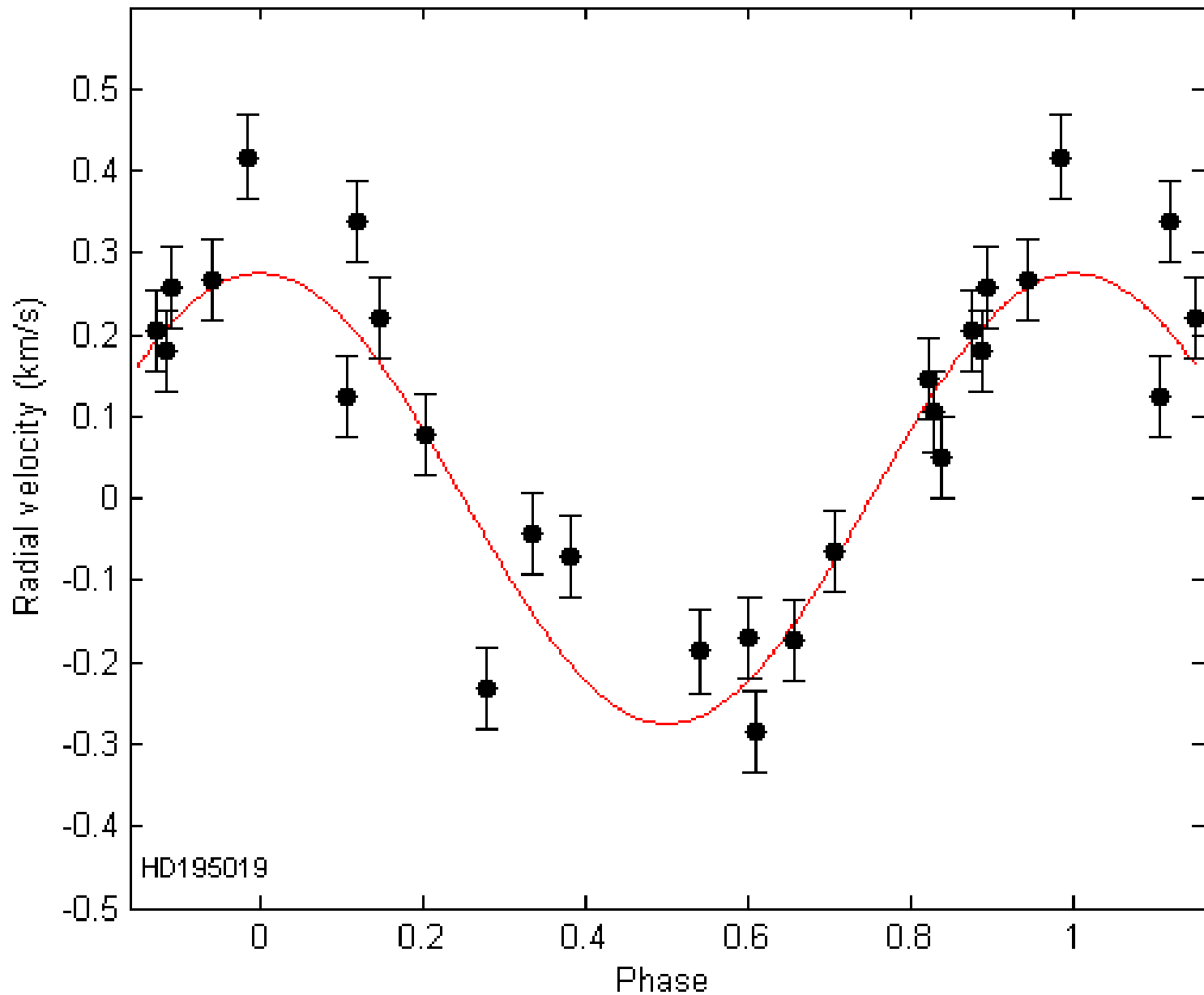


# Also a transiting exoplanet !



**P = 18.106 d (vs 18.202)**

# HD 195019



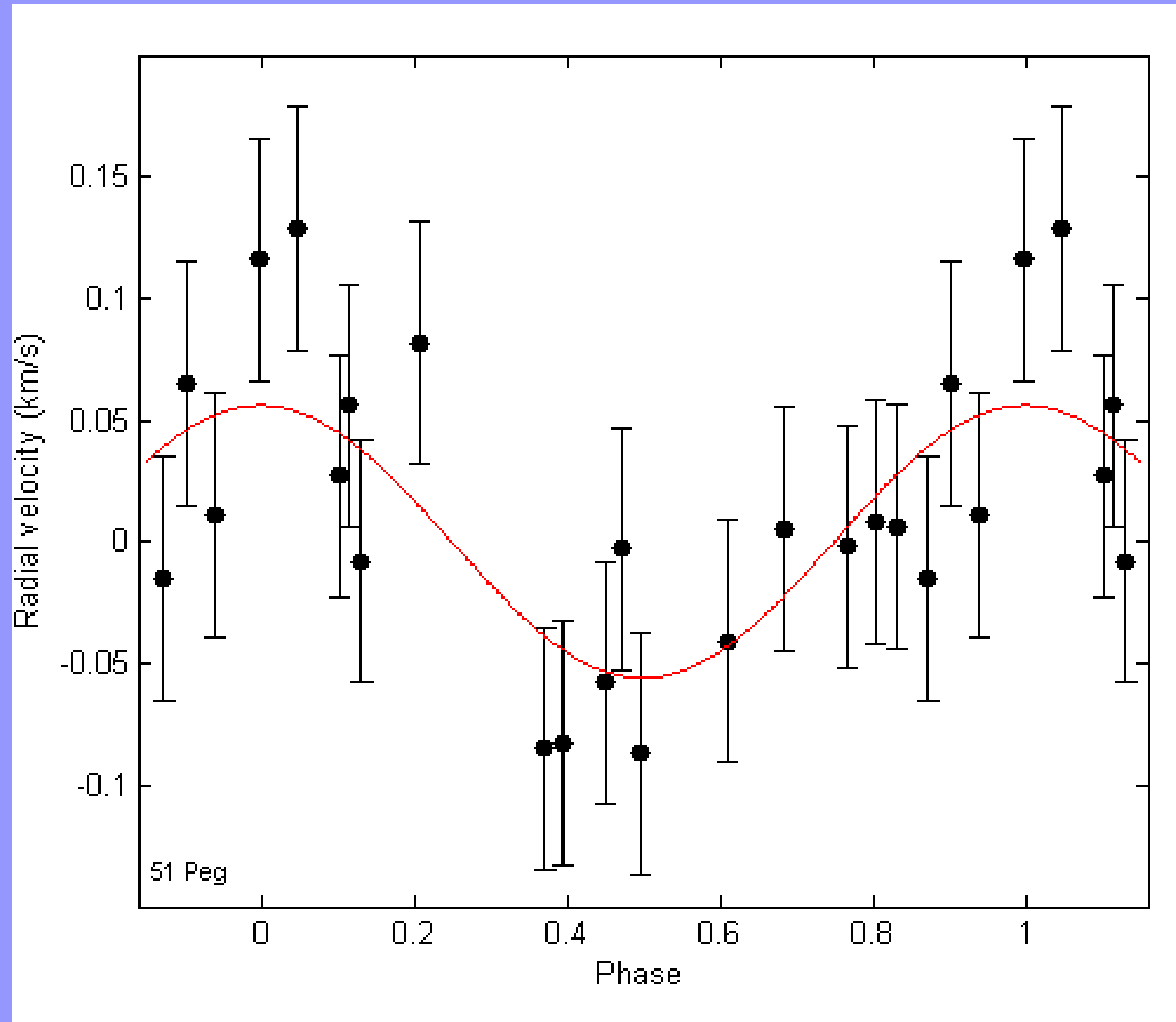
...and 51 Peg !



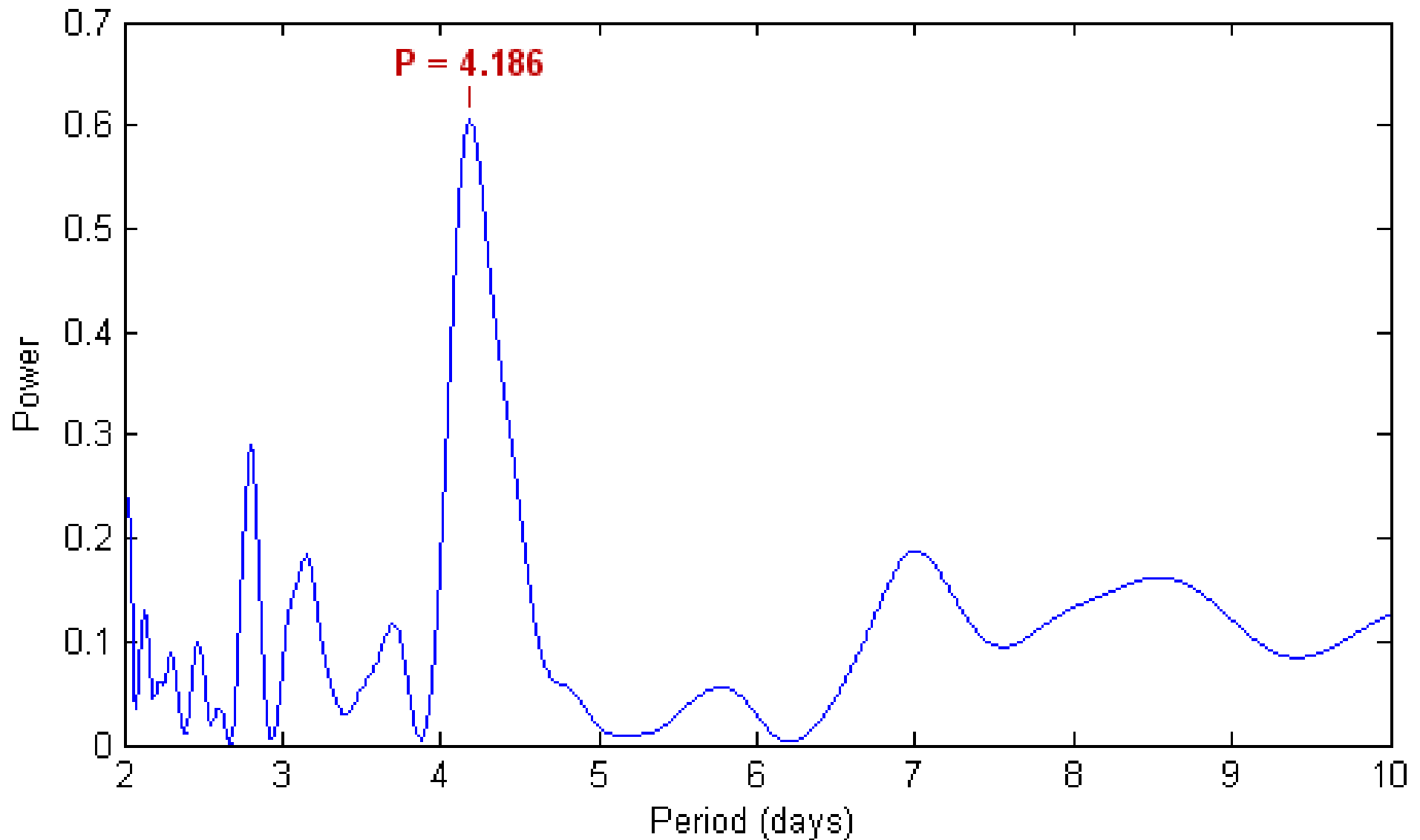
...looks a rather normal star !

**P = 4.186 d (vs 4.231)**

# 51 Peg RV curve



# 51 Peg periodogram



# Conclusion: eShel performances

- Optical fibre based spectroscopy:
    - Mechanical stability
    - Thermal stability
    - Less weight at telescope
  - Echelle spectrograph:
    - Multiple line measurement
- Higher accuracy  
for Radial Velocity measurement

# Conclusion: eShel performances

- Seeing : 3"

- sea level observation, star 45° above horizon

- A0 spectral type star

- S/N measured at 5500Å (550nm)

- Exposure time of 1 hour (6\*600sec)

- QSI532 ccd camera with KAF-3200ME (6.8 microns pixel size, 11.4 electron read noise level, 1.3 electron/ADU gain, dark current of 0.05 electron/sec)

## ***Limiting magnitude***

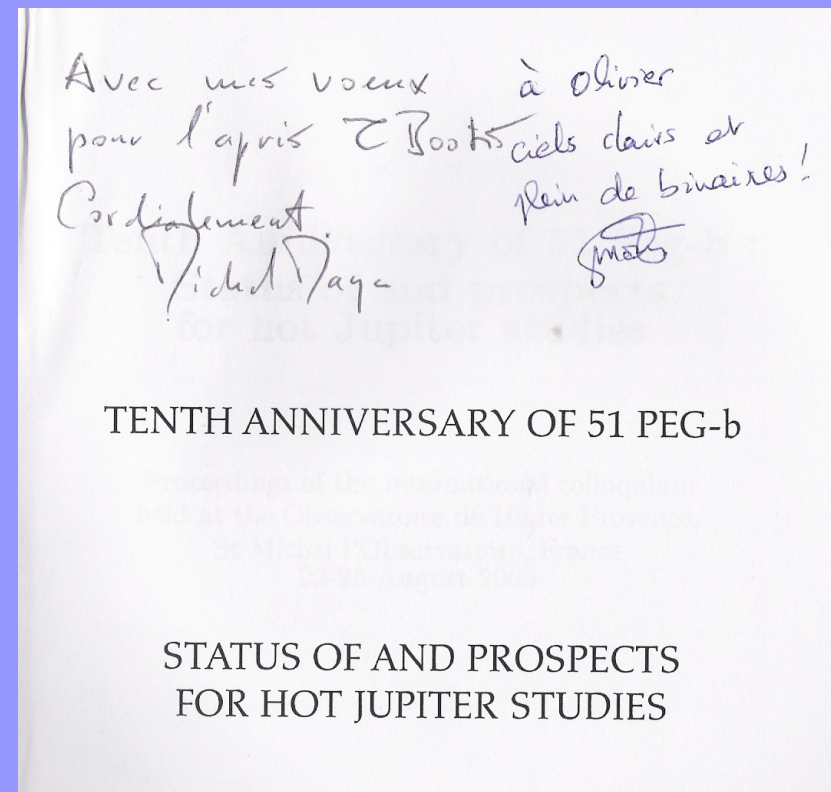
|                                | S/B = 20 | S/B = 50 | S/B = 100 |
|--------------------------------|----------|----------|-----------|
| D=20 cm F/D=5.9 (Celestron 8)  | 8.9      | 8.0      | 7.1       |
| D=28 cm F/D=5.9 (Celestron 11) | 9.6      | 8.7      | 7.7       |
| D=35 cm F/D=5.9 (Celestron 14) | 10.0     | 9.0      | 8.1       |
| D=40 cm F/D=4.0 (Dobson)       | 10.3     | 9.2      | 8.4       |
| D=60 cm F/D=3.5                | 11.0     | 10.0     | 9.1       |
| D=100 cm F/D=3.5               | 11.5     | 10.5     | 9.6       |

## ***Radial Velocity accuracy***

| Magnitude | Celestron 11 - f/5.9 | 60 cm - f/3.5 |
|-----------|----------------------|---------------|
| 3         | 37 m/s               | 18 m/s        |
| 4         | 56 m/s               | 28 m/s        |
| 5         | 95 m/s               | 46 m/s        |
| 6         | 175 m/s              | 75 m/s        |
| 7         | 360 m/s              | 140 m/s       |

# Conclusions

- High resolution + echelle + optical fibre is opening a door to higher accuracy RV work including exoplanets...
- But collaboration with professional teams still to be defined :
  - Pulsating stars  
(RR Lyr, bet Cep...)
  - Spectroscopic binaries ?
  - Exoplanets ?
- See... pro/am meeting next month !



# Some useful books



Groupe ARAS: <http://www.astrosurf.com/aras/>

Liste Spectro-L: <http://groups.yahoo.com/group/Spectro-l/>

CDS Strasbourg <http://http://cdsweb.u-strasbg.fr/>

ADS (articles) [http://http://adsabs.harvard.edu/abstract\\_service.html](http://http://adsabs.harvard.edu/abstract_service.html)

Shelyak <http://www.shelyak.com/en>

# THANK YOU

