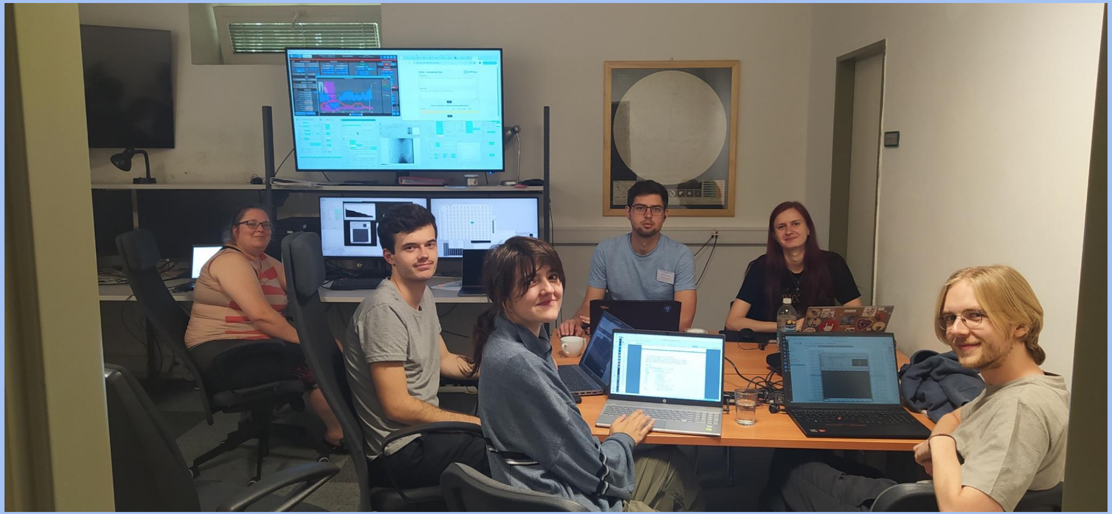
Determining the Mass of the Hot Jupiter HD 2685b

Using PLATOSpec radial velocities and TESS photometry



Contents

About me - Michal Zummer

Born in 2002.

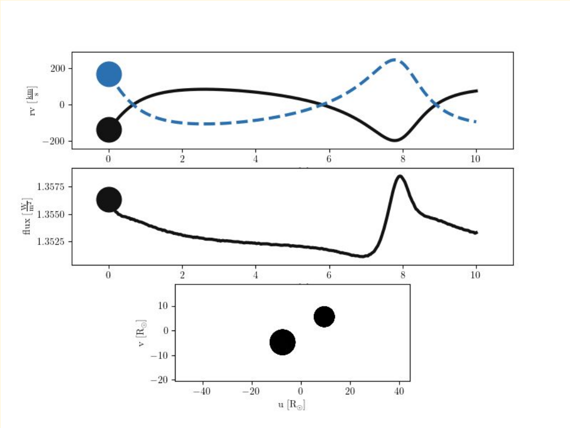
Originally from a small village in Slovakia.

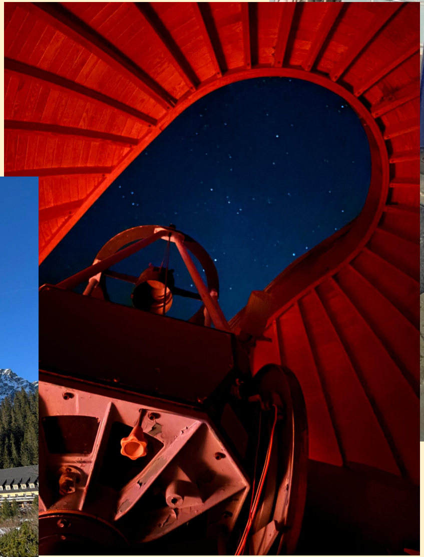
Finished a bachelor's degree just weeks ago.

- studied binaries, triples and quadruples

Starting master's studies soon.

Traveller, reader, and LEGO lover…





"Jen bychom rády věděly,"
vrch hlavy poulí zraky,
"jsou-li tam tvoři jako my,
jsou-li tam žáby taky!"

"We'd just like to know,"
the tops of their heads bulged their eyes,
"are there creatures like us there,
are there frogs there too?"

Seděly žáby v kaluži (Písně kosmické)

Jan Neruda (1834 - 1891)

Basic history

first planetary mass body outside Solar System Wolszczan & Frail 1992

first exoplanet found by Mayor & Queloz 1995 using RV method (Nobel prize 2019)

first photometric transit of a known planet

6000 confirmed exoplanets

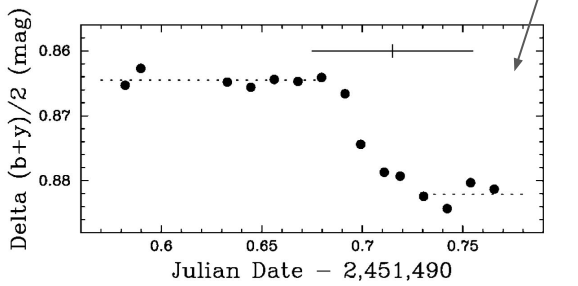


FIG. 3.—Photometric observations of HD 209458 from the night of 1999 November 7 UT showing ingress of the planetary transit. The measured transit depth is 0.017 ± 0.002 mag or 1.58% ± 0.18%. The error bar shows the time of inferior conjunction and its uncertainty predicted from the radial velocities in this Letter.

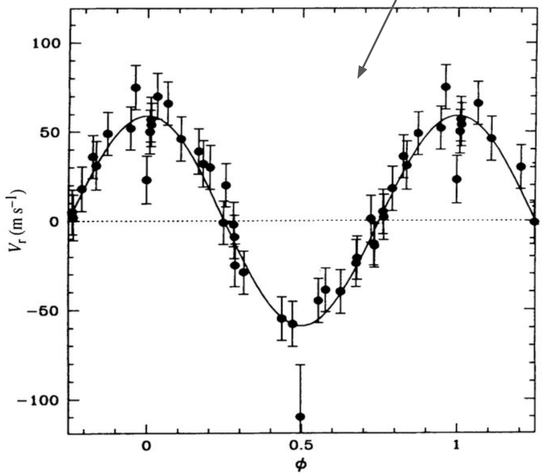
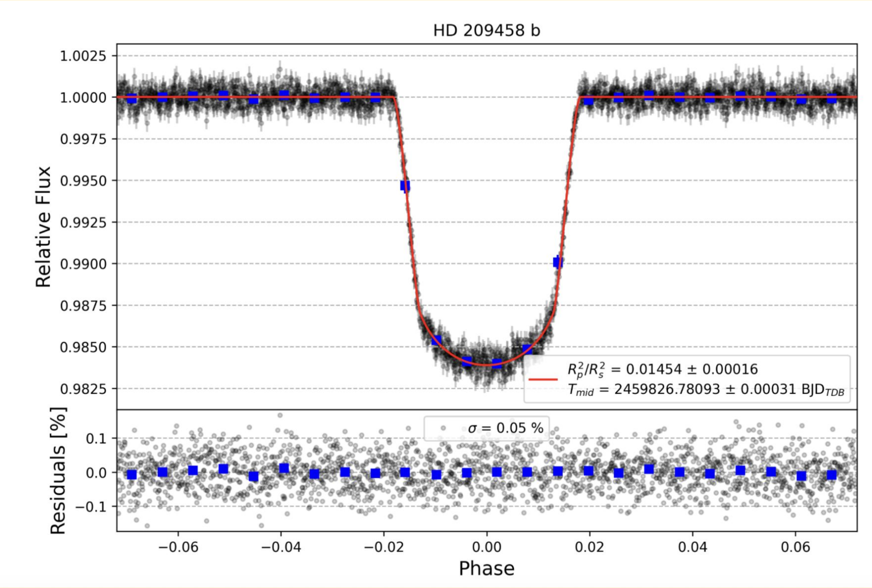


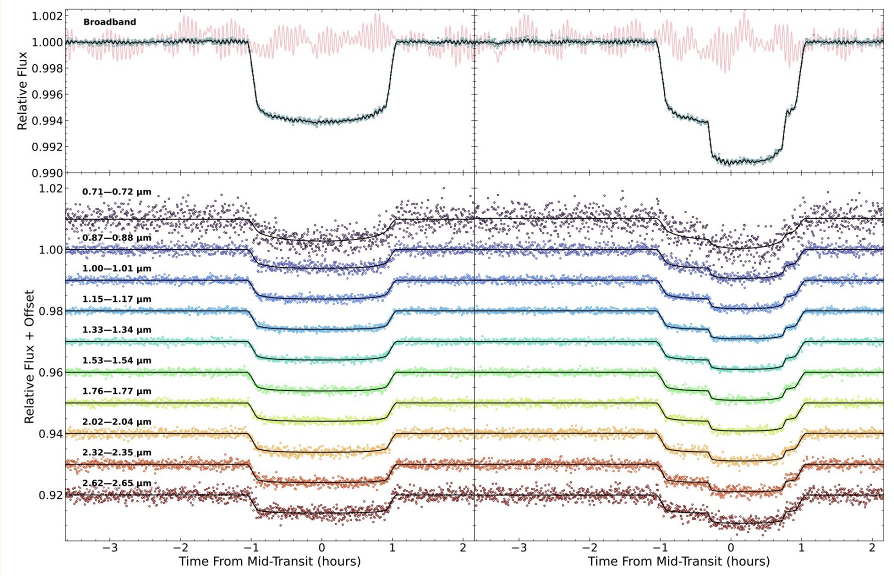
FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the γ-velocity. The solid line represents the orbital motion computed from the parameters of Table 1.

https://exoplanets.nasa.gov/alien-worlds/exoplanet-travel-bureau/?intent=021

And now…

HD 209458 from TESS and LHS 1140 b and c transiting from JWST

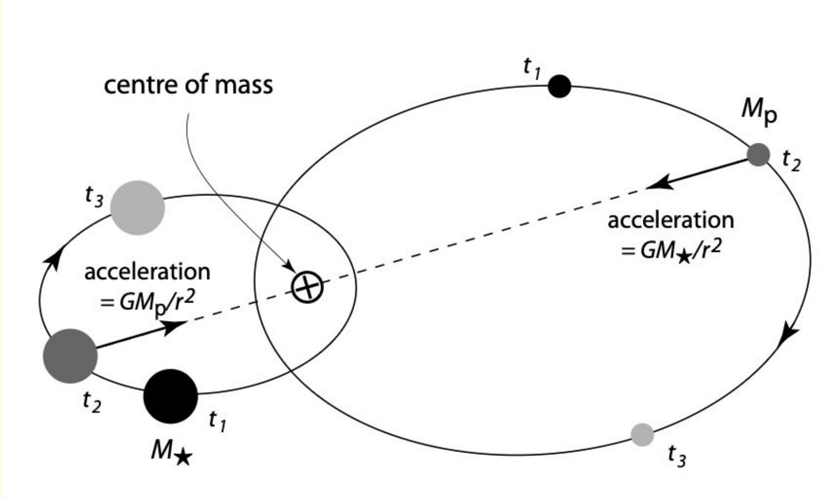




Radial velocities

$$P^2 = \frac{4\pi^2}{G(M_\star + M_\mathrm{p})} a_\mathrm{rel}^3$$

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



$$v_\mathrm{r} = K\,[\cos(\omega + \nu) + e\cos\omega]$$

$$K \equiv \frac{2\pi}{P}\,\frac{a_\star \sin i}{(1-e^2)^{1/2}}$$

from RVs we can get e, P, T_p, ω and $f(a, e, P, i)$

only $a \sin i$, not i and not a

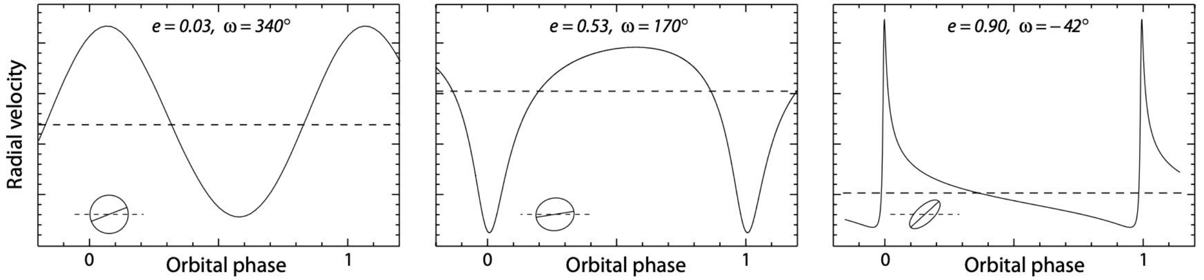


Figure 2.4: Example stellar radial velocity curves, illustrating their dependence on e and ω, for HD 73256 (Udry et al., 2003a, Figure 2), HD 142022 (Eggenberger et al., 2006, Figure 4), and HD 4113 (Tamuz et al., 2008, Figure 1). Horizontal dashed lines show the systemic velocity (viz. the radial velocity of the barycentre). The ellipses at lower left show the viewing geometries.

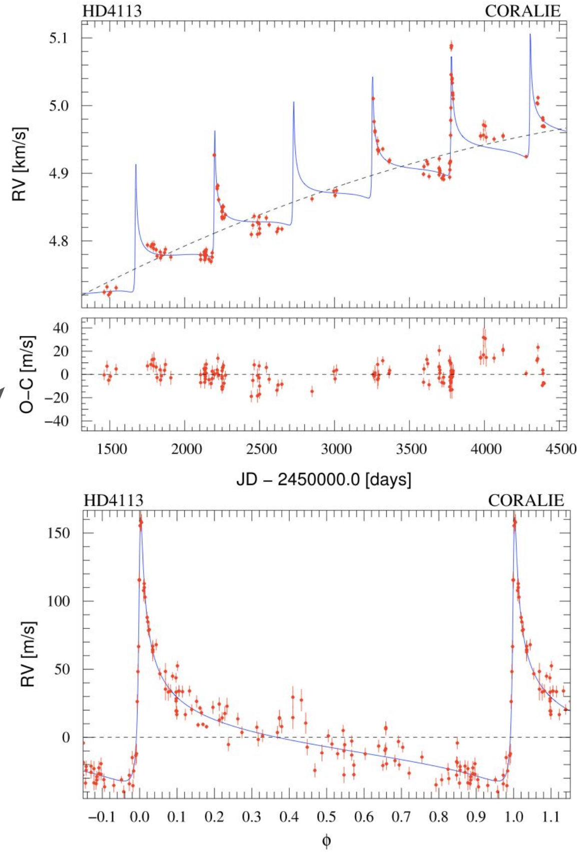


Fig. 1. Radial-velocity measurements as a function of Julian Date obtained with CORALIE for HD 4113, superimposed on the best Keplerian planetary solution (top figure). The residuals are displayed at the bottom of the top figure, and the phase folded radial-velocity measurements are displayed on the bottom diagram.

don't forget about γ and systemic trends (HD 4113)

$$v_{\mathrm{r}}(t) = K\left[\cos(\omega + \nu(t)) + e\cos\omega\right] + \gamma + d(t - t_0)\,.$$

$$v_{\rm r}(t) = \sum_{j=1}^{n_{\rm p}} \left[h_j \cos\nu_j(t) + c_j \sin\nu_j(t) \right] + v_0 + d(t - t_0), \quad (2.31)$$

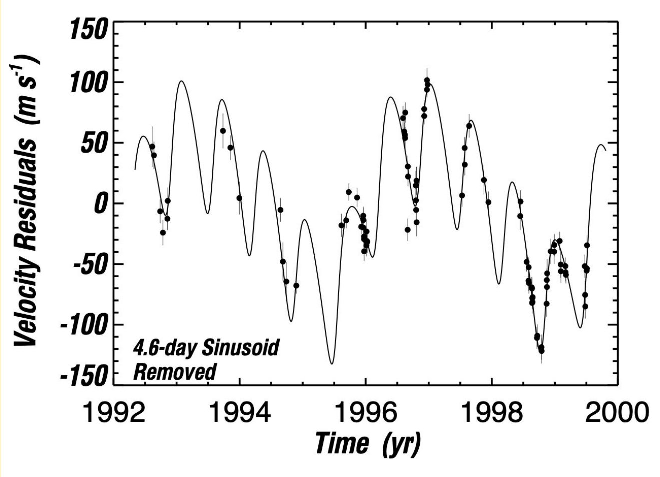
where, for each planet,

$$h_j = K_j \cos\omega_j\,, \;\; c_j = -K_j \sin\omega_j\,, \;\; v_0 = \gamma + \sum_{j=1}^{n} K_j e_j \cos\omega_j\,.$$

for multiple planets

for n planets you fit $5n$+1 Keplerian parameters

<u>evidence for multiple companions</u>



signal of Earth orbiting the Sun is 0.09 m/s, but solar radius is changing 0.06 m/s

-> stellar variability can mimic or mask RVs of Earth-like planet

The Pale Blue Dot

Rossiter–McLaughlin effect - heritage from the EB

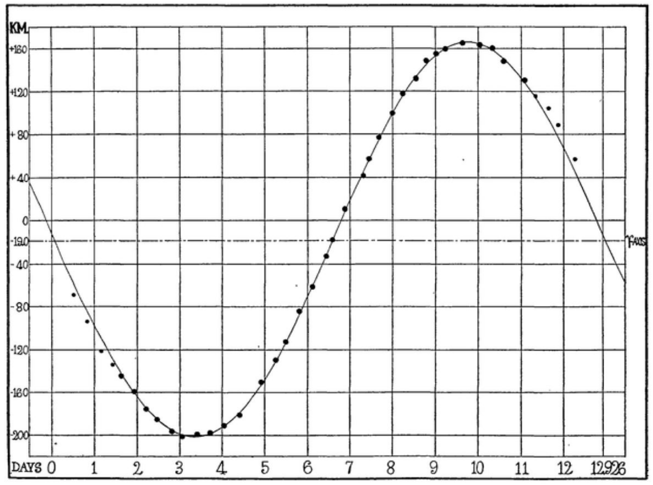


FIG. 1

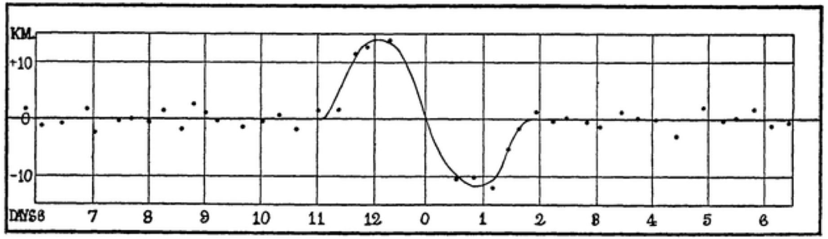
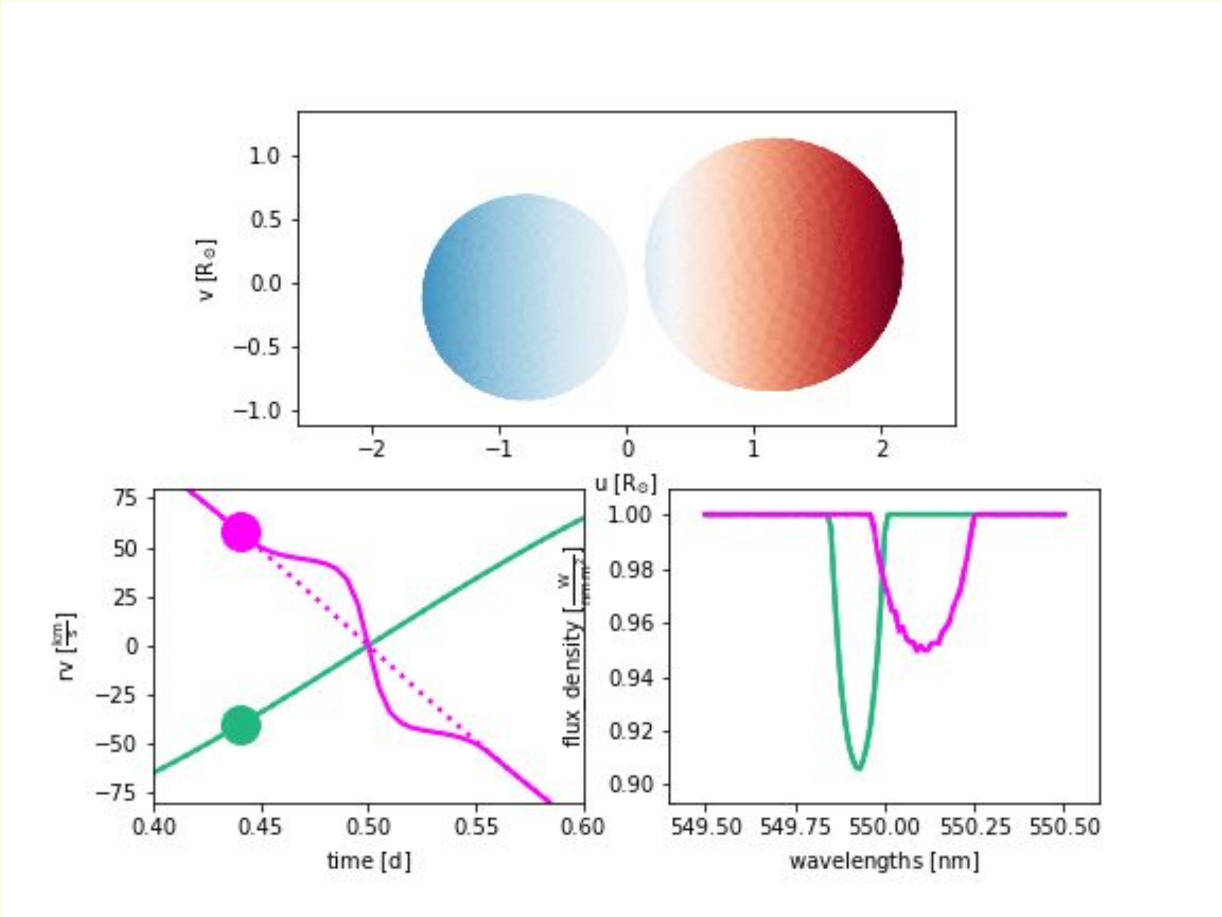


FIG. 2

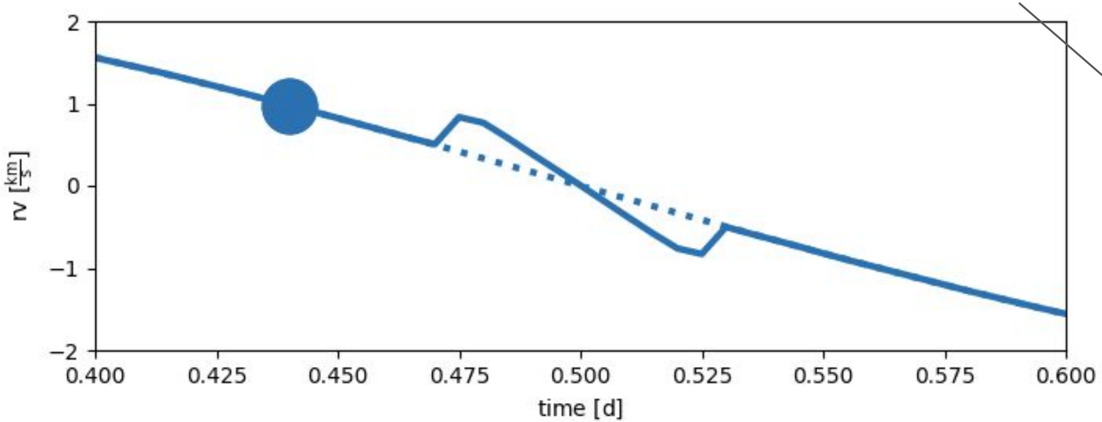
Rossiter explained the effect as

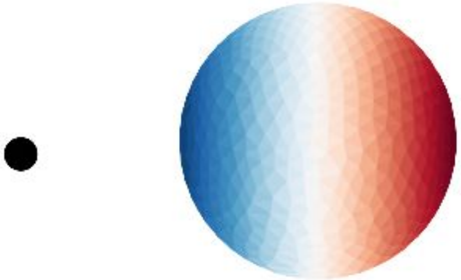
'When the star is entering eclipse, the receding limb is visible and the approaching limb is covered [and vice versa]'

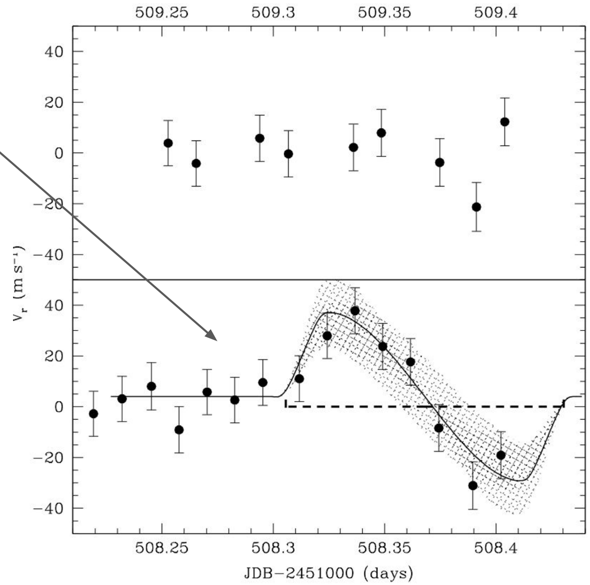


https://phoebe-project.org/docs/2.4/examples/rossiter_mclaughlin

First detection of Rossiter McLaughlin of exoplanet





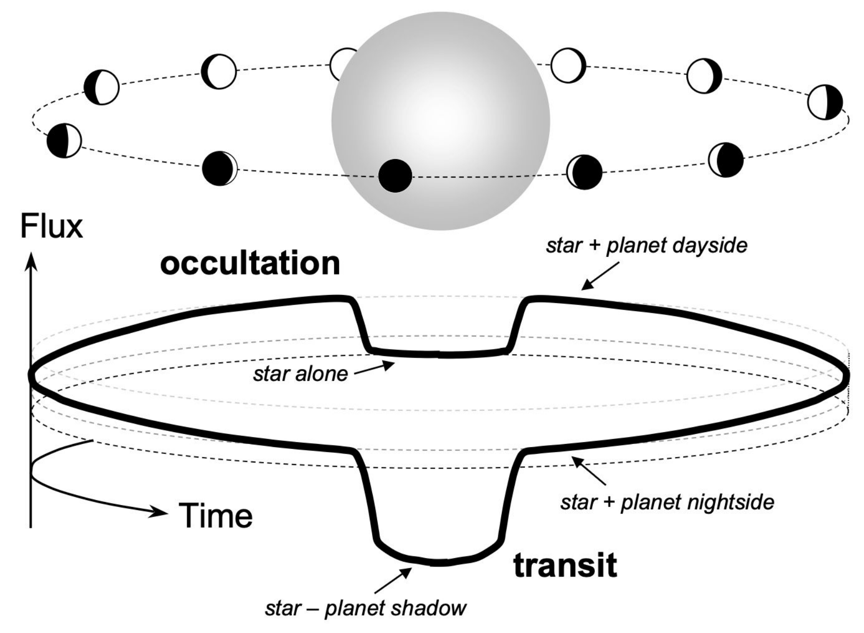


Transits

$$p = \frac{R_\star}{a}$$

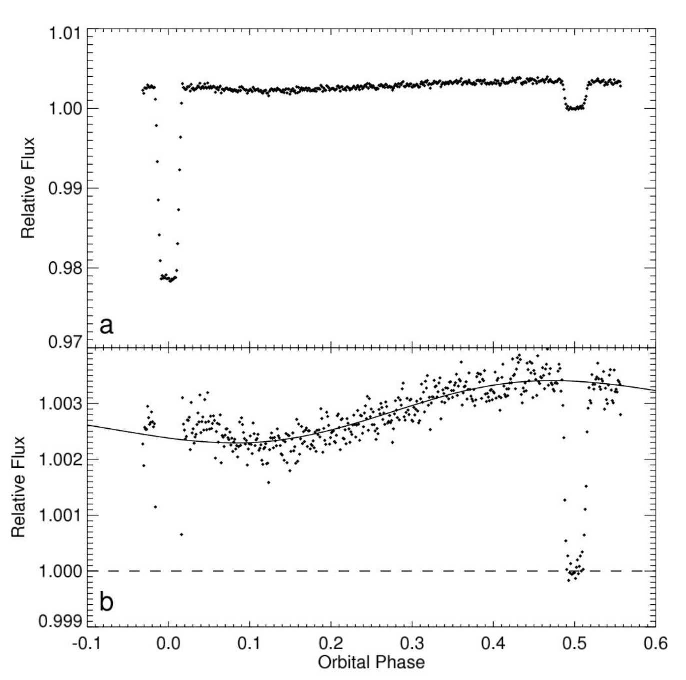
probability of randomly oriented planet on circular or elliptical orbit to transit

$$p_{\rm tra} = p_{\rm occ} = \left(\frac{R_\star \pm R_p}{a}\right)\left(\frac{1}{1-e^2}\right)$$



Reading for lonely nights:

Transits and Occultations by Joshua N. Winn



HD 189733

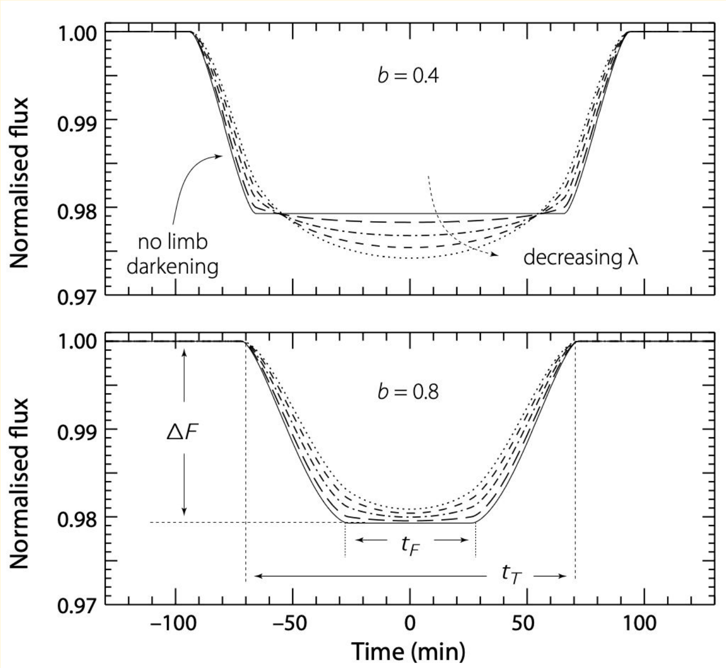
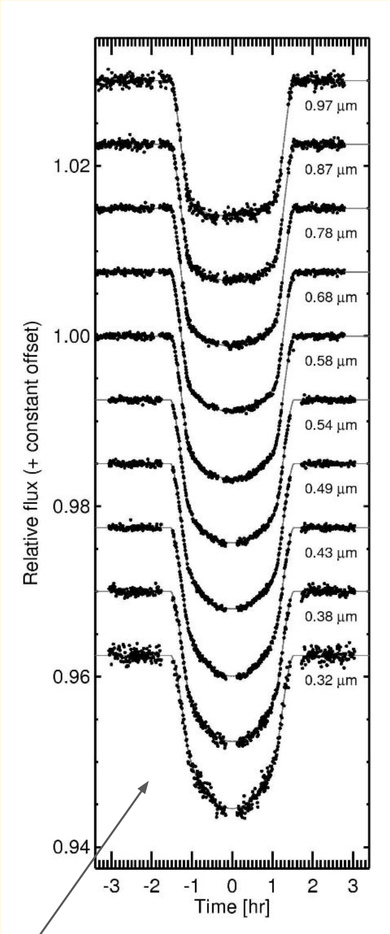


Figure 6.28: Theoretical transit curves for two impact parameters b, without (solid curves) and with (solar-type) limb darkening at 3, 0.8, 0.55 and 0.45 µm (effects increase towards shorter wavelength). Model parameters are: $R_\mathrm{p} = 1.4R_\mathrm{J}$, $a = 0.05$ au, $R_\star = R_\odot$, $M_\star = M_\odot$. From Seager & Mallén-Ornelas (2003, Figure 11), by permission of IOP Publishing/AAS.



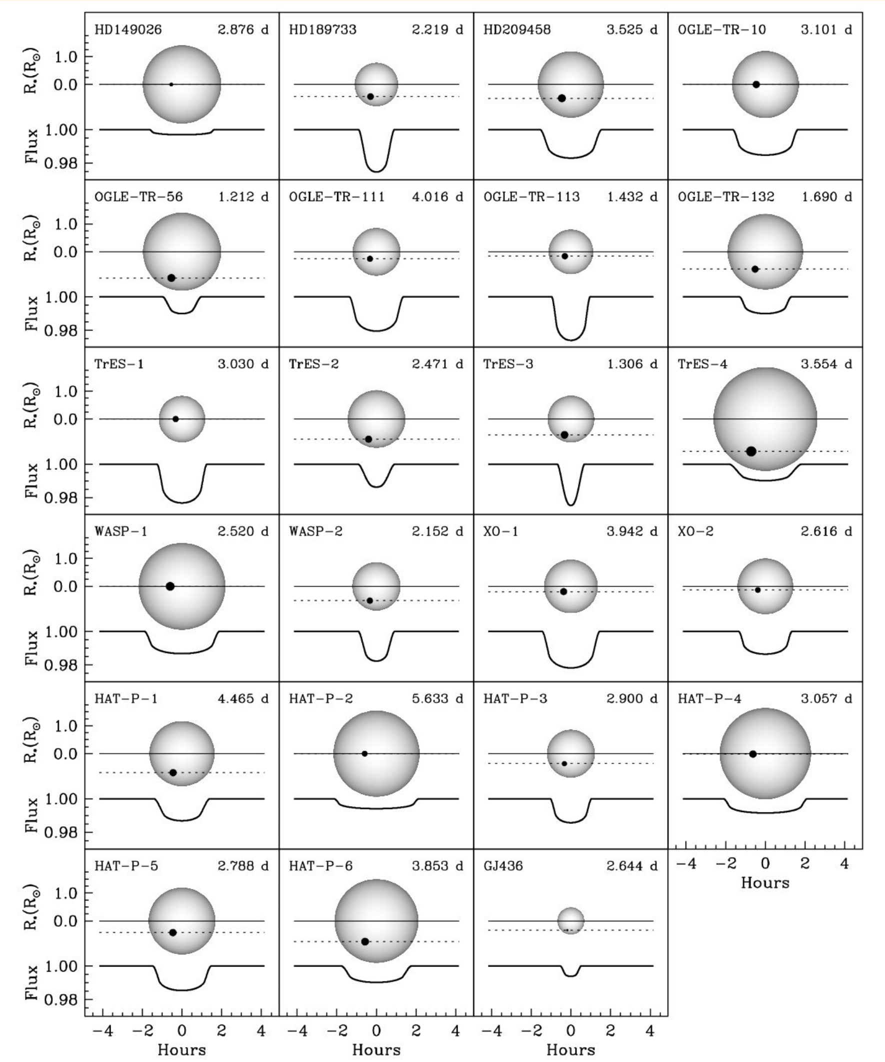
HD 209458b observed using Hubble

from LC we can get:

R_{planet}/R_{star}, a, i, T_0, P

+ limb-darkening coefficients

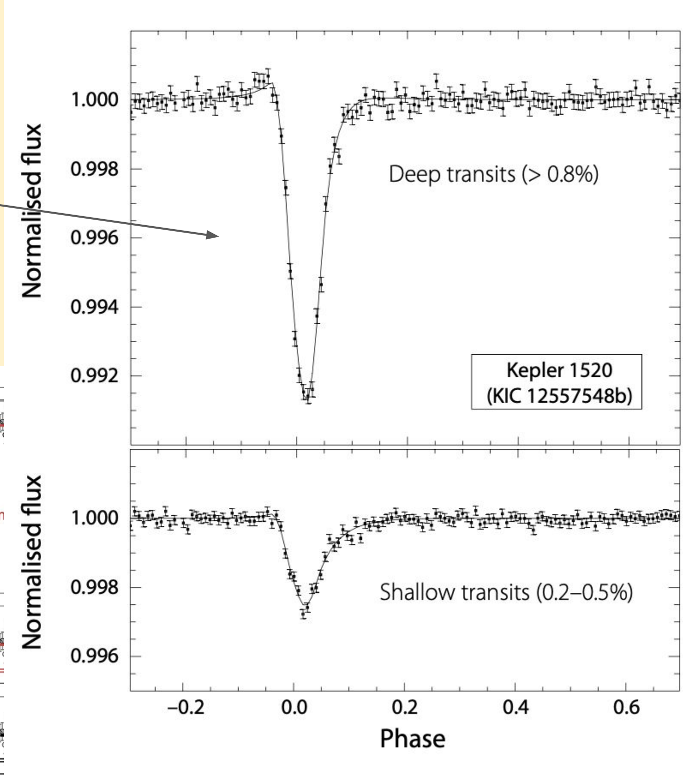
we have to estimate M_{star}



Interesting Transits

disintegrating planet

exomoons (or not)



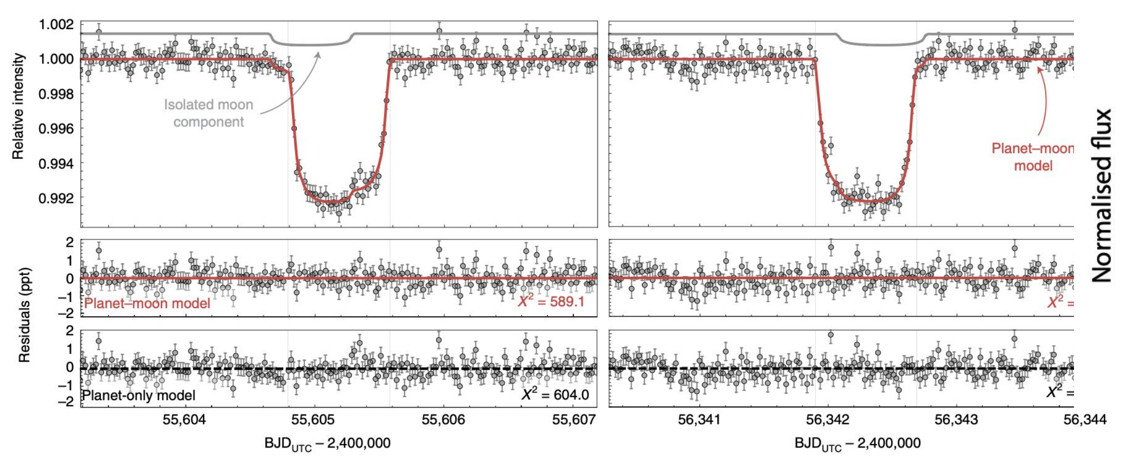
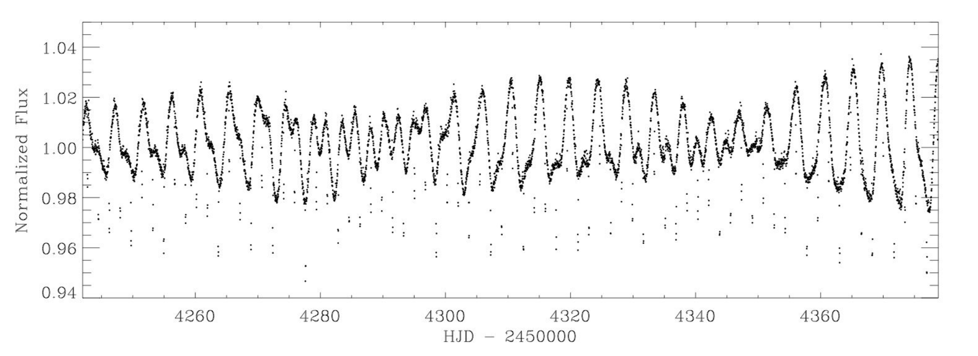
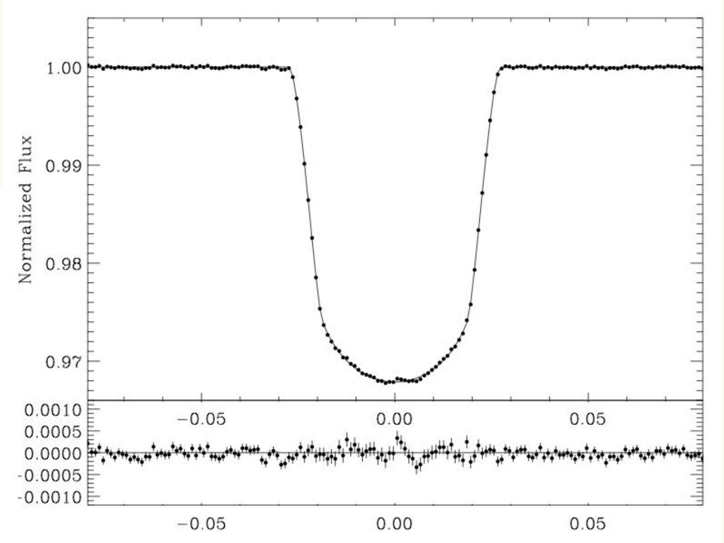


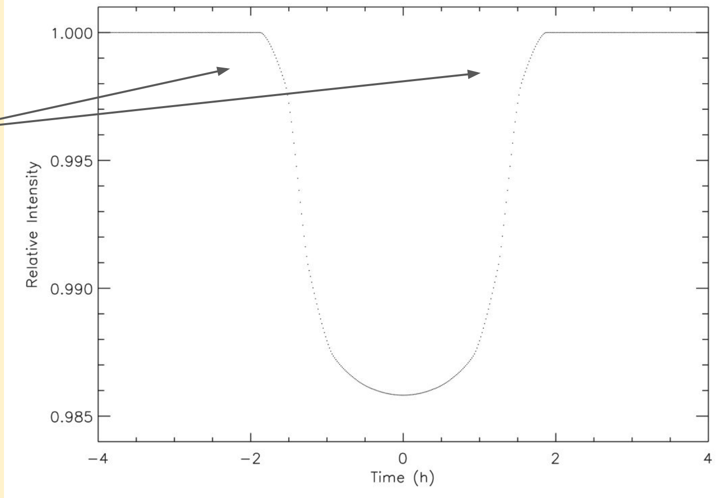
Fig. 2 | Transit light curves of Kepler-1708 b. The left/right column shows the first/second transit epoch, with the maximum-likelihood planet–moon model overlaid in solid red. The grey line above shows the contribution of the moon in isolation. Lower panels show the residuals between the planet–moon model and the data, as well as the planet-only model. BJD, barycentric Julian date; UTC, coordinated universal time.

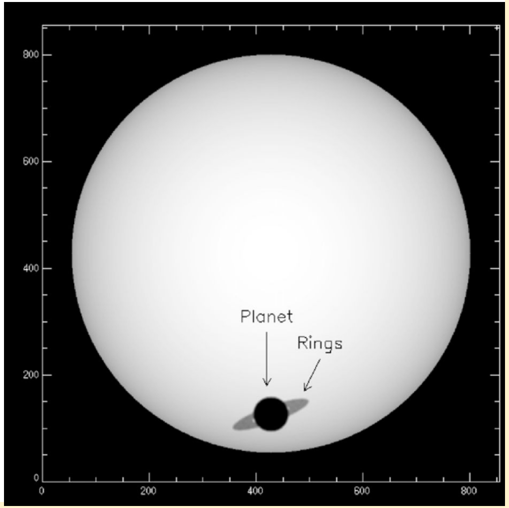
Huge stellar variability in CoRoT-Exo-2b





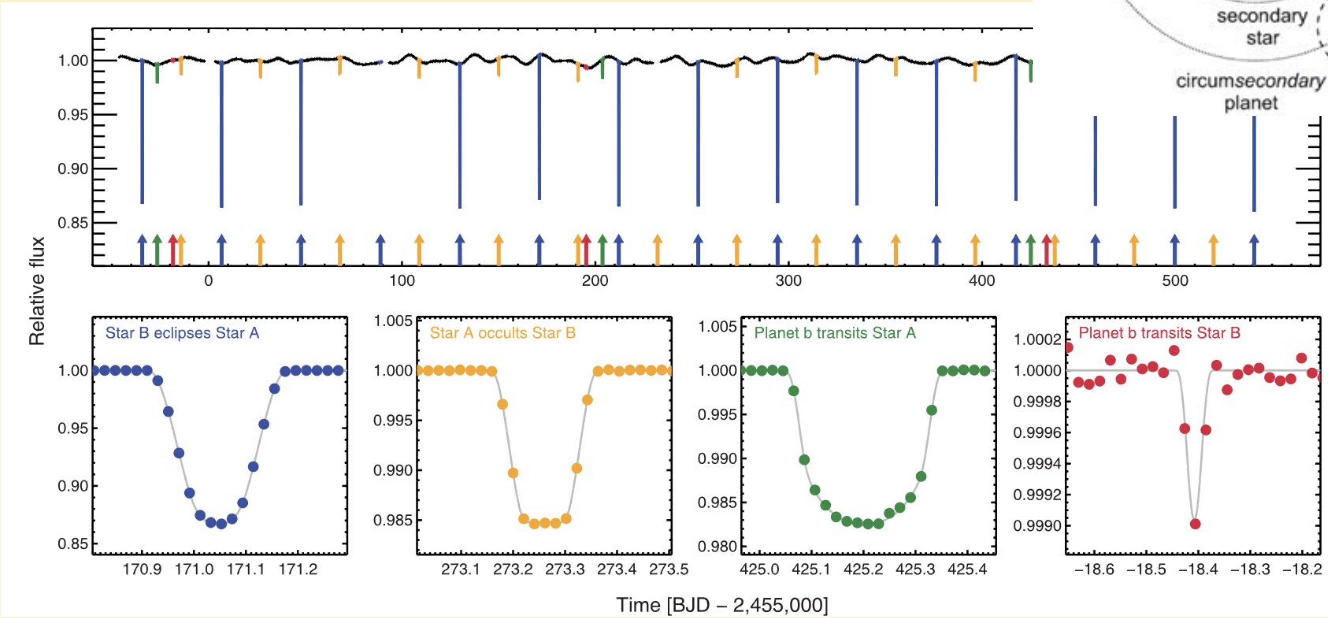
Effect of the rings

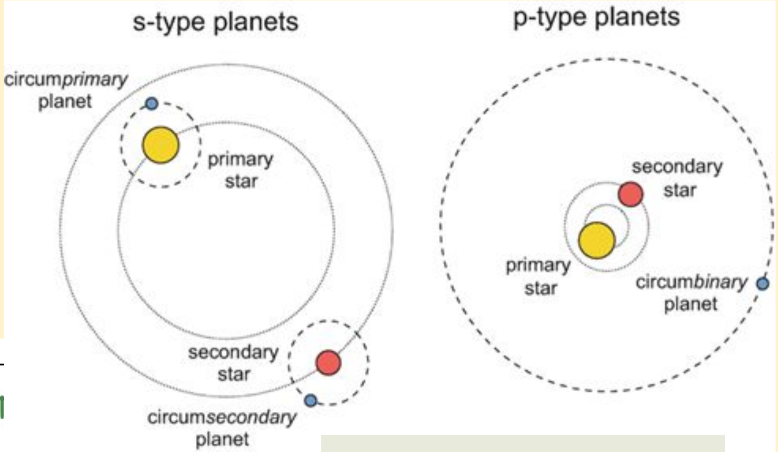


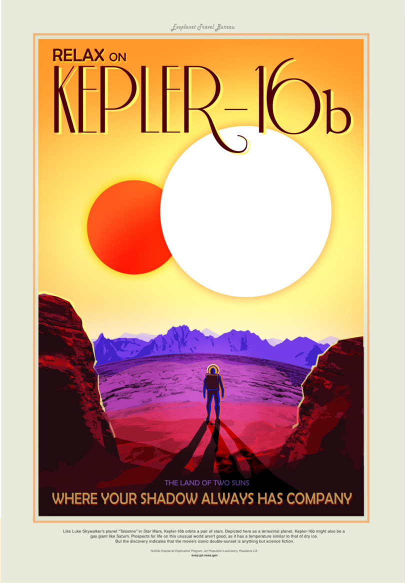


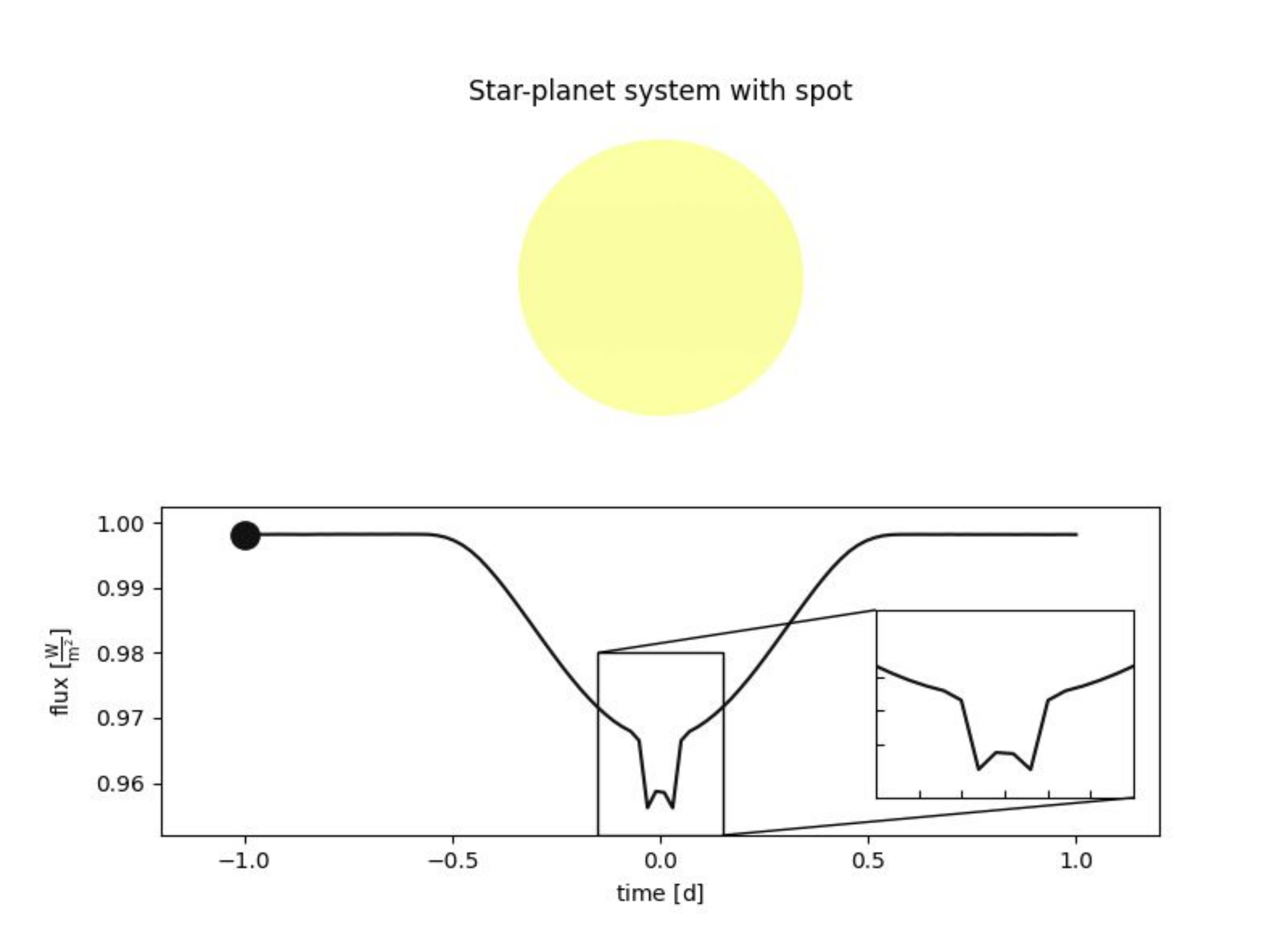
Circumbinary and circumprimary planets

circumbinary Kepler 16(AB)b









https://phoebe-project.org/docs/2.4/examples/animations_change_axes

About Me - Elias Hesse

Studied Physics at Leipzig University

Bachelor's thesis: **Determining Superflare Parameters around Active M-Stars**

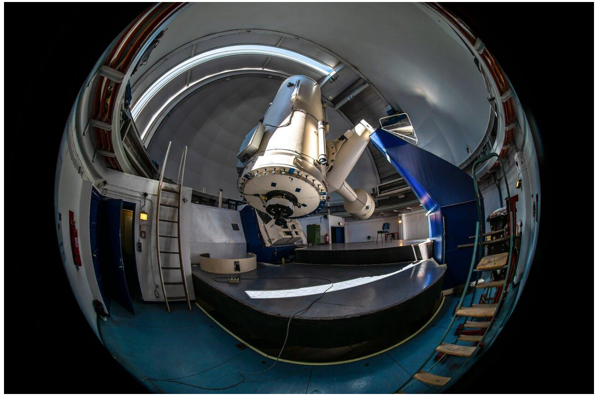
Soon: Astrophysics M. Sc. in Potsdam

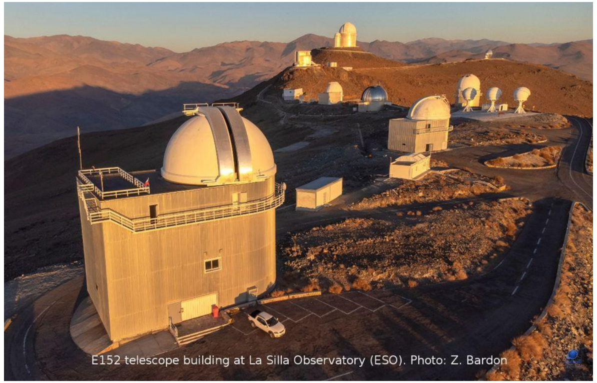
Plant-Lover, Tolkien-Scholar, Amateur-Musician

Instrumentation

ESO 1.52-metre telescope

- 29°15′27″S 70°44′15″W
- first light in 1968
- decommissioned in 2002
- refurbished until 2022
- mount with two feet → mechanical limits of movement





E152 telescope building at La Silla Observatory (ESO). Photo: Z. Bardon

Name:	ESO 1.52-metre telescope
Site:	La Silla
Altitude:	2375 m
Enclosure:	Classical dome
Type:	Spectrographic telescope
Optical design:	Cassegrain (f/14.9) or Coudé (f/31)
Diameter. Primary M1:	1.52 m

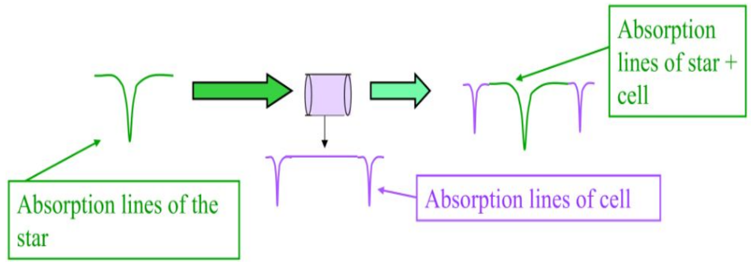
Source: eso.org/public/teles-instr/lasilla/152metre/

PlatoSpec echelle spectrograph

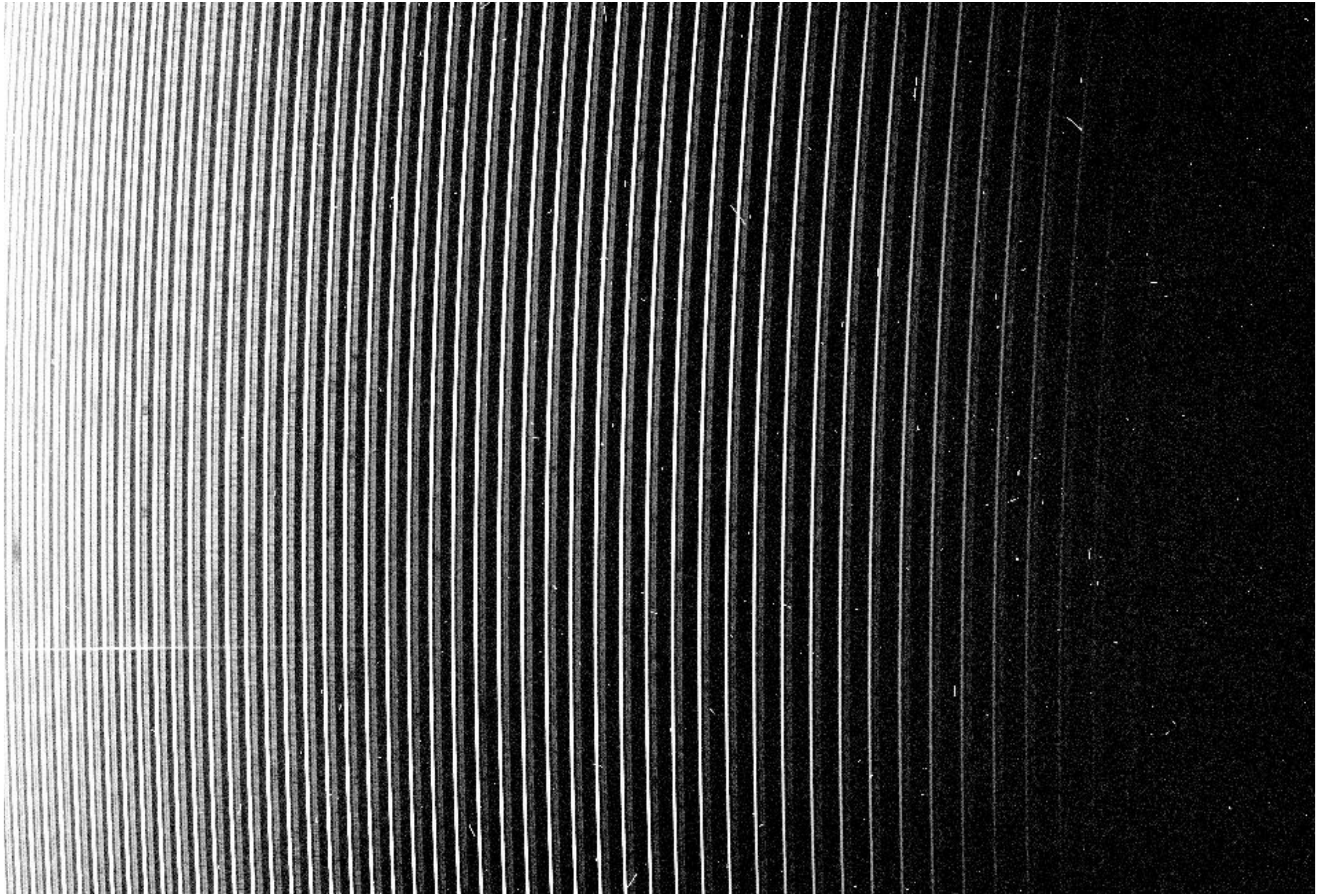
- high resolution echelle spectrograph
- CCD-cooling around -80°C
- fiber - fed CCD
- first light on 10.10.2024
- currently in science verification mode
- ThAr or **Iodine** simultaneous calibration

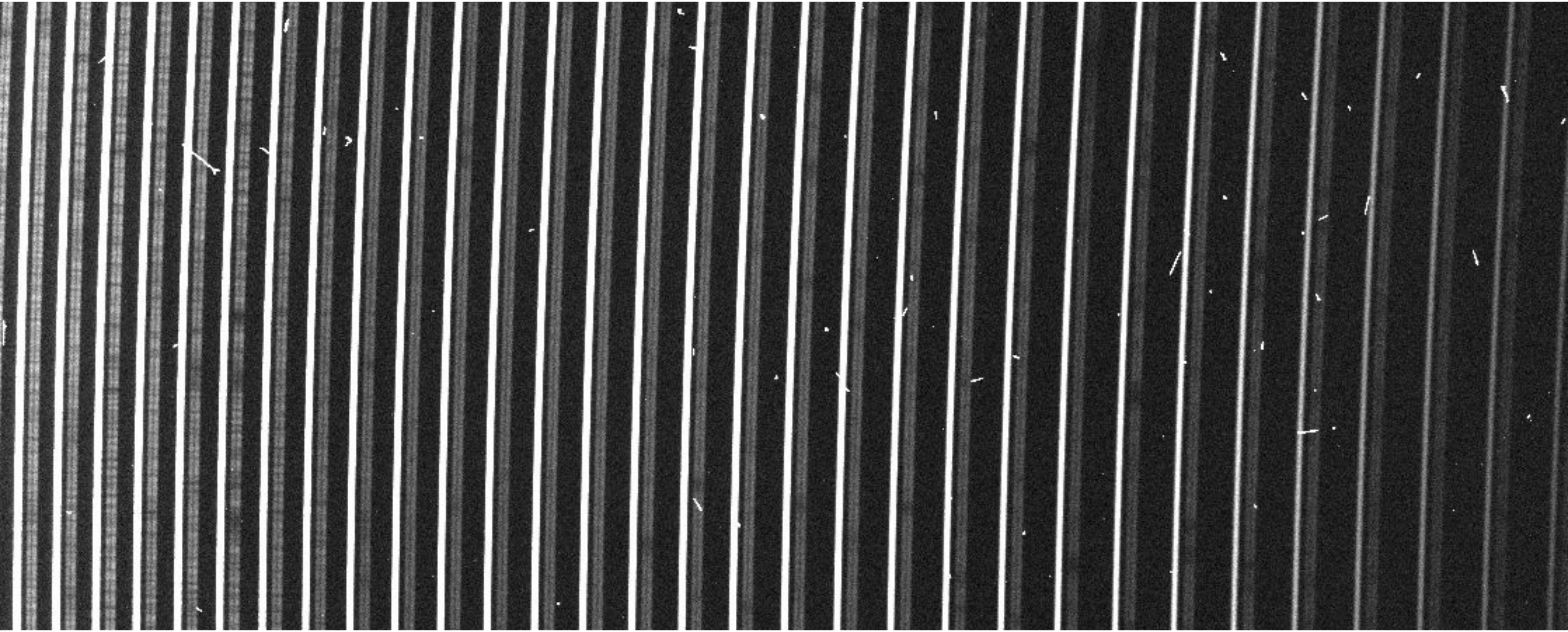
Echelle spectograph	Parametere value
Wavelength coverage	360-680 nm
Spectral resolution	70k
Thermal stability	0.1deg
RV precision	3m/s
Calibration	ThAr+Iodine cell

Source: stel.asu.cas.cz/plato/index.html



Source: Veronika’s presentation

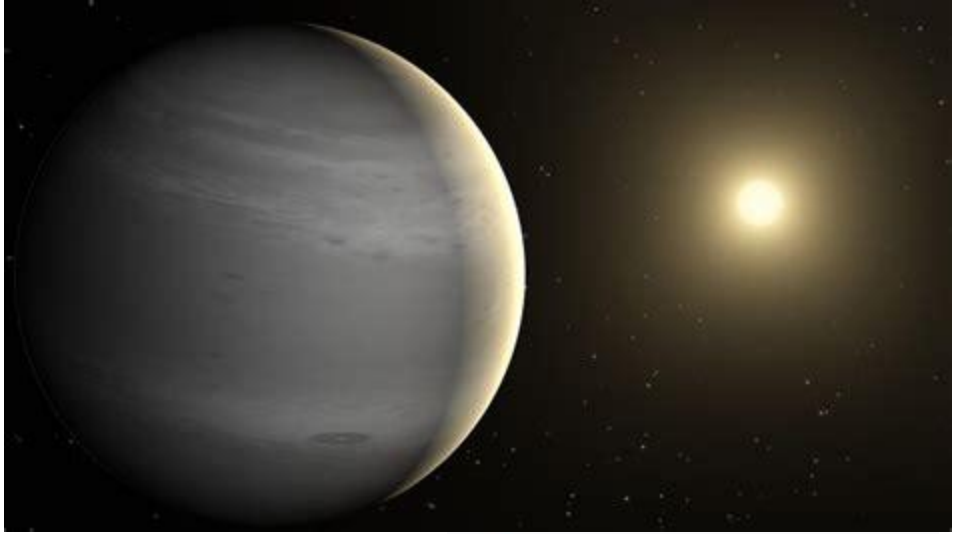




The Hot Jupiter HD 2685b

- HD 2685 is an F-Star at around 6800K (V=9.6 mag)

- Rotational Period: 4.13 days
- Mass: 1.17 ± 0.12 M_J
- semi-major axis: 0.06 au
- inclination ≈ 90° → transit observable
- T_{eq} ≈ 2000K



NASA Exoplanet Archive (https://science.nasa.gov/exoplanet-catalog/hd-2685-b/)

RA
00h29m18.94s

DEC
-76d18m14.52s

DISTANCE
$196.852^{+0.777}_{-0.771}$ pc

PARALLAX
5.0510900±0.0198125 mas

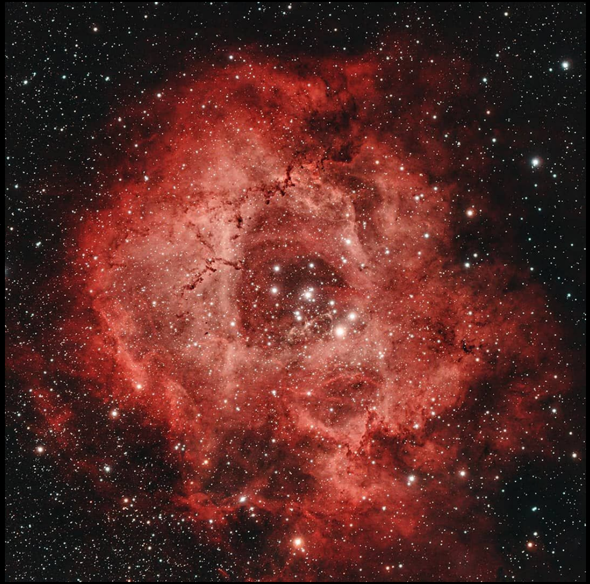
About Me - Vojtěch Dienstbier

FACULTY
OF MATHEMATICS
AND PHYSICS
Charles University

Bachelor's thesis: Photometric study of eclipsing binary with pulsating component (2025)

Astrophotography

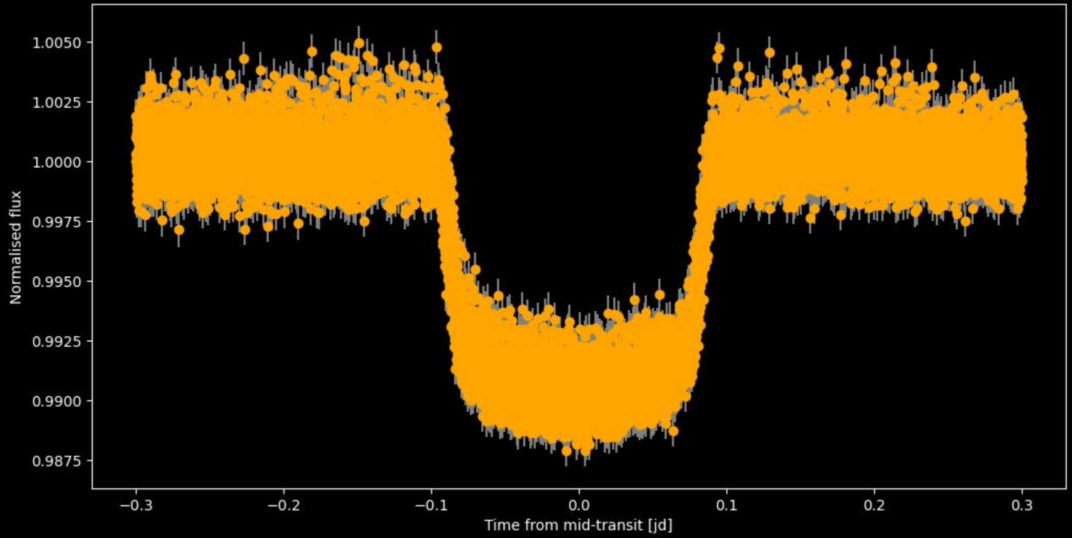
Travelling



Discovery of HD 2685 b

Data from 7 sectors
(1, 27, 28, 67, 68, 94, 95)
August 2018 - August 2025

P = 4.126912(1) d



Data extracted by the Lightkurve Python package (Lightkurve Collaboration, 2018)

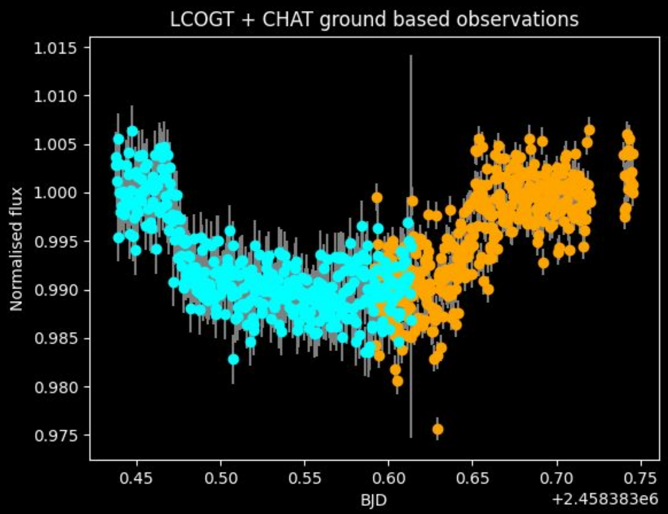
Confirmation by Jones et al., 2019

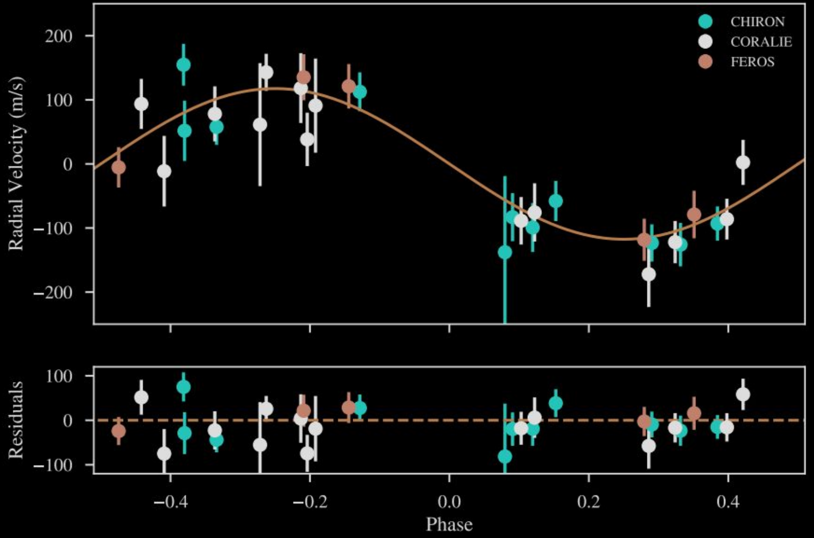
TESS S1 + LCOGT + CHAT (ground based)

→ 1.44(1) R_J | 89.4 deg

RVs from CHIRON, CORALIE & FEROS

→ 1.18(9) M_J | 89.4 deg



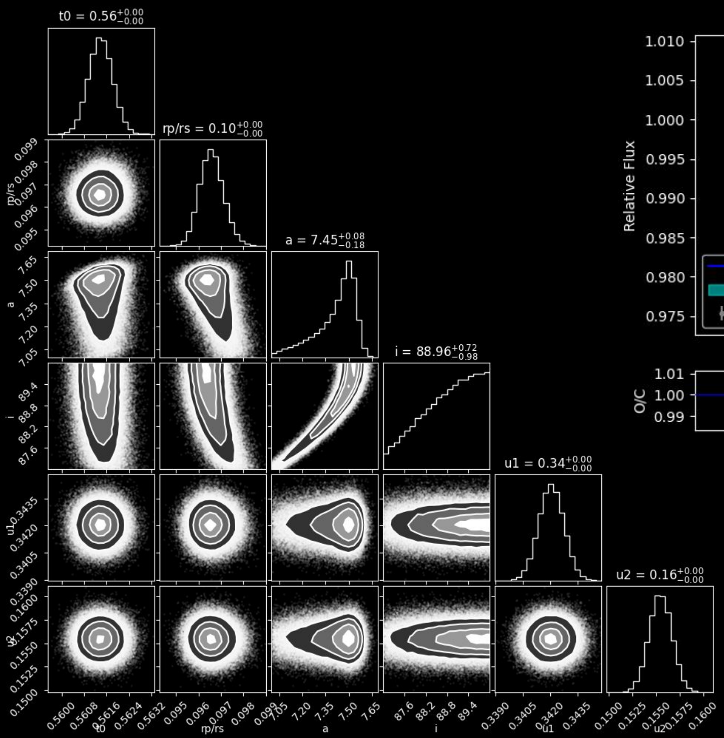


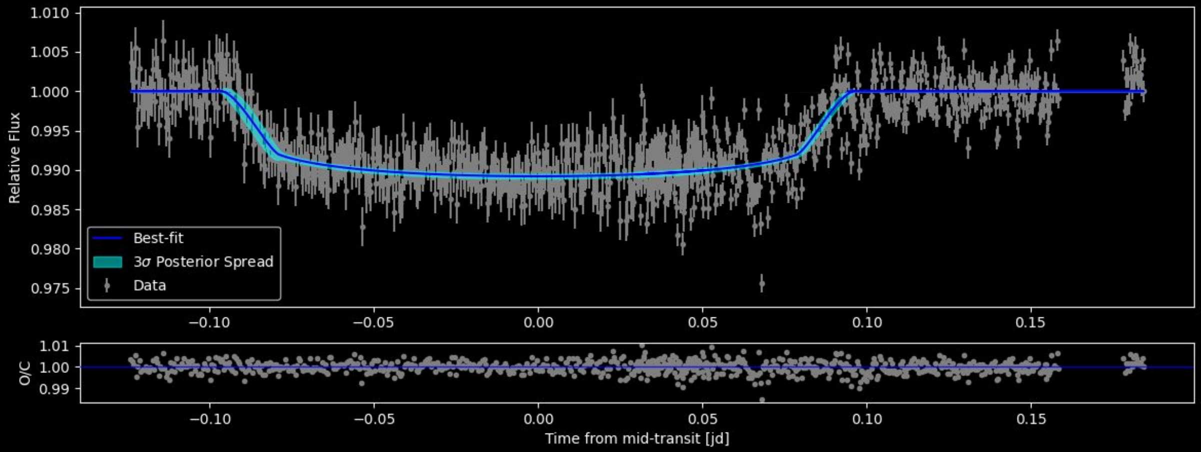
Size estimation - fitting the transit lightcurve

```python
import emcee
# functions for calculating the Bayesian relation
def log_likelihood(theta, t, flux, flux_err):
    t0, rp, a, inc, u1, u2 = theta
    model_flux = transit_model_full(theta, t)
    return -0.5 * np.sum(((flux - model_flux) / flux_err) ** 2)

def log_prior(theta):
  t0, rp, a, inc, u1, u2 = theta
  if not (0.9 < t0  < 1.10 and 0.085 < rp < 0.11 and 7. < a < 8.4  and 87. < inc < 90. and 0 <= u1 <= 1 and -1 <= u2 <= 1):
      return -np.inf

  ln_prior_u1 = -0.5 * ((u1 - cq[0][0]) / eq[0][0]) ** 2
  ln_prior_u2 = -0.5 * ((u2 - cq[0][1]) / eq[0][1]) ** 2
  return ln_prior_u1 + ln_prior_u2

def log_posterior(theta, t, flux, flux_err):
    lp = log_prior(theta)
    if not np.isfinite(lp):
        return -np.inf
    return lp + log_likelihood(theta, t, flux, flux_err)

# initializing the walkers
ndim     = len(params)
nwalkers = 25
pos      = [params + 1e-4*np.random.randn(ndim) for i in range(nwalkers)]

# define the sampler and run MCMC
sampler = emcee.EnsembleSampler(nwalkers, ndim, log_posterior,
                                args=(times,fluxes,flux_errs))
sampler.run_mcmc(pos, 20000, progress=True)
```

Modelling done using batman (Kreidberg, L., 2015) and emcee

Size estimation - fitting the transit lightcurve

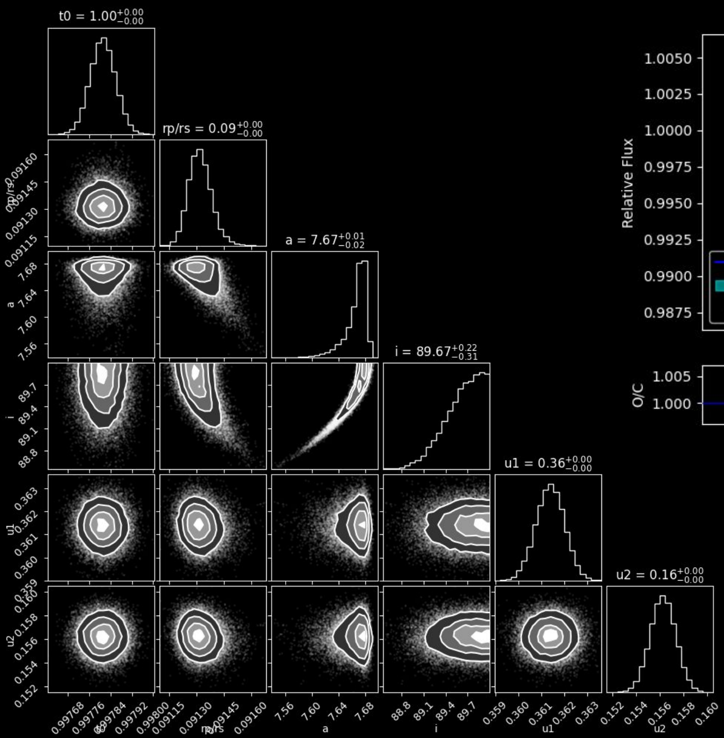


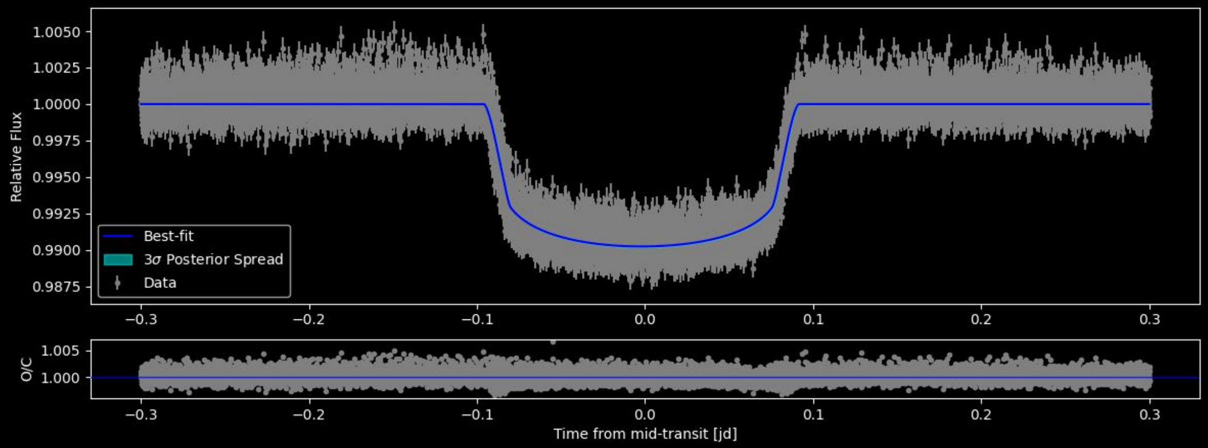


LCOGT + CHAT single transit

→ 1.47(3) R_J | ~90 deg

Size estimation - fitting the transit lightcurve





TESS 7 sectors

→ 1.40(1) R_J | ~90 deg

About me - Alžběta Maleňáková

FACULTY
OF MATHEMATICS
AND PHYSICS
Charles University

Bachelor’s thesis - Multispectral analysis of gamma ray burst 190919B

Masters’s thesis - GRB optical afterglows: the first ten minutes (hopefully soon)

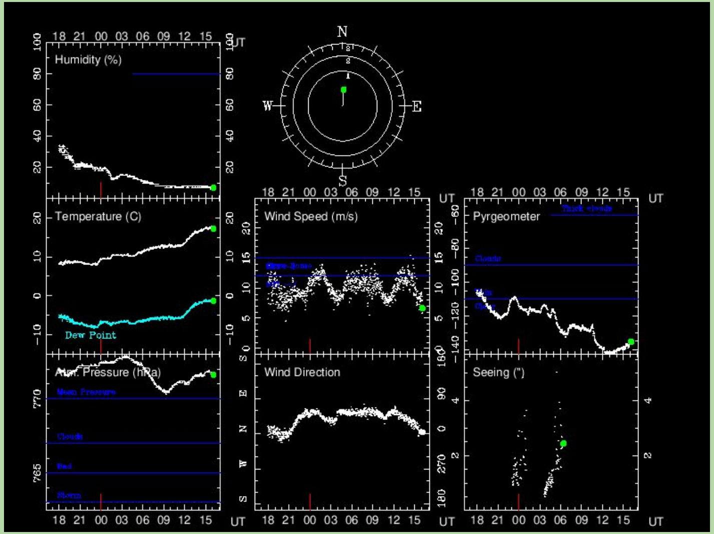
ardent concert-goer, baker and daydreamer

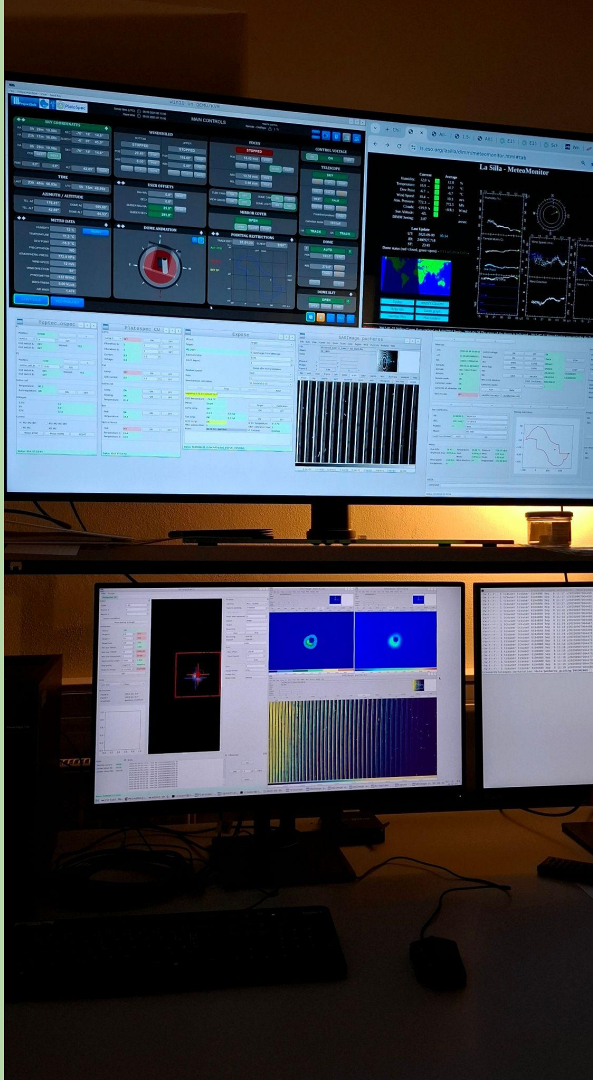
Observation

Nights of September 2-8 (with September 3 left out)

Long exposures (30 minutes) in series, using Iodine cell to increase precision.

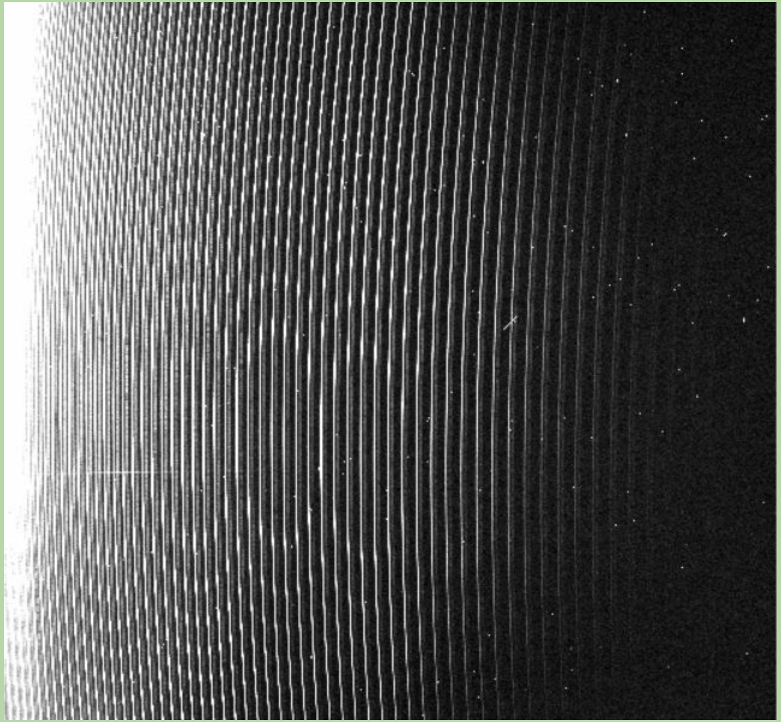
PROBLEM:
windy weather!!!

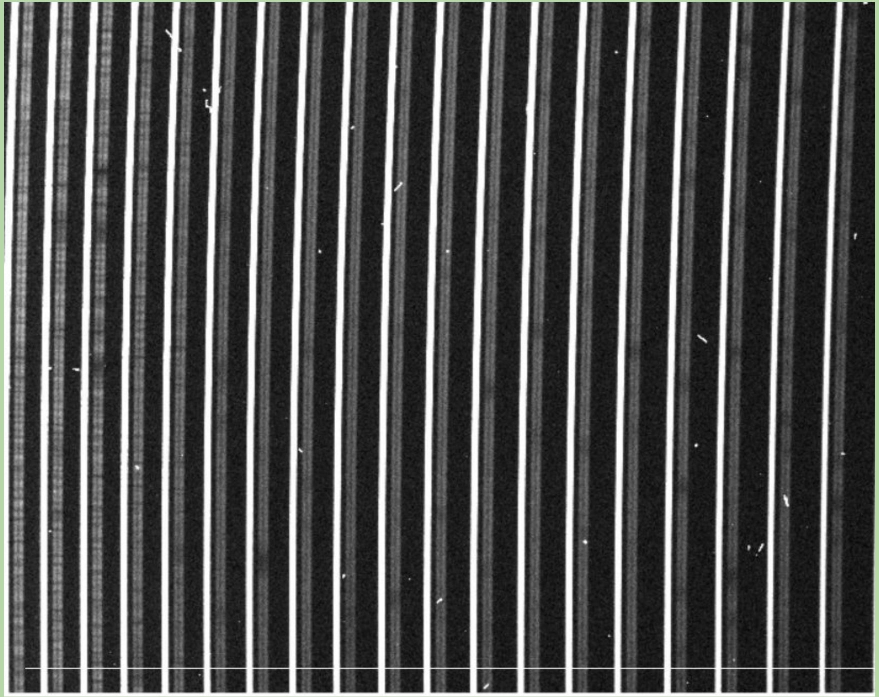




Data reduction (IRAF)

noao.imred.echelle





Data reduction (IRAF)

BIAS - average + combine

FLAT - we need non-zero flux outside of orders - average + subtract BIAS + find orders + apflatten

SCIENCE FRAMES - subtract BIAS, divide by FLAT

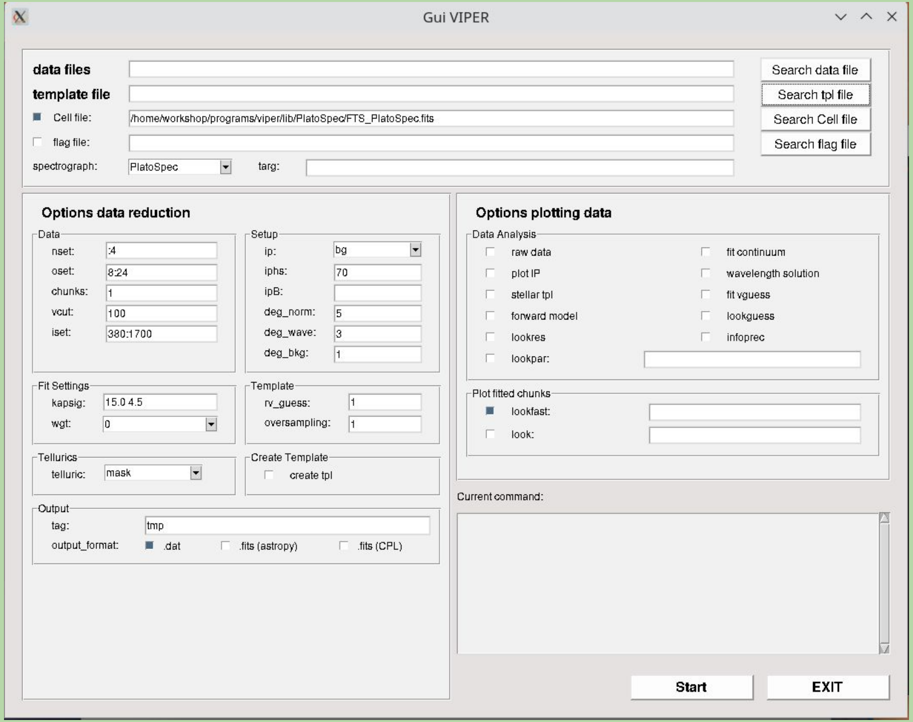
SCATTERED LIGHT - problems, skip

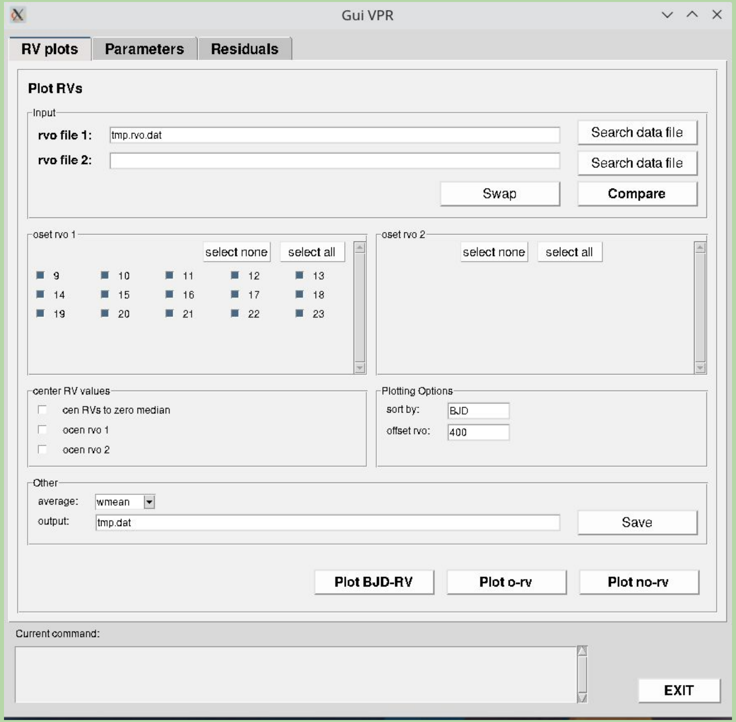
EXTRACTING SPECTRA - with orders, one line (small issues)

WAVELENGTH CALIBRATION - ThAr spectrum (with done reduction), let IRAF identify lines, assign ThAr spectrum to SCIENCE FRAMES

Extraction of the Radial Velocity

Could be done in IRAF, Viper has interface.

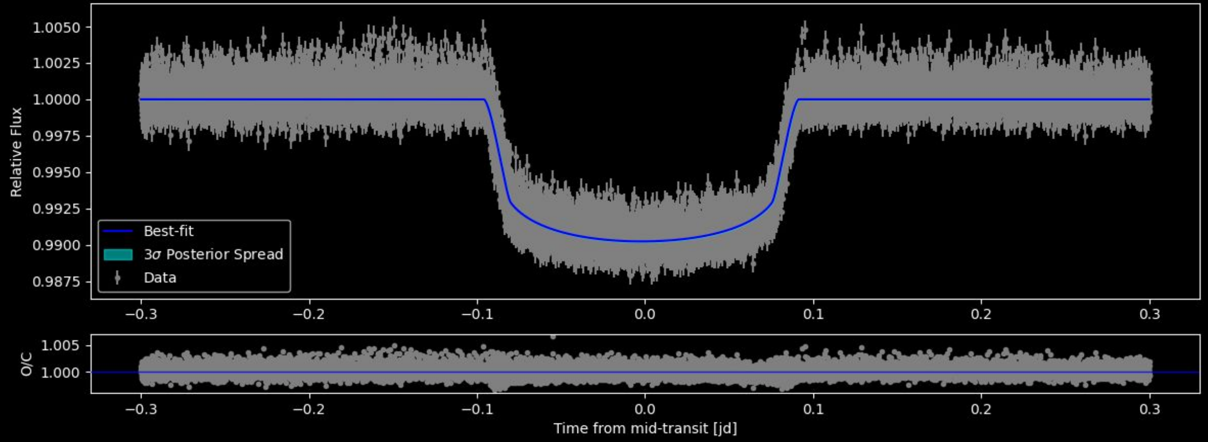




[viper: High-precision radial velocities from the optical to the infrared (Reaching 3 m/s in the K band of CRIRES+ with telluric modelling)]

Results

Size estimation



TESS S1 + LCOGT + CHAT (ground based)

→ 1.44(1) R_J | 89.4 deg

(Jones et al., 2019)

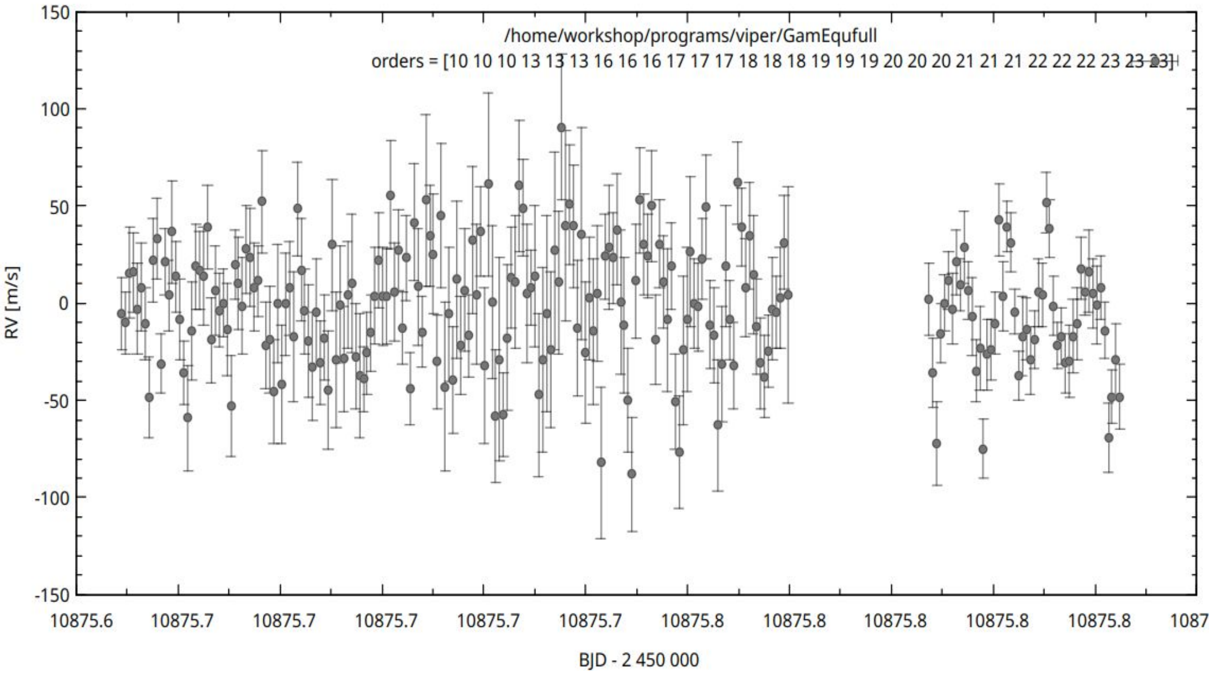
TESS 7 sectors

→ 1.40(1) R_J | ~90 deg

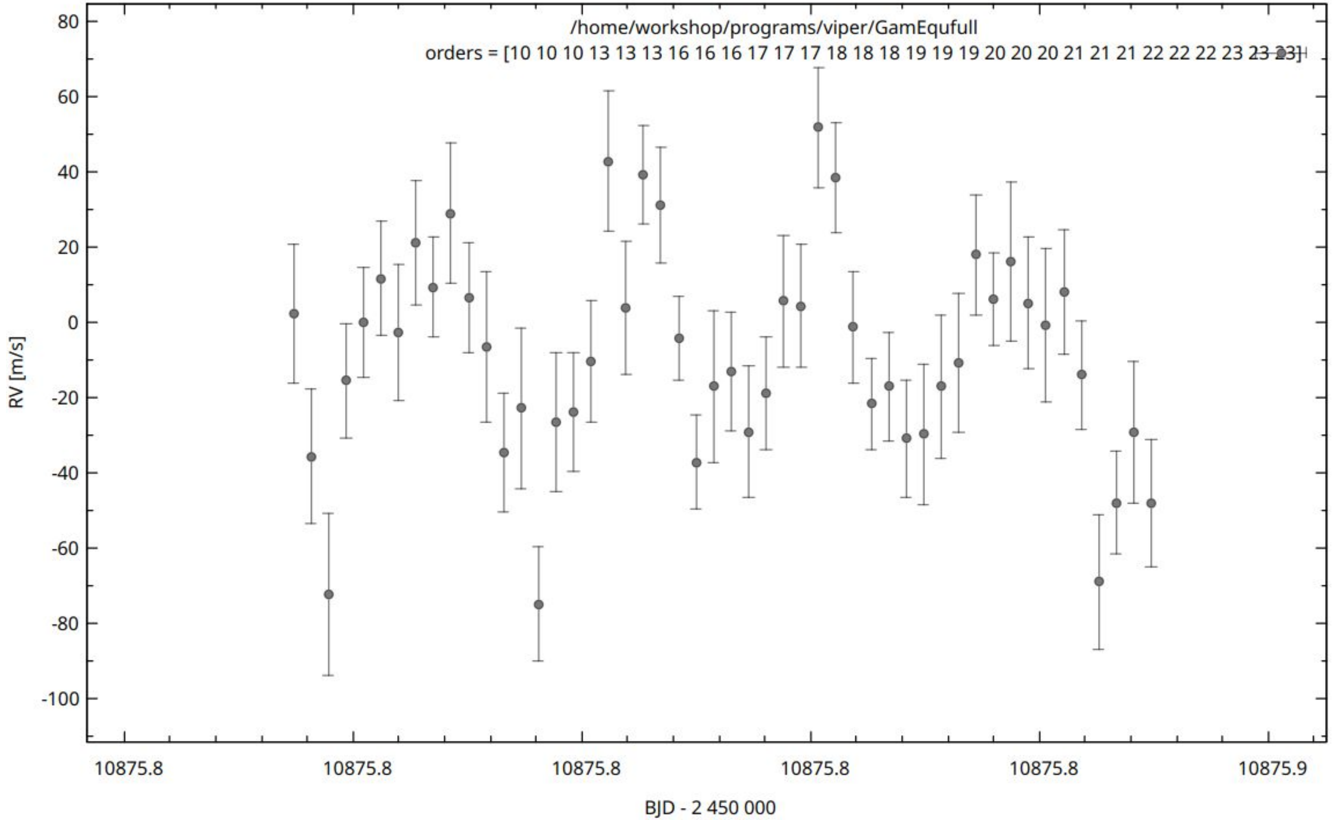
Our result

Results from VIPER analysis - γ Equulei

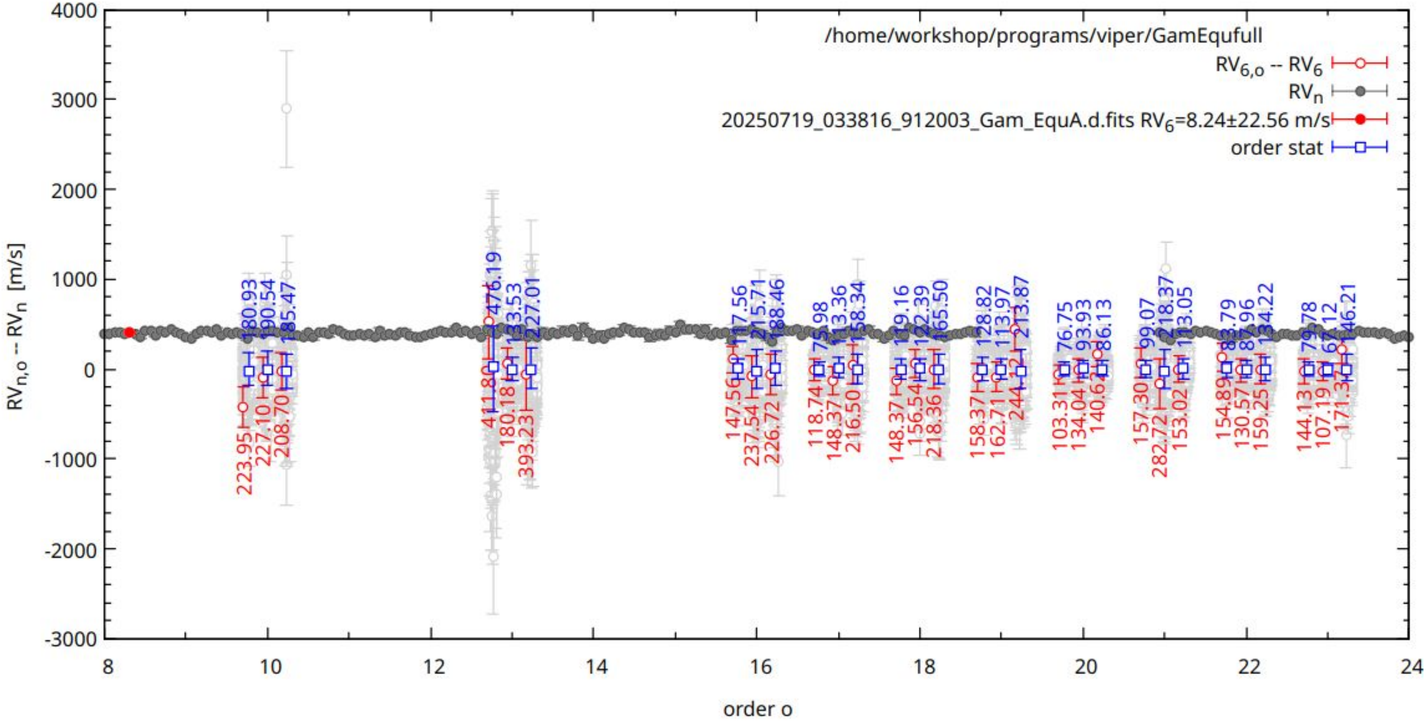
- VIPER is designed to automatically read the spectra, mask telluric lines and extract the radial velocity.
- Best feature: Interactivity!
- Obtain best fitting through systematic trials and experience.



Results from VIPER analysis - γ Equulei



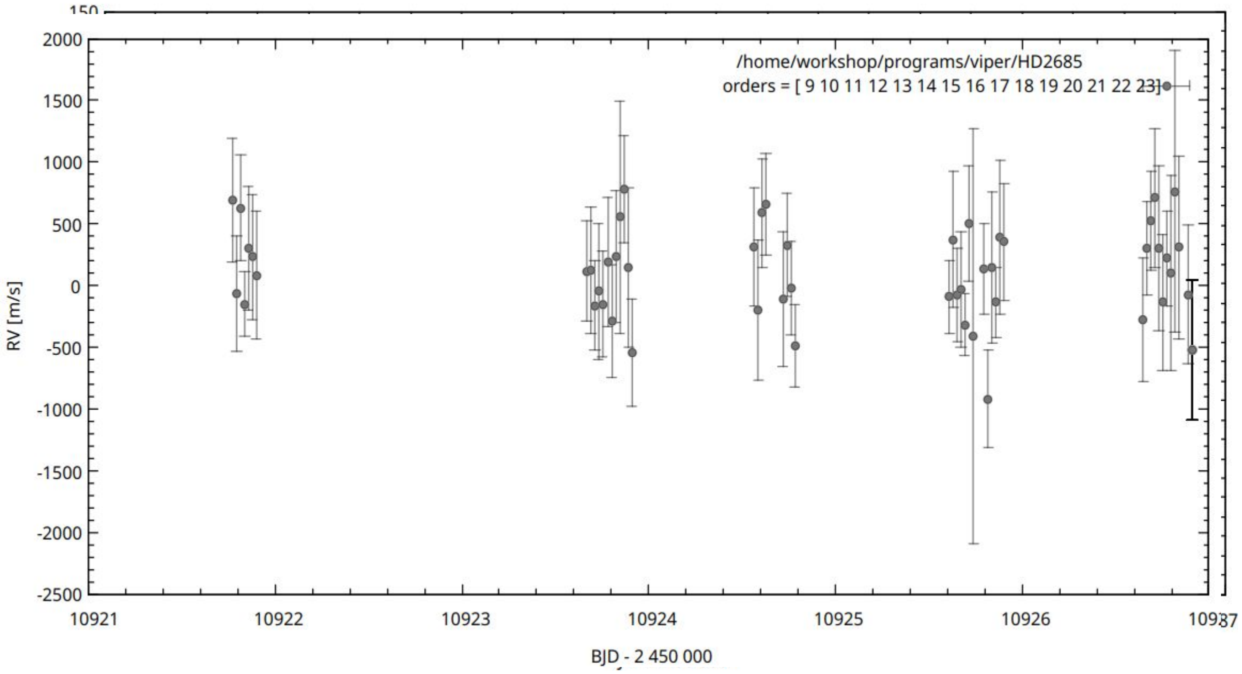
Results from VIPER analysis - γ Equulei



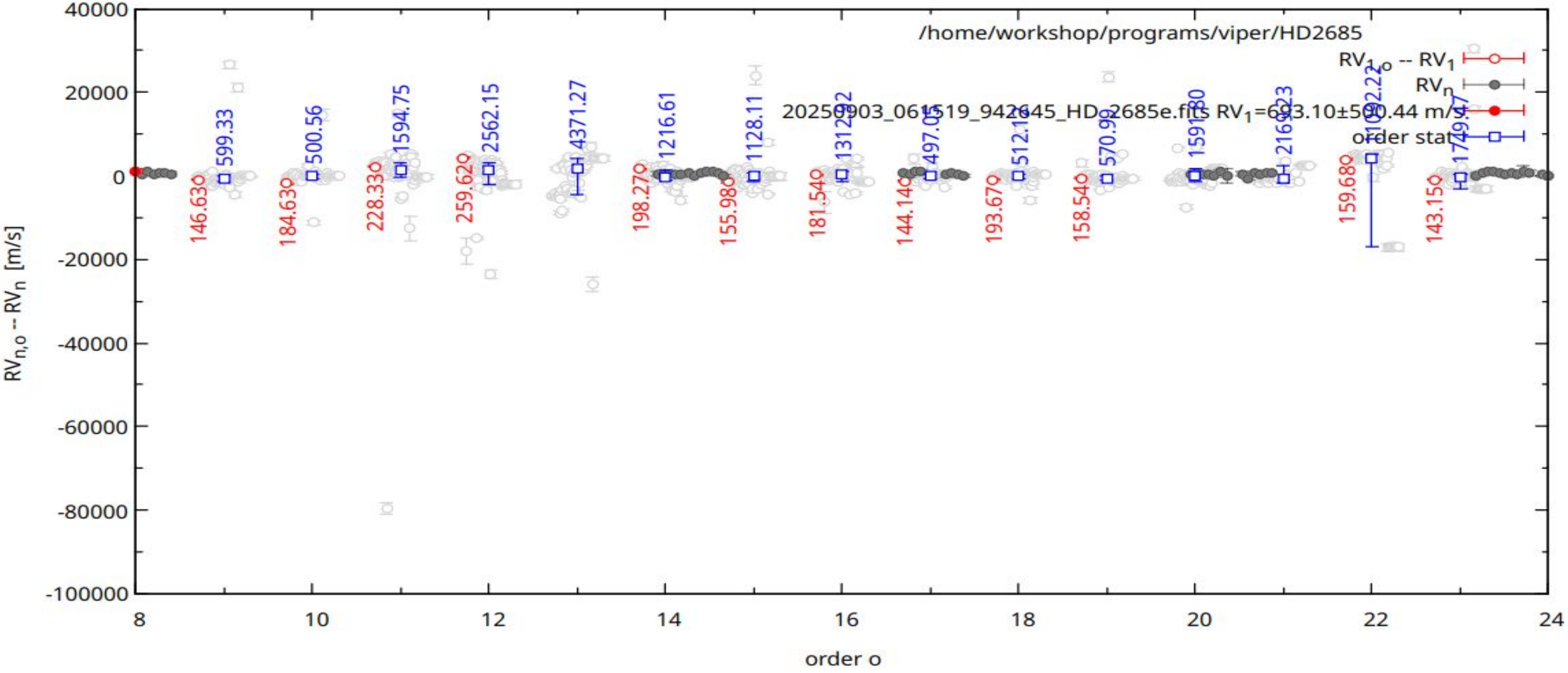
Results from VIPER analysis - HD 2685

- apparently no periodicity
- large errorbars
- insufficient phase coverage

→ **no realistic results expected**



Results from VIPER analysis - HD 2685

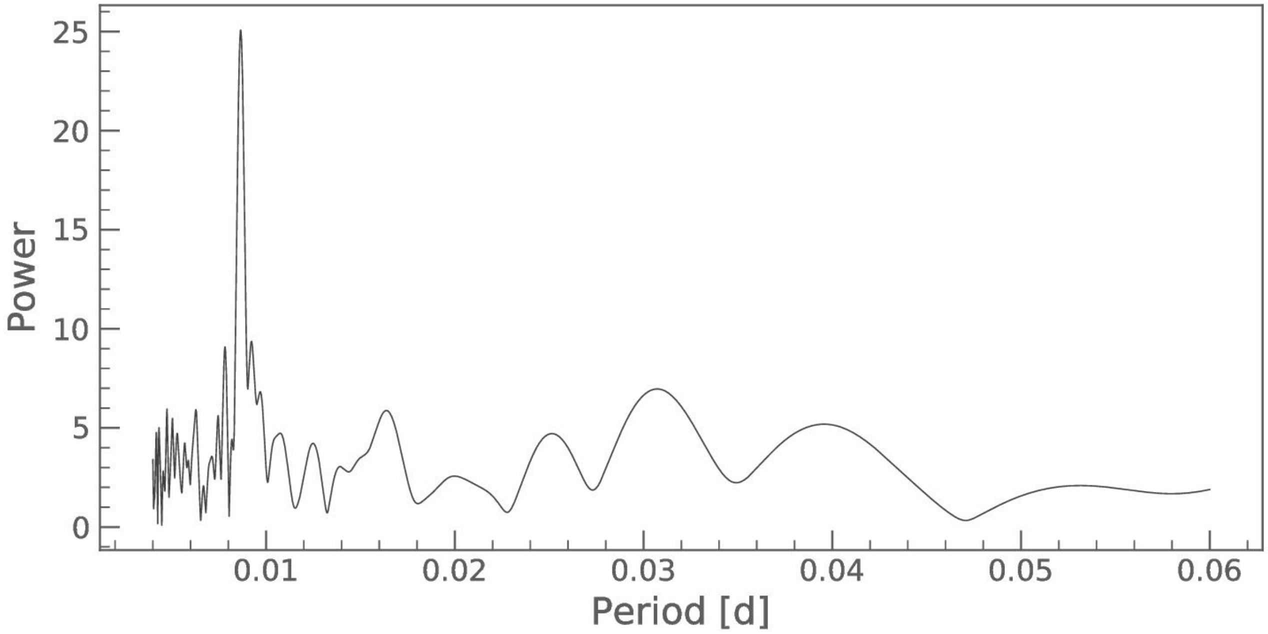


Fourier Transform of the RV Curve - γ Equulei

- FFT returns a periodic signal

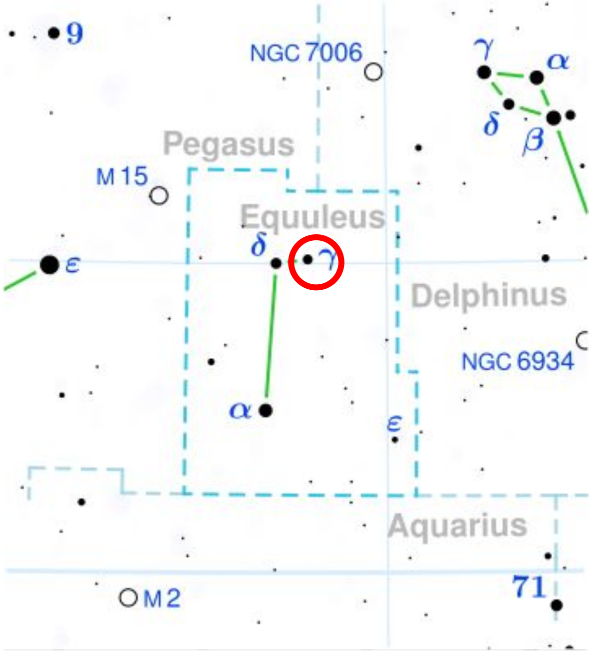
- P_{peak} = 0.00865 days = 12.46 minutes

→ **used in fitting the RV curve**



Fourier transform of the RV curve - γ Equulei

- The 12 min signal is not originating from a planet.
- γ Equulei is a rapidly oscillating, chemically peculiar A star (roAp) undergoing pulsations (pressure modes).
- The pulsations can be seen in both magnitude and radial velocity.
- Literature: 12.2 min

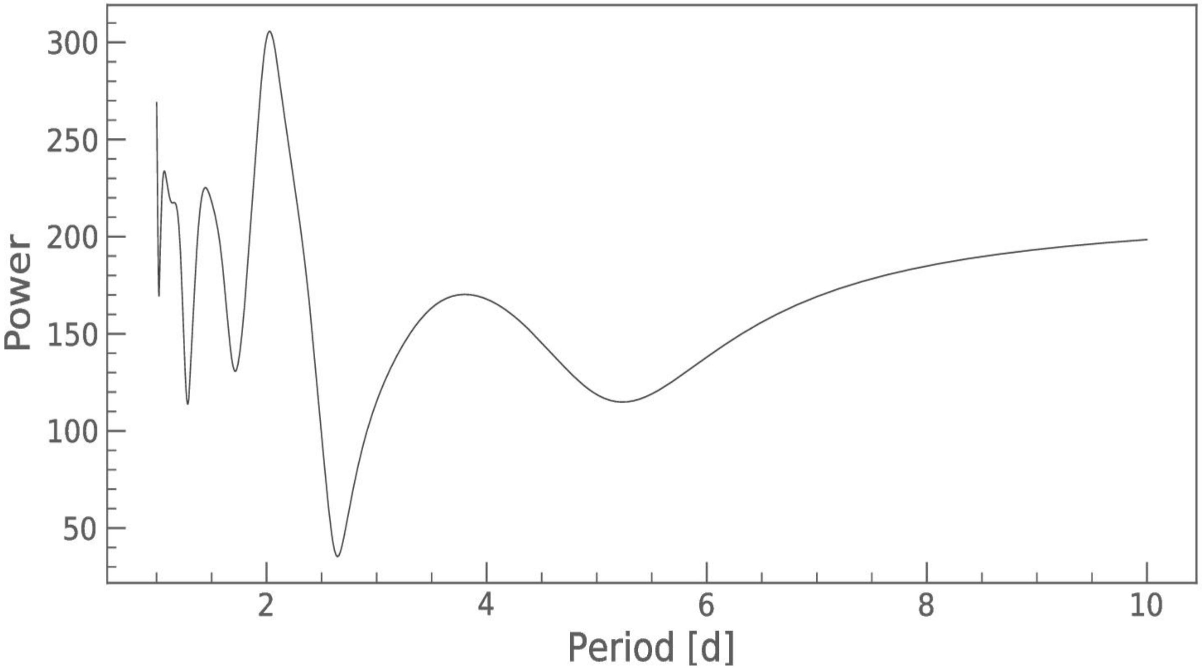


Source: https://en.wikipedia.org/wiki/Gamma_Equulei

Fourier transform of the RV curve - HD 2685

- no clear periodicity
- peaks could result from the sampling every night/ every few nights

→ **planetary orbital period was not derived**

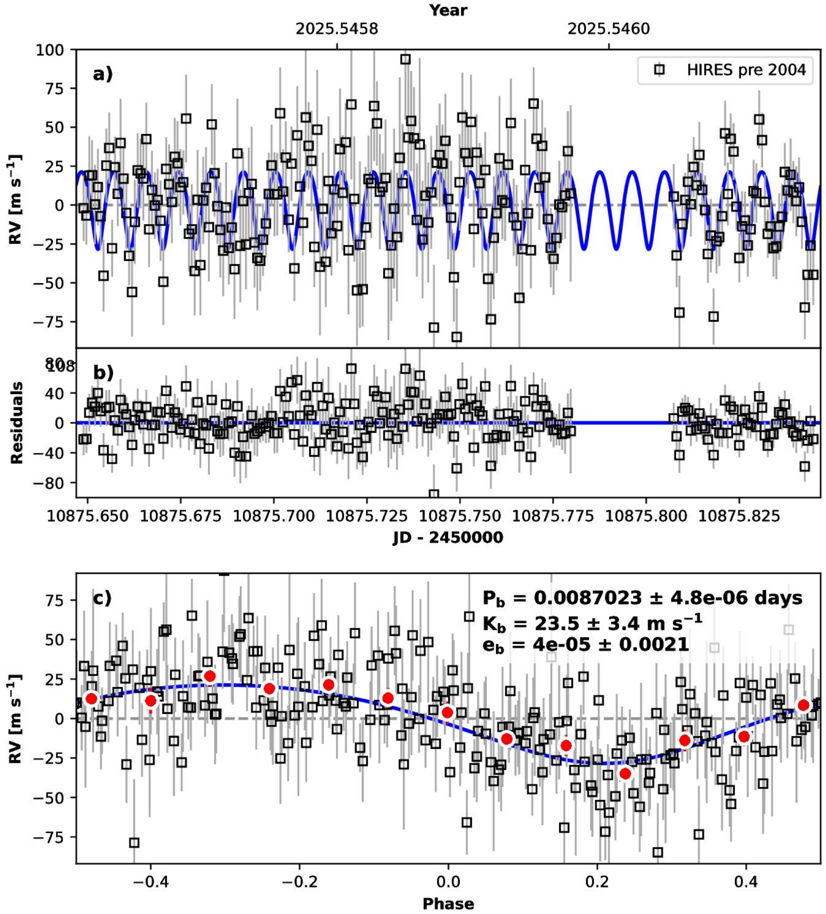


Radial velocity fitting with RadVel - γ Equulei

- RadVel requires good initial parameters:

  time of transit, period, RV amplitude

- phase diagram shows good coverage
- Markov-Chain Monte Carlo method to determine uncertainties (should not be trusted unconditionally)

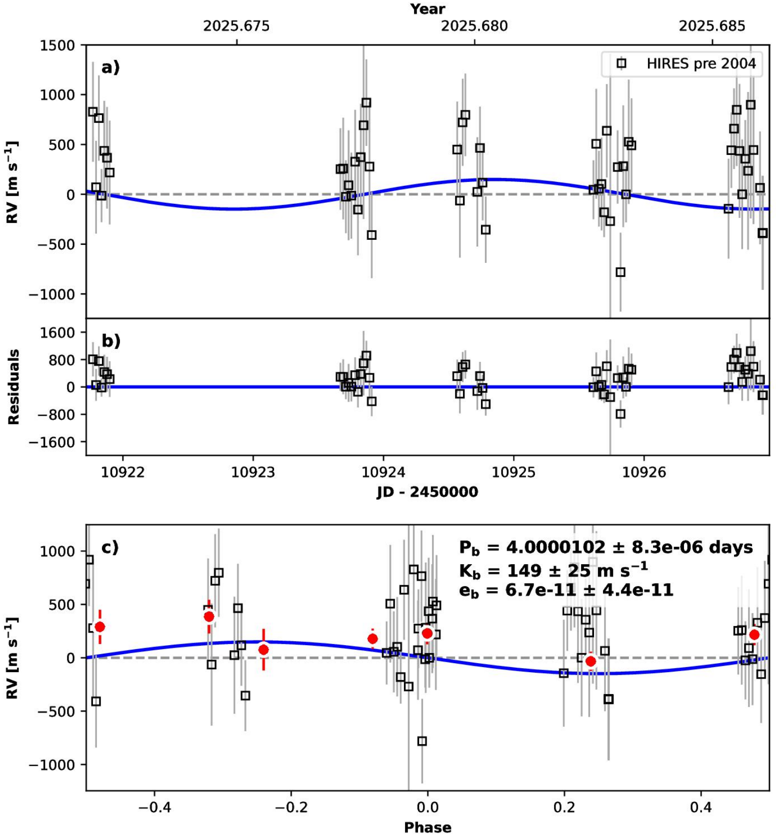


Radial Velocity fitting with RadVel - HD 2685

- fitted with literature values for P and T0

- basically no correlation found

→ **good example of unsuccessful fitting**



Determining the planetary parameters - EXAMPLE

- RadVel returned RV amplitude: $v_{obs} = 149 \pm 25 \ \frac{\mathrm{m}}{\mathrm{s}}$ (not trustworthy)
- stellar mass: $M_\star = 1.44 \pm 0.02 \ M_\odot$
- inclination angle: $i = 89.4 \ \pm \ 0.3 \ \mathrm{deg}$
- orbital period: $P = 4.12692 \ \pm \ 0.00004 \ \mathrm{days}$ (from literature)

$$M_P = \frac{v_{obs} \ P^{1/3} \ M_\star^{2/3}}{28.4 \ \sin i}$$

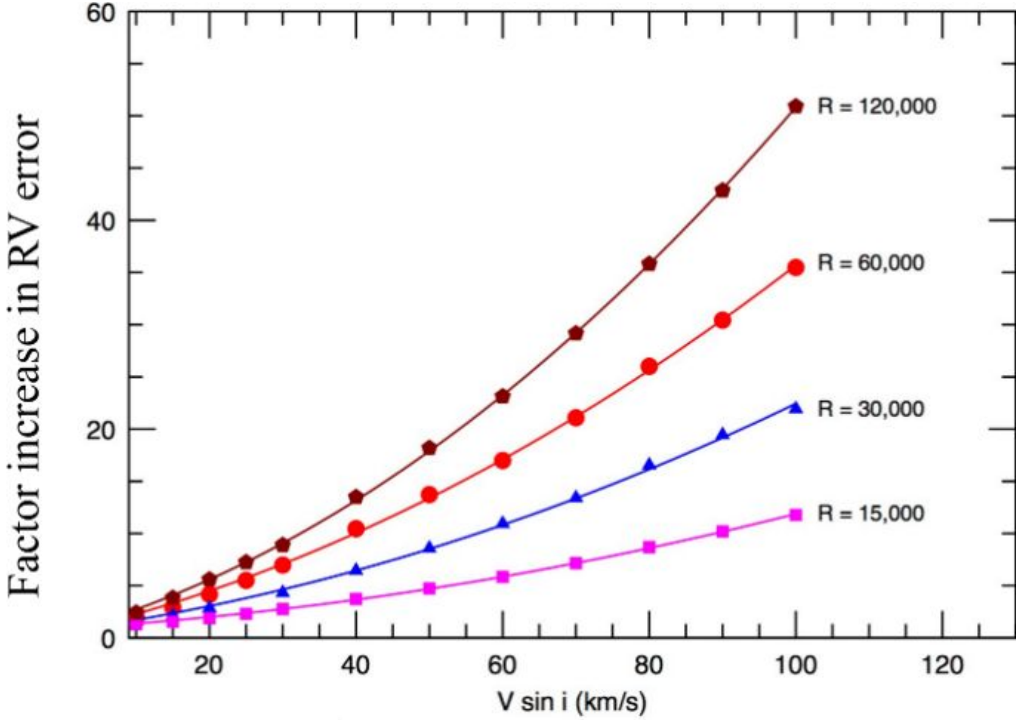
$$M_P = 1.52 \ \pm \ 0.26 \ \mathrm{M_J}$$

Errors

Increase in error with stellar rotation

HD 2685:

v sin i = 15.4 km/s



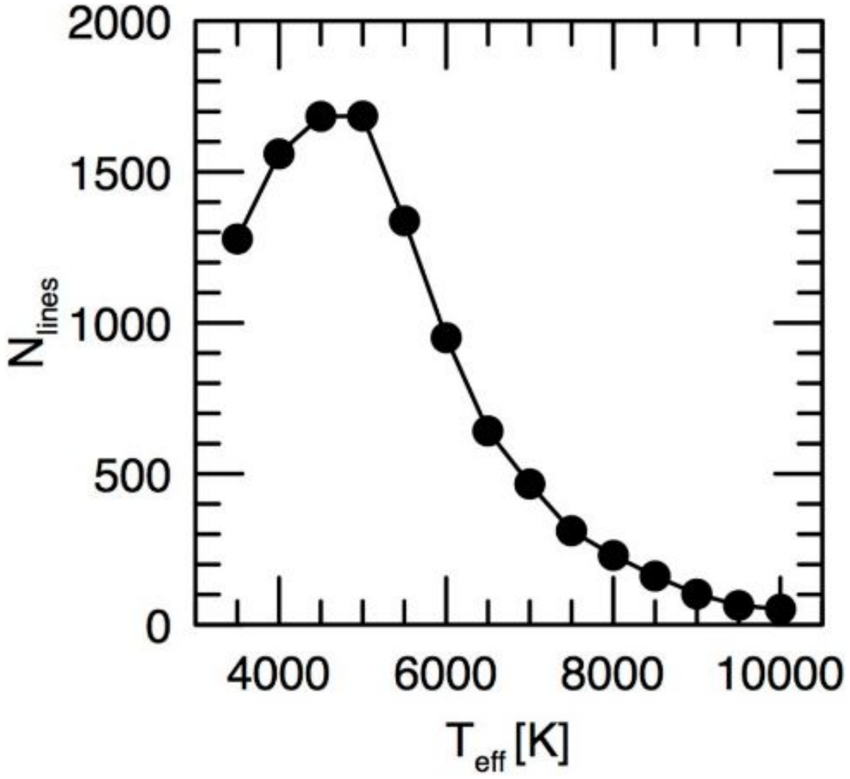
Source: Veronika's presentation

Decrease of useful lines with increase of effective temperature

HD 2685:

T_{eff} = 6800 K

heavily influencing RV determination



Source: Veronika’s presentation

Further error sources

- magnitude of the star (9.6 mag) + iodine cell
- limited number of observing nights
- issues with weather and high winds (> 15 m/s)

→ SNR between 5 and 10

- exposure time is limited by amount of cosmic particles

→ **Overall, the main problem was the target selection.**

Sources

Textbooks: The Exoplanet Handbook by Michael Perryman,

Exoplanets by Sara Seager.

(also available on https://stel.asu.cas.cz/public/files/Presentations/)

And all the references and hyperlinks throughout the presentation.

Useful websites: https://exoplanetarchive.ipac.caltech.edu/

https://exoplanet.eu/home/

https://exofop.ipac.caltech.edu/tess/

Sources

- ESO 1.52-metre telescope: www.eso.org/public/teles-instr/lasilla/152metre/
- PlatoSpec: https://stel.asu.cas.cz/plato/index.html
- HD2685 data: M. I. Jones et al. 2019 (https://doi.org/10.48550/arXiv.1811.05518)
- VIPER: Zechmeister, Koehler and Chamarthi 2021 (2021ascl.soft08006Z)
- γ Equulei period: Bahlona 2022 (https://doi.org/10.1093/mnras/stac011)
- RadVel: Fulton, Petigura, Blunt & Sinukoff 2018 (10.1088/1538-3873/aaaaa8)