Ľ. Hambálek

Short-term* spot evolution

Wavelet analysis of time series

of photometry of T Tauri stars
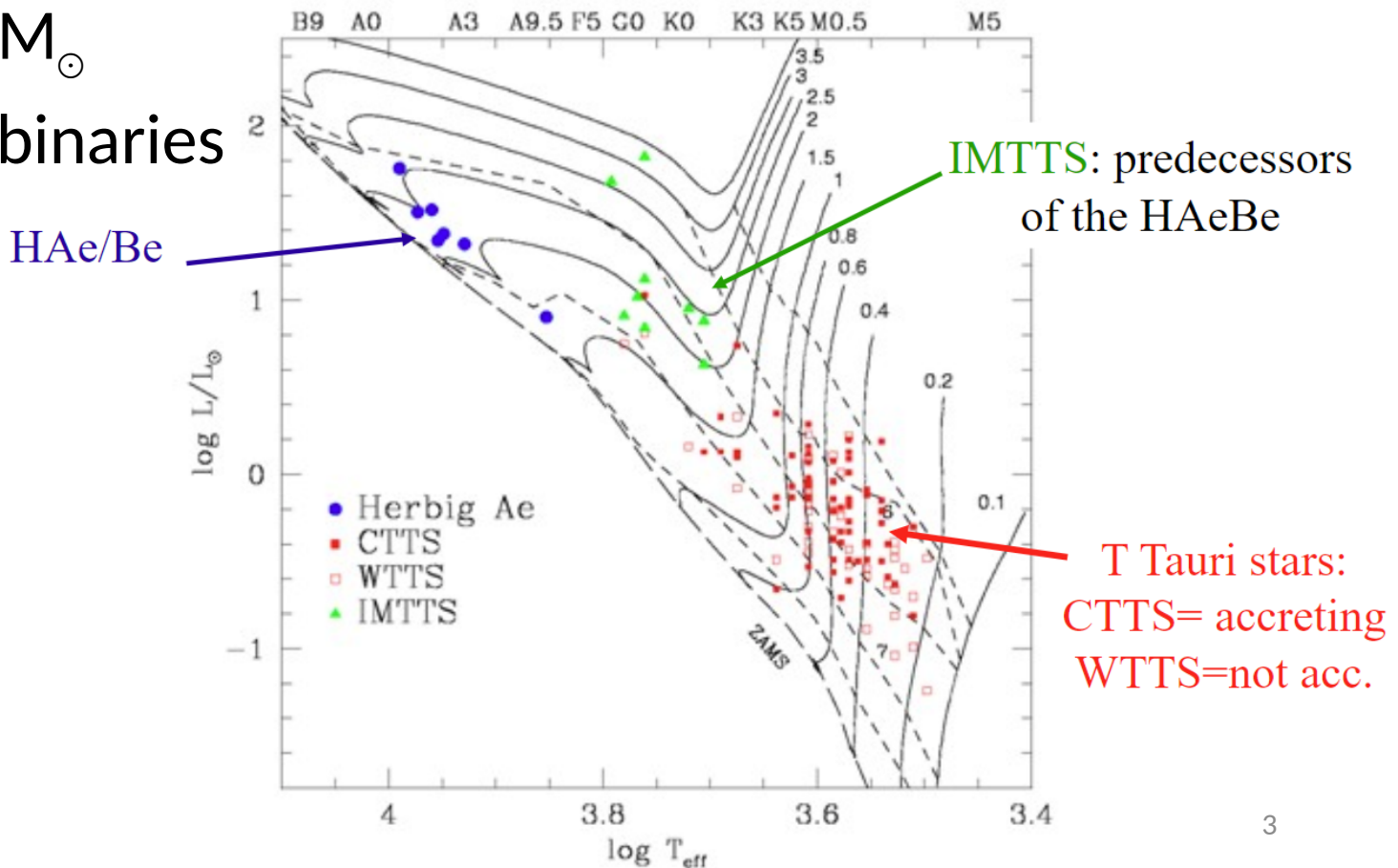
13.6.2018

Outline

1) T Tauri stars
2) Spots and the period estimation
3) Wavelet analysis
4) Time series
5) Simple spot model
6) Results

T Tauri stars

- Young (Li λ6707 Å absorption)
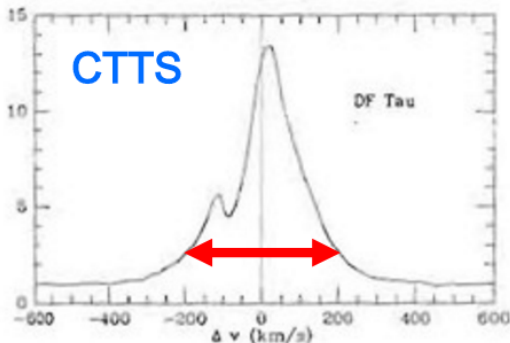
- 0.5-2.5 $M_\odot$

- usually binaries

HAe/Be

IMTTS: predecessors of the HAeBe

T Tauri stars: CTTS= accreting WTTS=not acc.

Herbig Ae
CTTS
WTTS
IMTTS

T Tauri stars

Classical

EW H_α > 10 Å

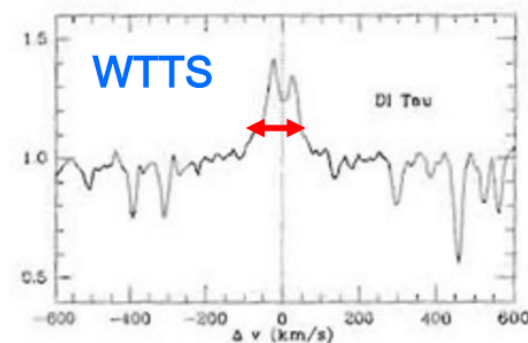NIR excess – accretion disk

jets and outflows

mag. disk interaction

Weak-lined

EW H_α < 10 Å

almost no NIR excess - dissipated disk
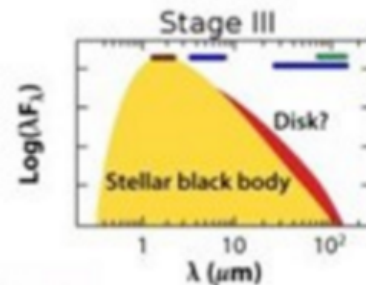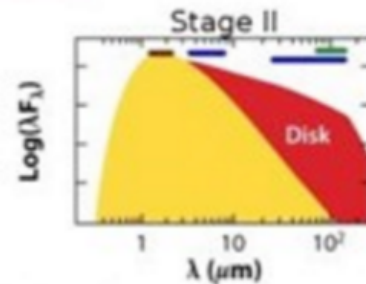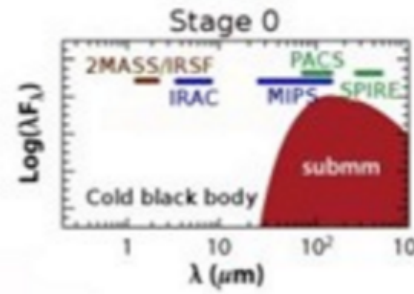
no jets or outflows

solar-type mag. activity

Lee Hartmann, 2000

T Tauri star

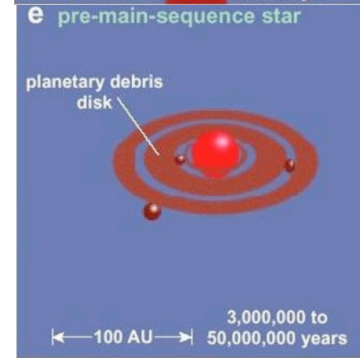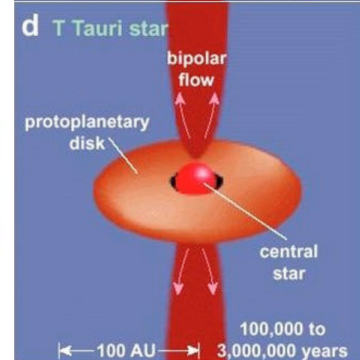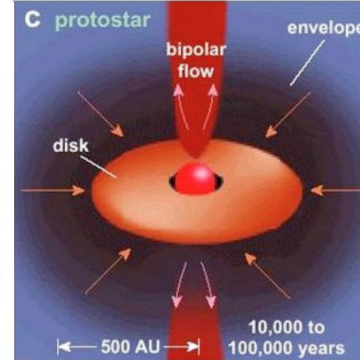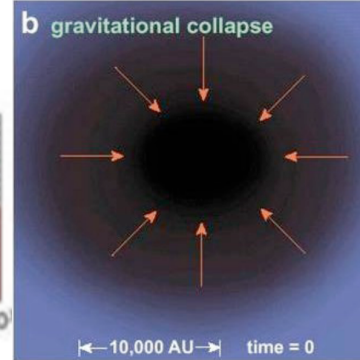$$\alpha_{IR} = \frac{d \log \lambda F_\lambda}{d \log \lambda} > 0$$

$$0 > \alpha_{IR} > -1.5$$

$$\alpha_{IR} < -1.5$$

Stage 0

Stage I

Stage II

Stage III

b gravitational collapse
c protostar
d T Tauri star
e pre-main-sequence star
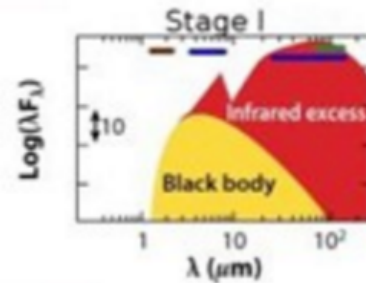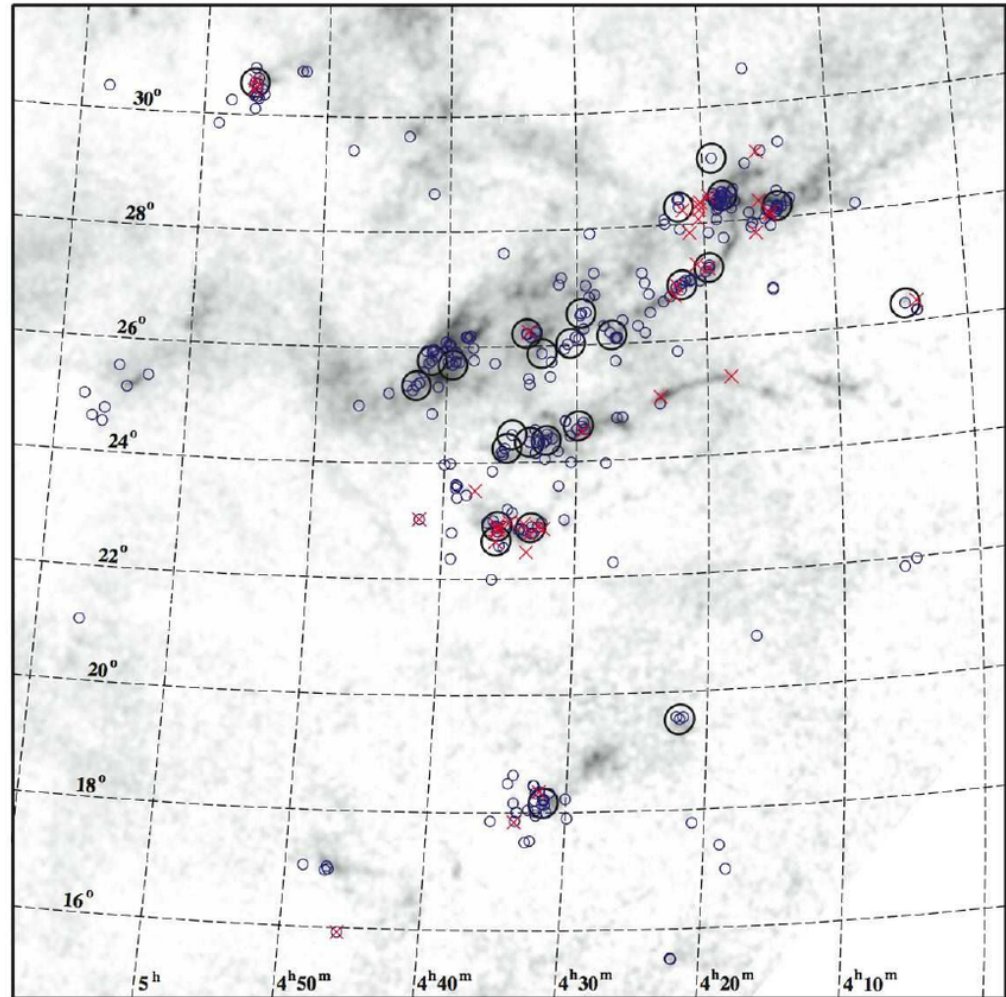
Protostar

CTTS

WTTS

time

André, 2002

Greene, 2002
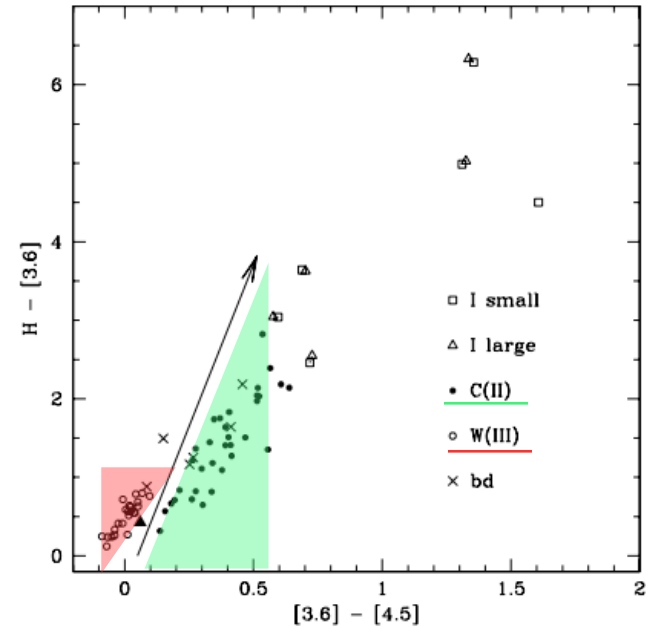
5

Taurus-Auriga

- Nearest SFR
- Distance: 140 pc
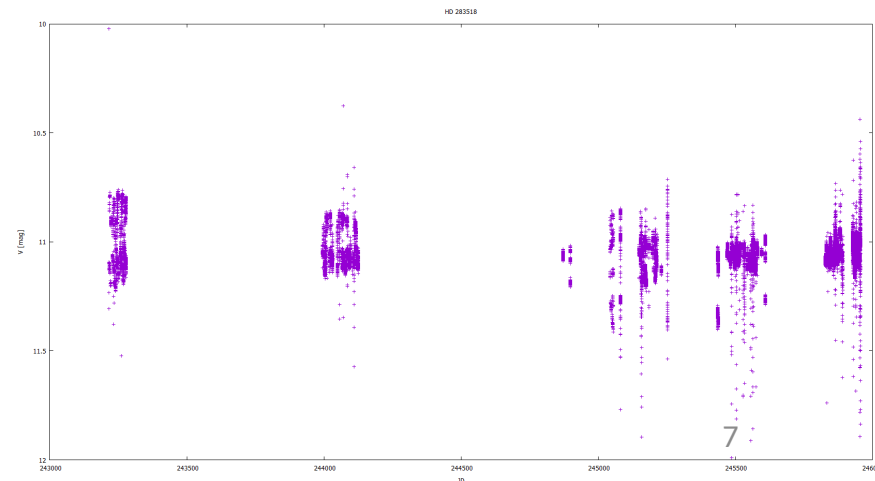- Diameter: 30 pc
- Mass: 35000 M$_\odot$

Mamajek, 2009

6

Our sample

- 20 WTTS stars

- dubious or no rotation period in literature

- NSVS+SWASP data from 1998-08-06 to 2012-01-30 (4560 days) in 8 continuous seasons

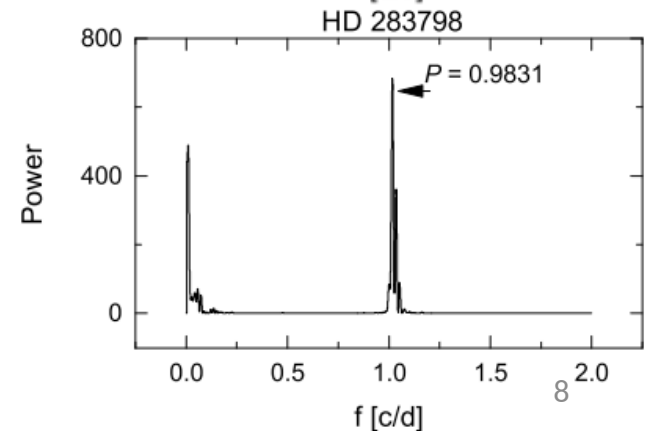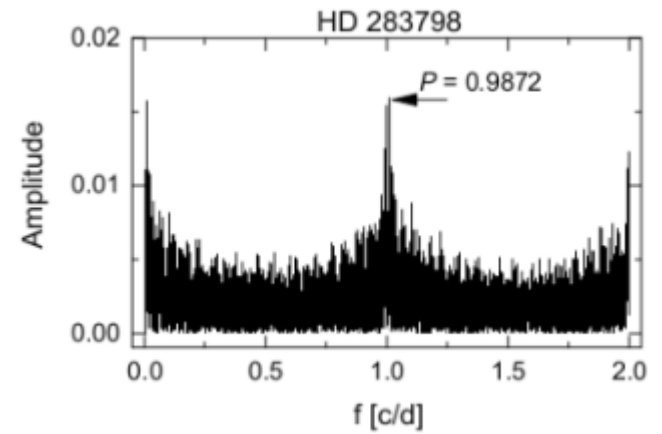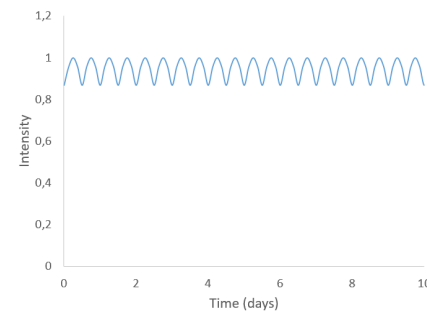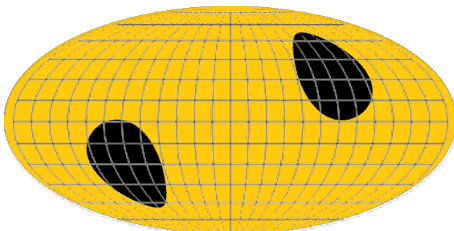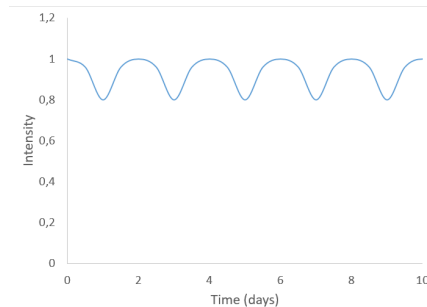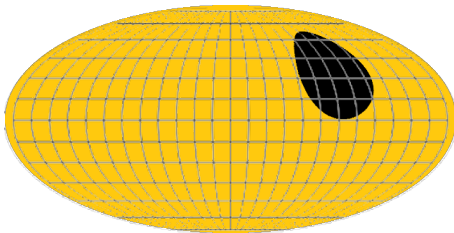- Period analysis (DC DFT) on whole dataset and season-wise

Hartmann+ 2005
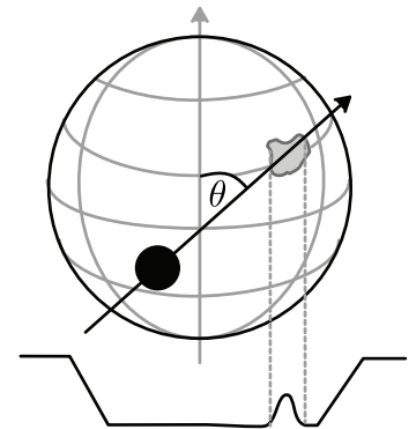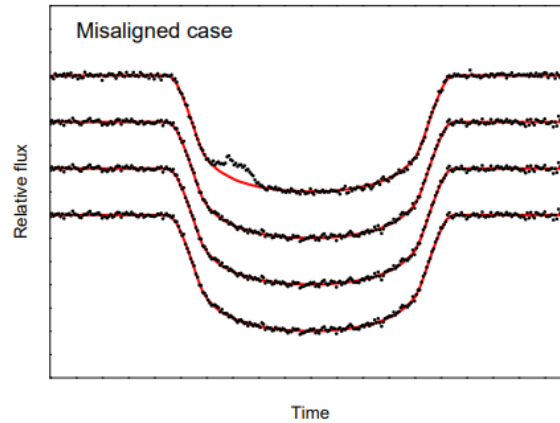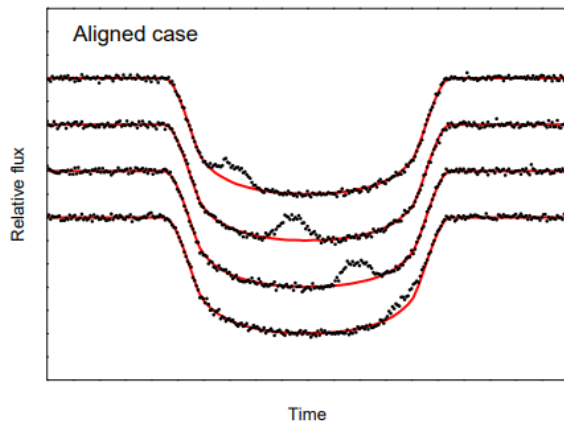
Spots and the period estimation

Caveats:

- Double/single period light curve
- Periods close to window size

Spots and the period estimation

- From 2008 (Silva-Valio, Dittmann+)
- Transiting exoplanets and spotted stars
- Obliquity: planetary inclination vs rotation axis

Sanchis-Ojeda+, 2012

Wavelet analysis

- Decomposition and analysis with emphasis on time-frequency localization.

- Weighted Wavelet Z-transform (WWZ)
  - $f \in \langle 0.1 : 2.0 \rangle$ c/d, $\Delta f = 0.0001$ c/d, $w = 50$ d

- Period estimation in different time bins

- 3D plot: Time – Frequency (period) – Z value
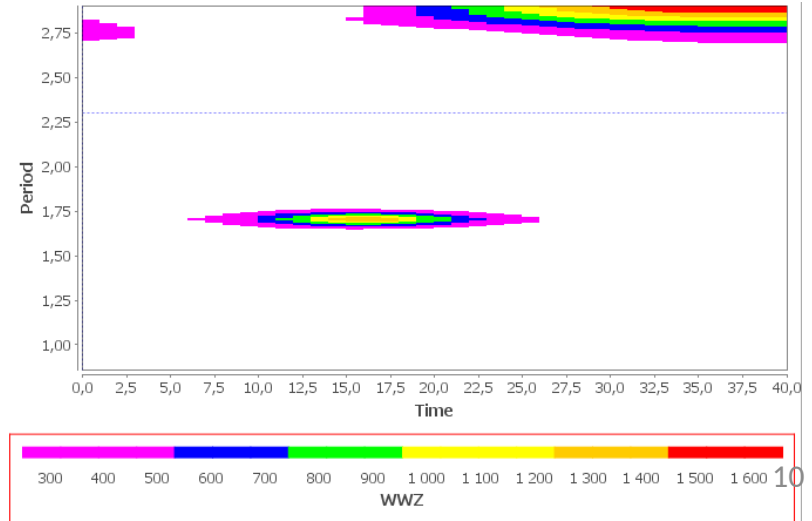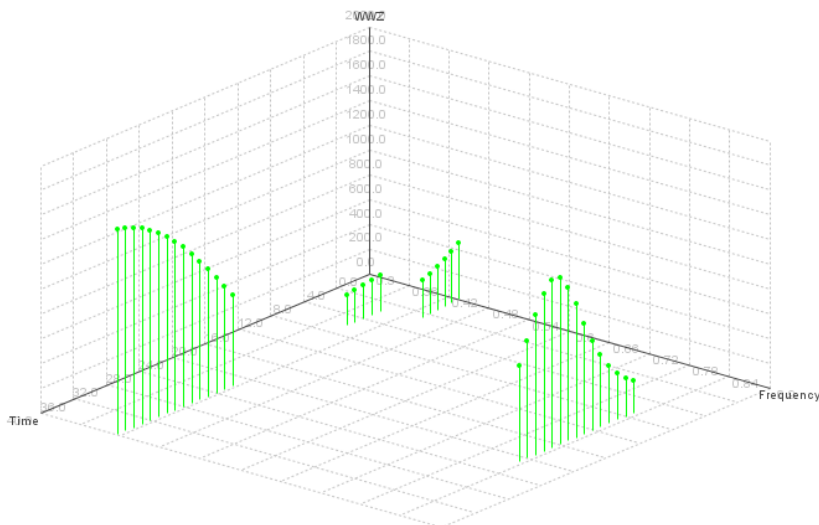
Time series

- Kepler K2 data (around 80 days, 30 min cadence)
- C4 and C13 fields
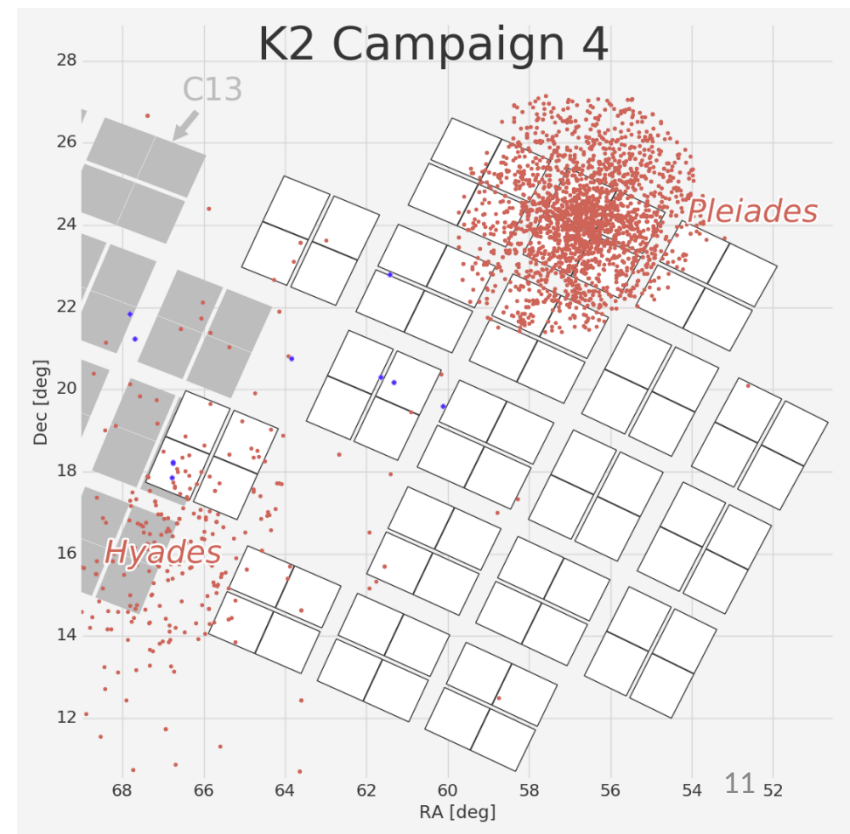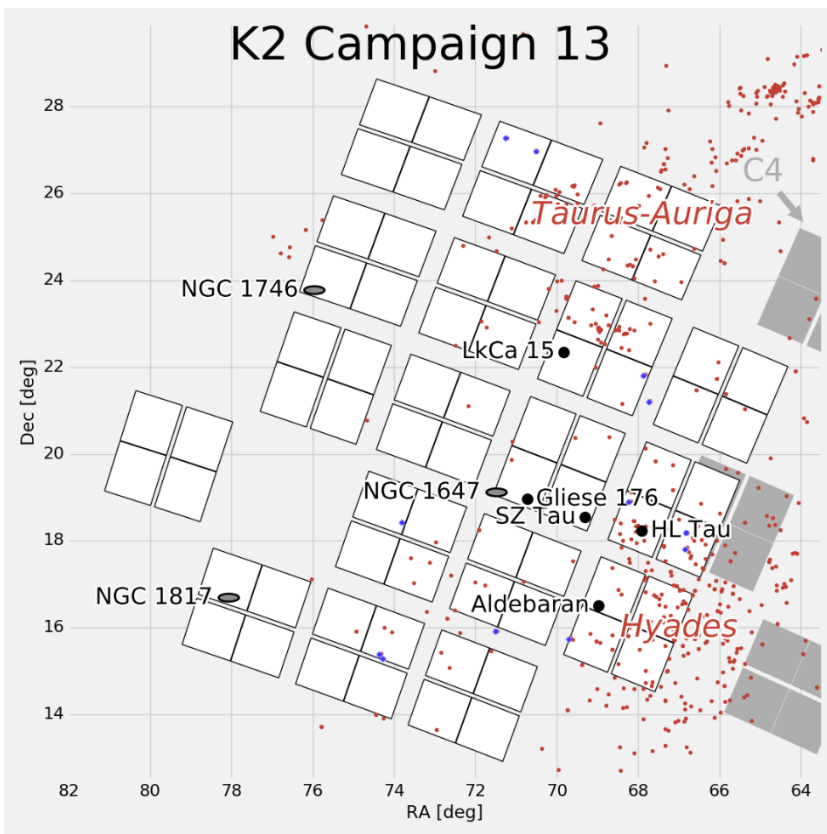
HD 284496

$P_{lit} = 2.71$ d

$P_{SWASP} = 2.6880(195)$ d

$P_{K2} = 2.7738(8) / 2.6525(6)?$ d
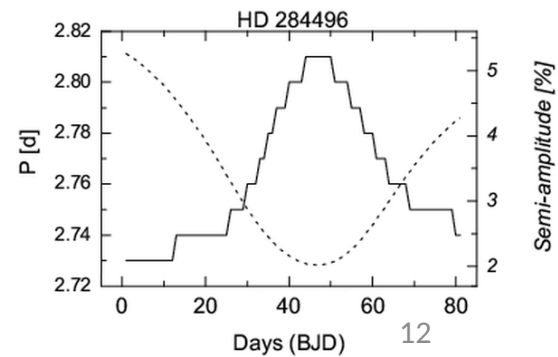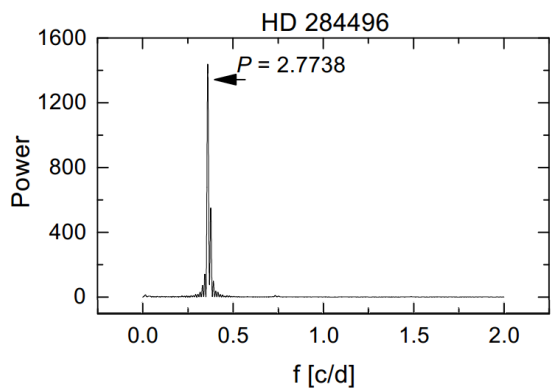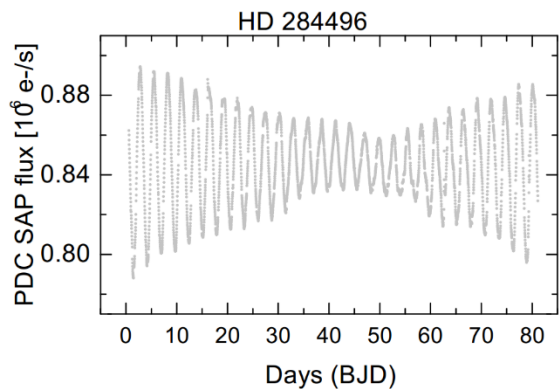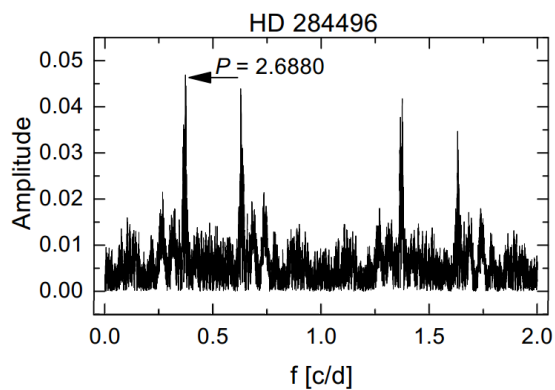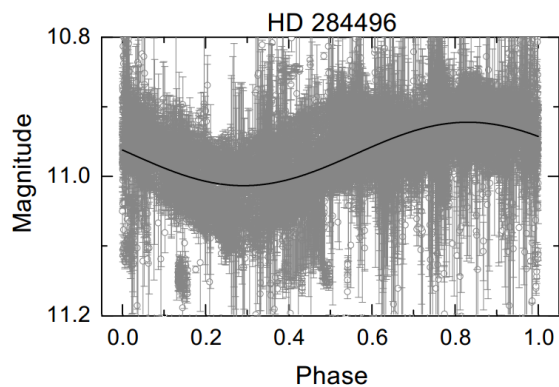
HD 283782

$P_{lit} = ??? \, \mathrm{d}$

$P_{SWASP} = 0.8704(1106)? \, \mathrm{d}$

$P_{K2} = 2.0181(4) \, \mathrm{d}$
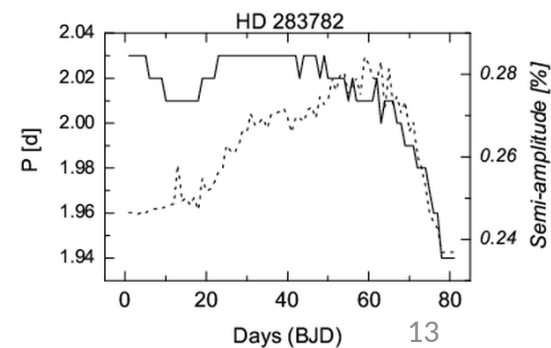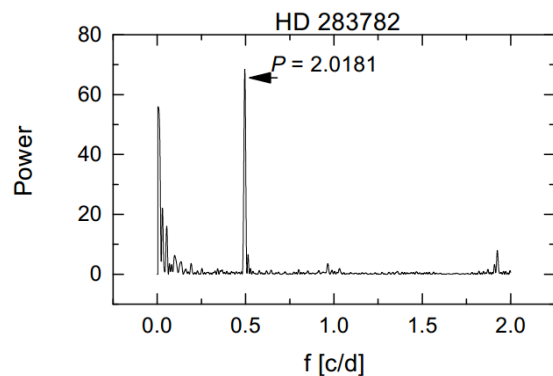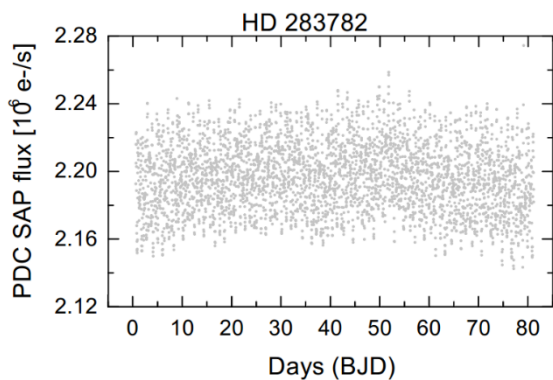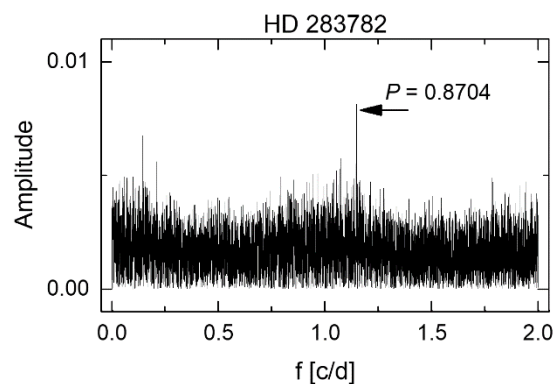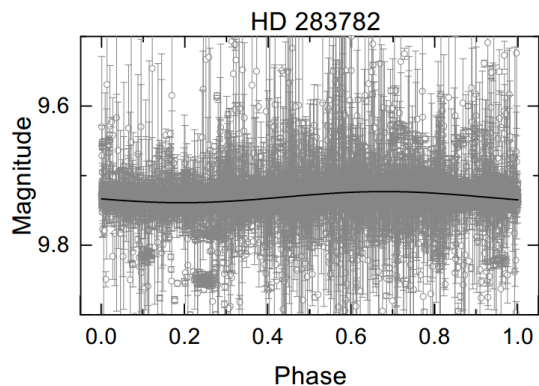
HD 31281

$P_{lit} = ???\,\mathrm{d}$

$P_{SWASP} = 0.7913(15)?\,\mathrm{d}$

$P_{K2} = 0.6771(1)\,/\,0.7999(1)?\,\mathrm{d}$
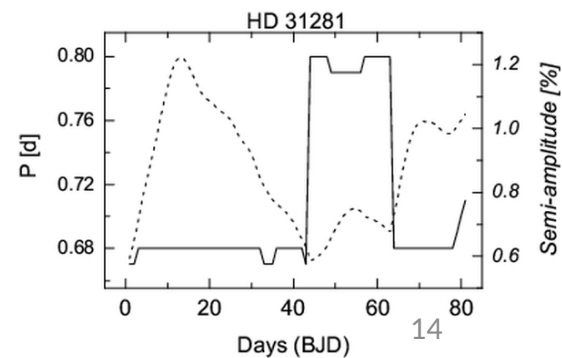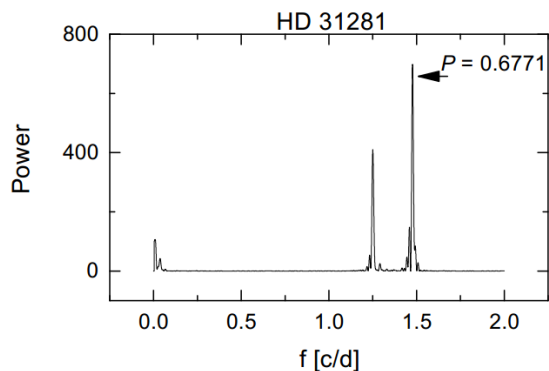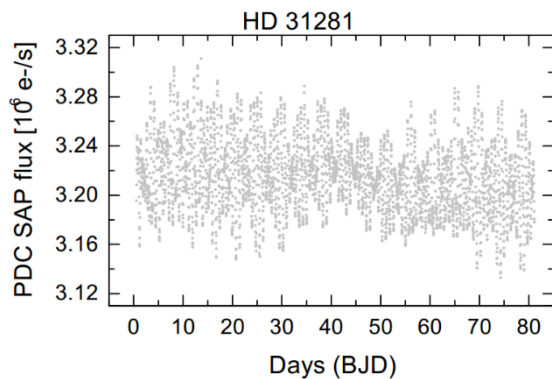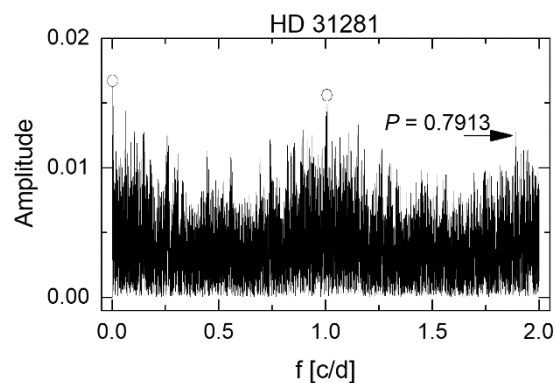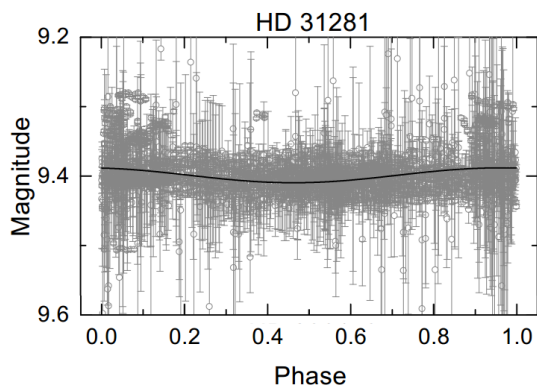
HD 286178

$P_{lit} = 2.39$ d

$P_{SWASP} = 2.4125(164) / 1.7001(81)?$ d

$P_{K2} = 2.3562(11) / 1.7027(6)? / 1.1813(3)?$ d
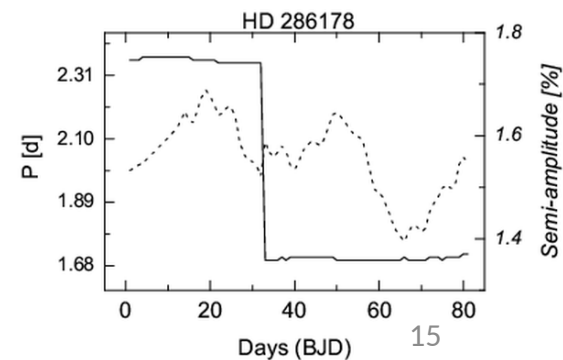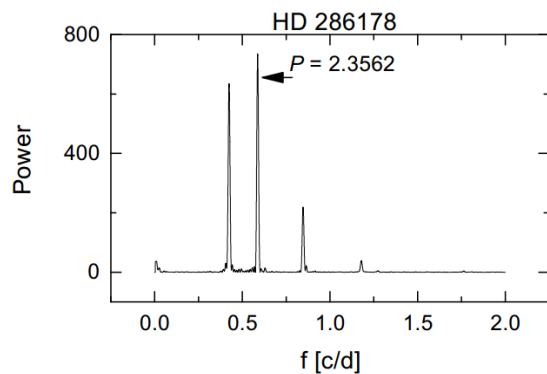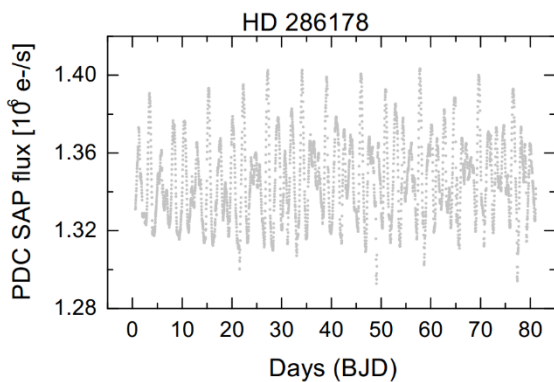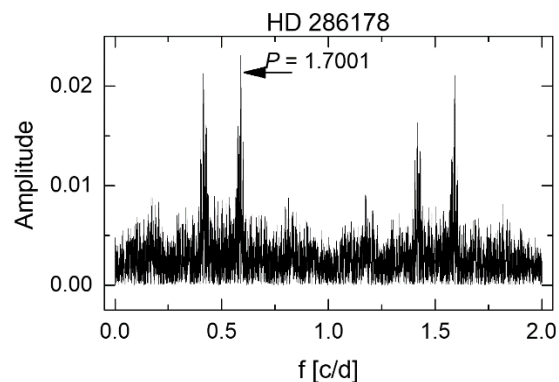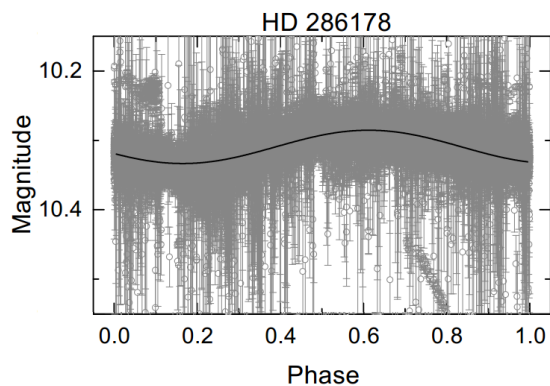
Spot models

Research on existing spot models

Purpose
LC domain
Multiple spots
New spots
Spot migration

Spot models

Research on existing spot models

	WD & deriv.	Exoplanets	Spotted stars
Purpose			
LC domain			
Multiple spots			
New spots			
Spot migration			
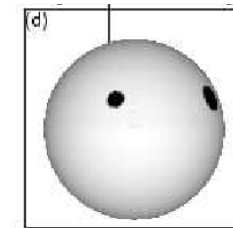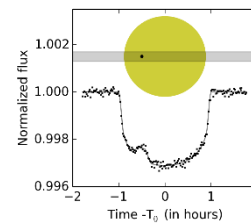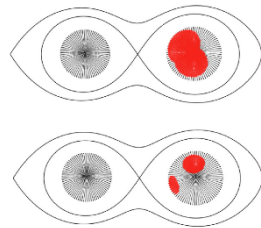
Spot models

Research on existing spot models

	WD & deriv.	Exoplanets	Spotted stars
Purpose	**Binaries**	**Transit align.**	**Single stars**
LC domain	**Phase**	**Time**	**Phase**
Multiple spots	**Yes**	**Some**	**Yes**
New spots	**No**	**No**	**No**
Spot migration	**No**	**No**	**No**

Spot models

Research on existing spot models

	WD & deriv.	Exoplanets	Spotted stars
Purpose	**Binaries**	**Transit align.**	**Single stars**
LC domain	**Phase**	**Time**	**Phase**
Multiple spots	**Yes**	**Some**	**Yes**
New spots	**No**	**No**	**No**
Spot migration	**No**	**No**	**No**

Had to write one :(

Simple spot model

- Rectangular grid
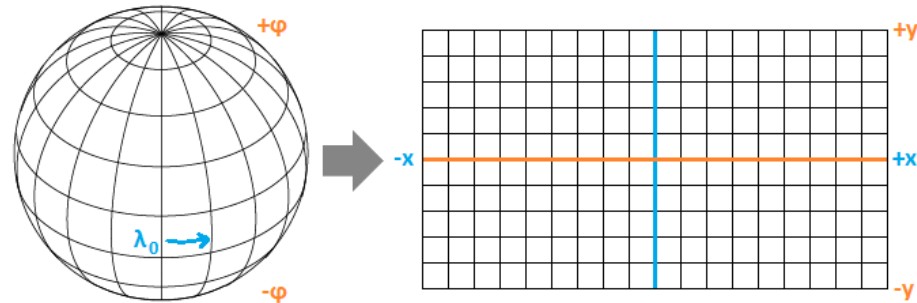

```
                struct GRID //structure for parametrization of the spherical star surface
                {
NP_deg            int pixperdeg; //number of pixels per one degree (one size only)
   i              float inc; //inclination of the stellar rotation axis in radians
  T_*             float tmp; //star temperature in Kelvins
  T_s             float tmps; //spot temperature in Kelvins
   u              float u; //linear limb-darkening coefficient
  μ_s             float mu; //spot migration rate (in degrees/revolution)
   k              float diffk; //differential rotation coefficient (0 = no diff. rot.), must be n
   z̄              XYZ antiLOS; //Cartesian anti line-of-sight vector (depends on inclination)
  F_0             float totalflux; //total flux in (visible) part of the grid unaffected by spots
                };
```

Simple spot model

- Stellar rotation: P_{rot} from WWZ
- Duration of the total simulated LC: several P_{rot}
- Temporal resolution: $P_{rot}/200$

```
        struct TIMESERIES
        {
$P_{rot}$    float period; //(equatorial) rotational period
$\Omega$     float omega; //angular rotational velocity of the star (at equator
$\Delta t$   float stepintime; //size of step in time (days) for LC generation
$T$          float duration; //total duration of output light curve in days
$N$          int Nstep; //total number of steps in the time series
        };
```

Simple spot model

- Multiple spots (no overlapping)
- Spot activation/deactivation (visibility change)
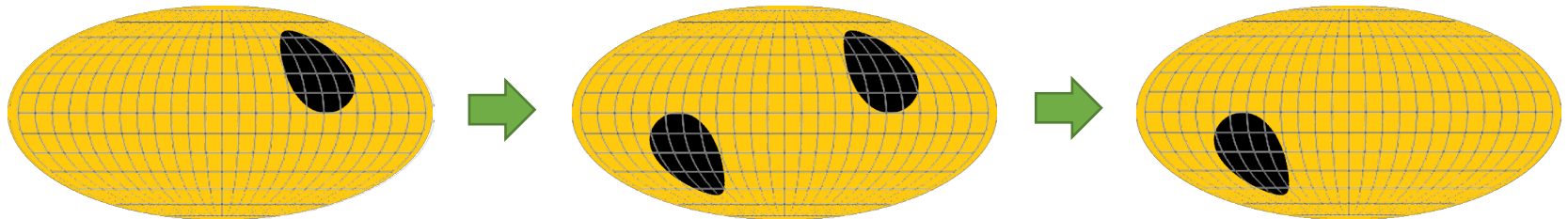

```
struct SPOT //structure for spot parameters (stored usually in radians!)
{
    float lng; //longitude of spot center in radians
    float lat; //latitude of spot center in radians
    float rad; //radius of spot (from center) in radians
    bool active; //if the spot should be present
    XYZ center; //Cartesian coordinates of spot center
    int num; //spot number (not checked)
    int stepon; //step at which the spot will be activated
    int stepoff; //step at which the spot will be DEactivated
};
```

λ
ϕ
r_s
A
$\overrightarrow{r_c}$
n_s
t_1
t_0

Simple spot model

T_{eff} (K)	Logg	[M/H]	linear u
4000	4.50	0.00	0.6888
4250	4.50	0.00	0.7215
4500	4.50	0.00	0.7163
4750	4.50	0.00	0.6977
5000	4.50	0.00	0.6779
5250	4.50	0.00	0.6550
5500	4.50	0.00	0.6307
5750	4.50	0.00	0.6074
6000	4.50	0.00	0.5842
6250	4.50	0.00	0.5640
6500	4.50	0.00	0.5459
6750	4.50	0.00	0.5312
7000	4.50	0.00	0.5191
7250	4.50	0.00	0.5085
7500	4.50	0.00	0.5003

- Limb-darkening (linear):

$$\frac{I(\mu)}{I(1)} = 1 - u(1 - \mu), \mu = \cos\theta$$

- Kepler LD coefficient table (Sing, 2009)
- Per-cell (bolometric) flux computation:

$$f_i(x, y) = \begin{cases} a_i \sigma_{SB} T_*^4 (\vec{n} \cdot \vec{z}), \text{if no spot} \\ a_i \sigma_{SB} T_s^4 (\vec{n} \cdot \vec{z}), \text{if spot} \end{cases}$$
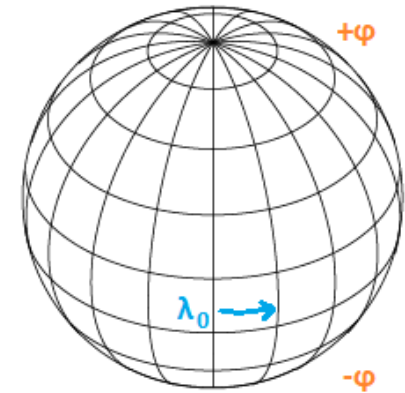
$$F_{visible} = \sum_i I_i(\mu) f_i$$
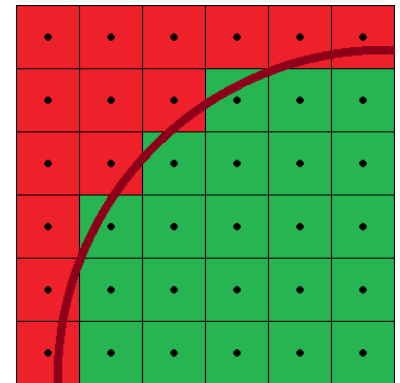
No spot overlapping so far

Simple spot model

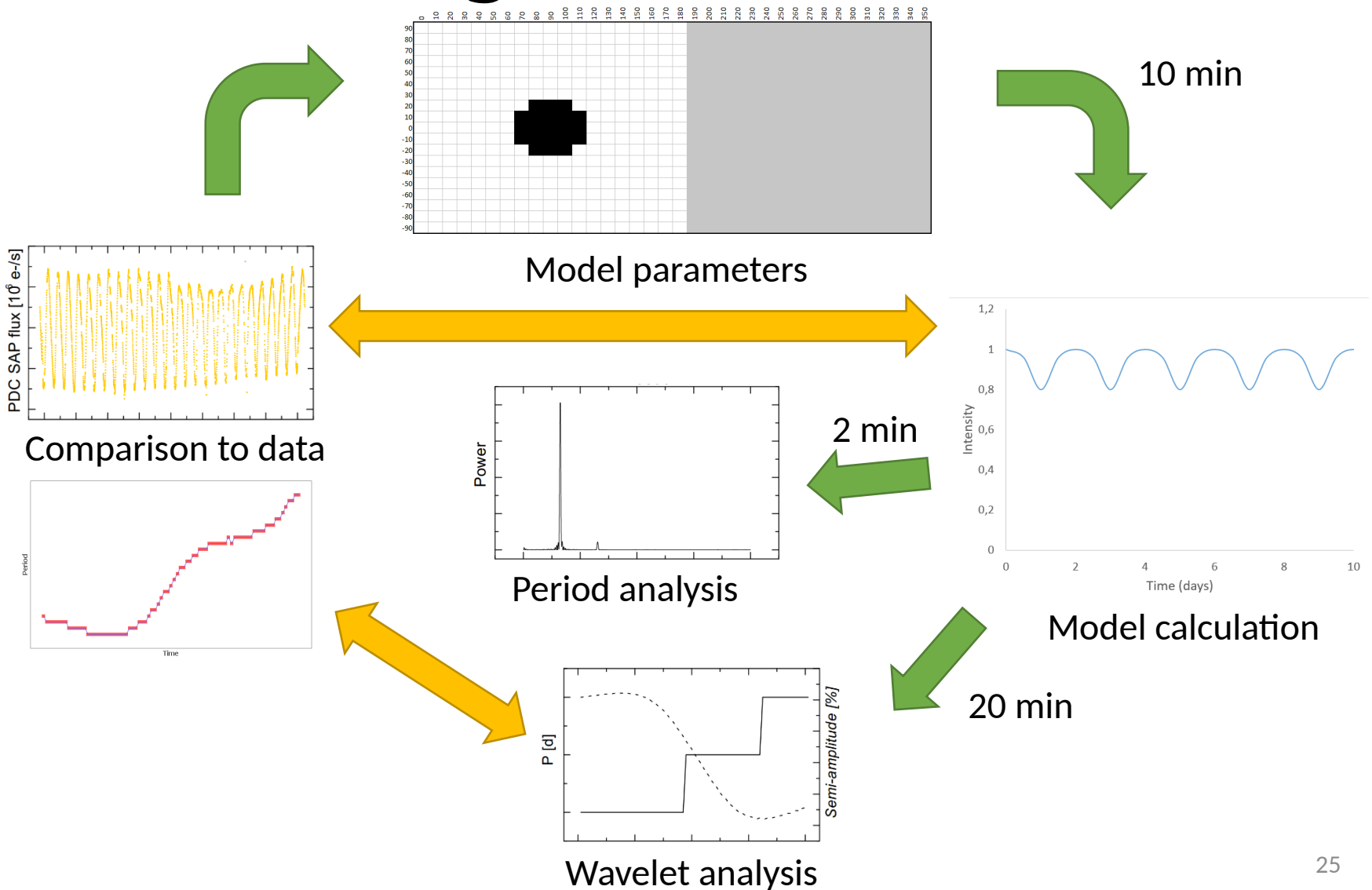- (optional) differential rotation
- (optional) spot migration

$$\Delta\varphi = \mu_s \frac{\Delta t}{P_{rot}}, \; \varphi_i = \begin{cases} \varphi_{i-1} - \Delta\varphi, \text{if } \varphi_{i-1} - \Delta\varphi > 0 \\ 0, \text{if } \varphi_{i-1} - \Delta\varphi \leq 0 \end{cases}$$
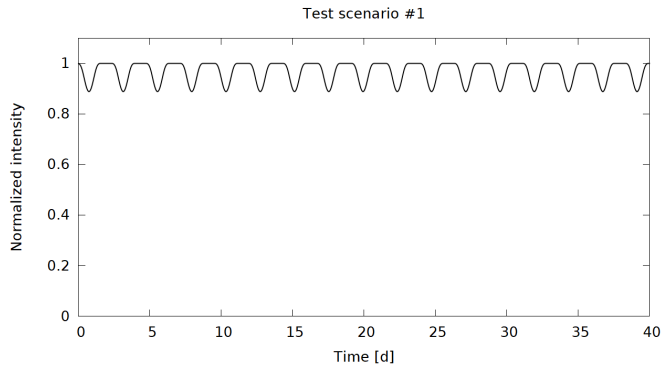
$$\Delta\lambda = \Delta t \, \Omega \left[1 - k \sin^2(\varphi)\right], \lambda_i = \lambda + \Delta\lambda$$
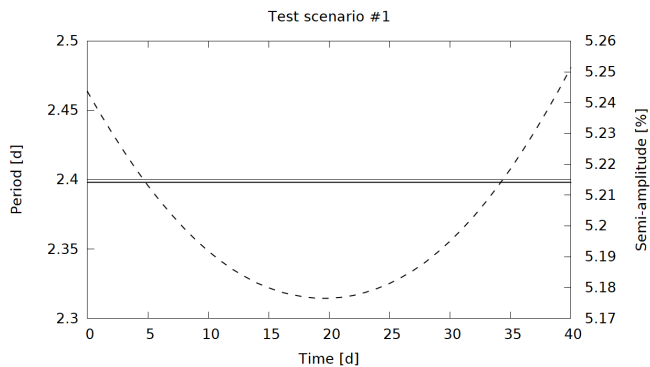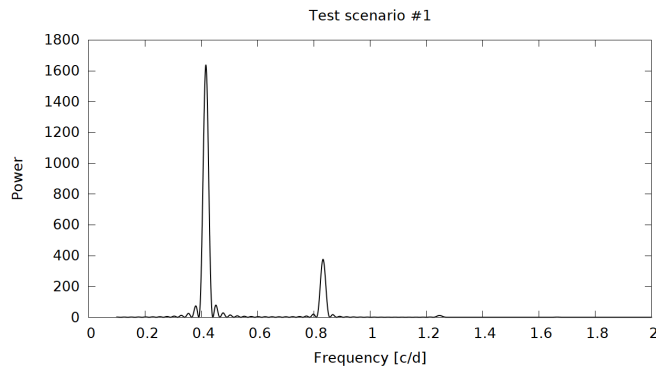
$(k_\odot = 0.2)$ other values from
Balona + Abedigamba, 2016

Modelling workflow

Model parameters

Comparison to data

Period analysis

Model calculation

Wavelet analysis

10 min

2 min

20 min

Test scenario #1

Test scenario #1

Test scenario #1

Test scenario #1

- small edge effect in semi-amplitude

Parameter	Value
P_{rot} [d]	2.4
Δt [d]	0.01
t [d]	40
T_* [K]	4500
T_S [K]	4000
u []	0.7
i [deg]	0

	Spot 1	Spot 2
λ_S [deg]	340	N/A
φ_S [deg]	0	N/A
r_S [deg]	30	N/A

Test scenario #2
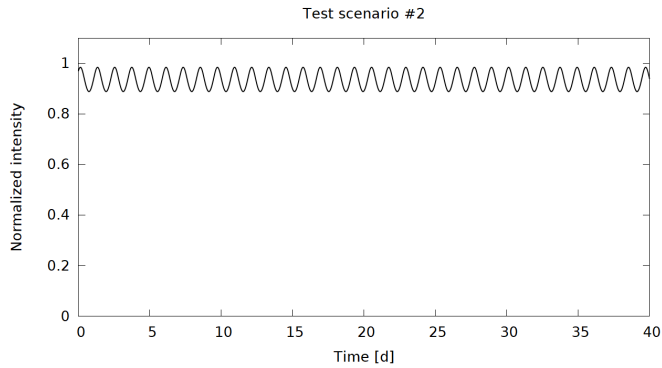
- small edge effect in semi-amplitude
- ½ of true period

Parameter	Value
P_{rot} [d]	2.4
Δt [d]	0.01
t [d]	40
T_* [K]	4500
T_S [K]	4000
u []	0.7
i [deg]	0

	Spot 1	Spot 2
λ_S [deg]	340	160
φ_S [deg]	0	0
r_S [deg]	30	30

Test scenario #3

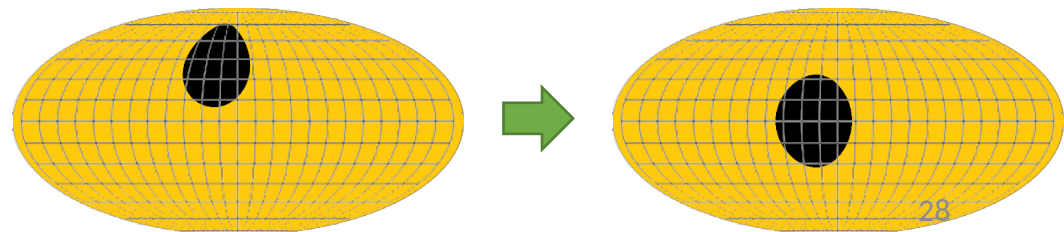Test scenario #3

Test scenario #3

Test scenario #3
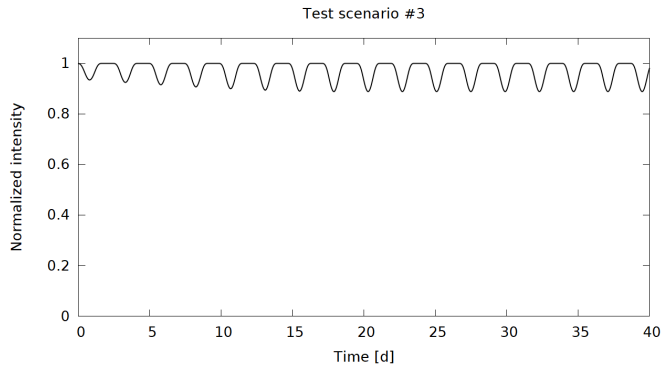
- semi-amplitude change with spot migration
- change of period due to differential rotation
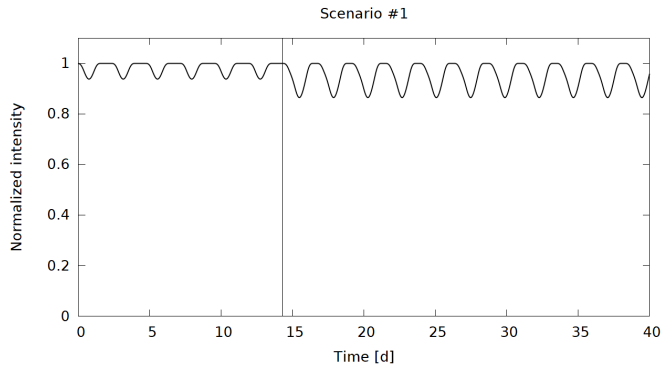- peak power duration of given period
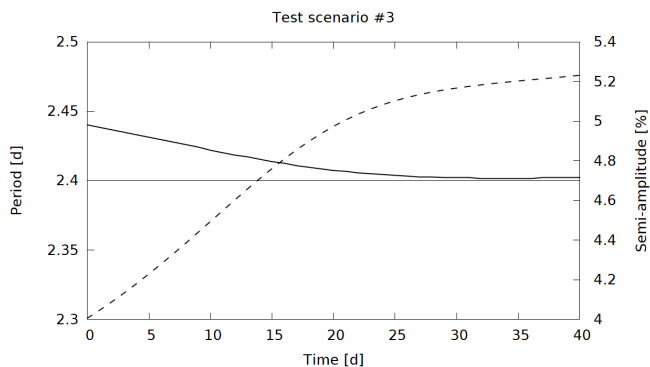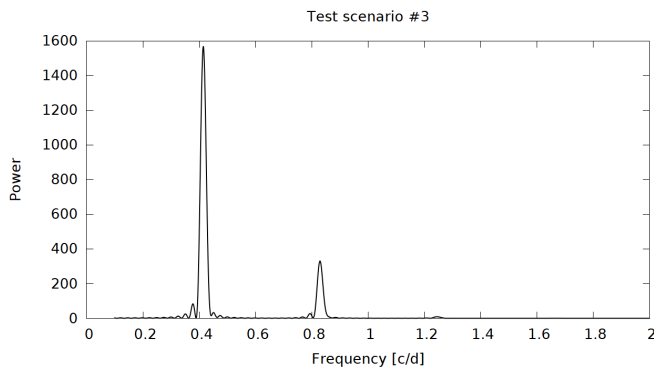
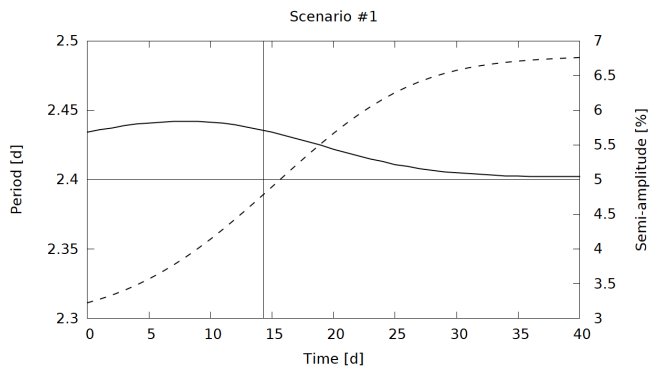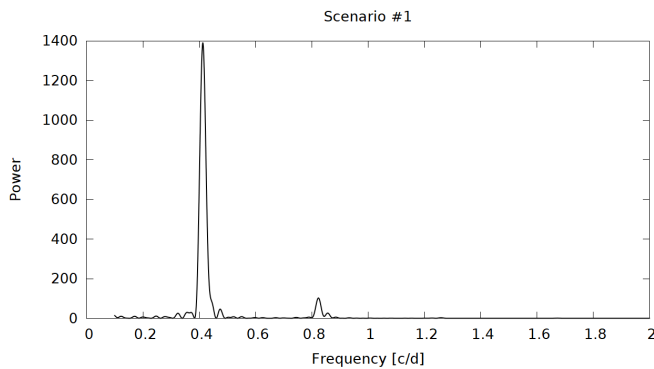| Parameter	Value
P_{rot} [d]	2.4
Δt [d]	0.01
t [d]	40
T_* [K]	4500
T_S [K]	4000
u []	0.7
i [deg]	0
μ_S [deg/P]	5
k []	0.126

	Spot 1	Spot 2
λ_S [deg]	340	N/A
φ_S [deg]	40	N/A
r_S [deg]	30	N/A

Scenario #1

Scenario #1

Scenario #1

Scenario #1
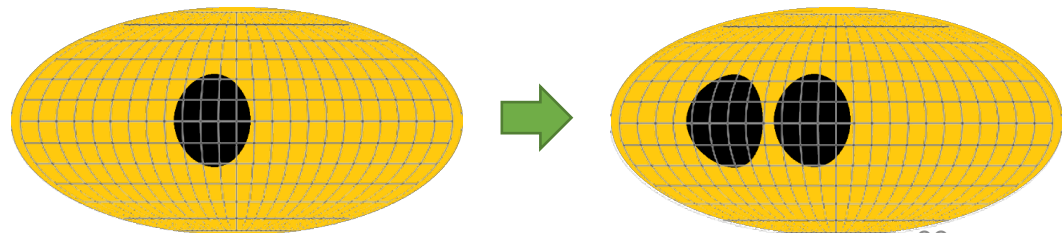
- sharp change of amplitude is not reflected in WWZ
- period in WWZ reacts smoothly when close spots

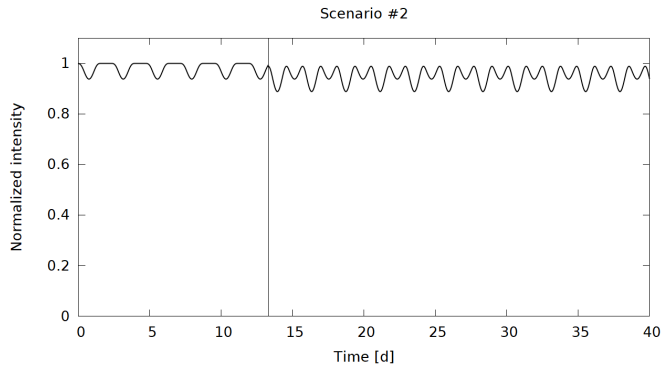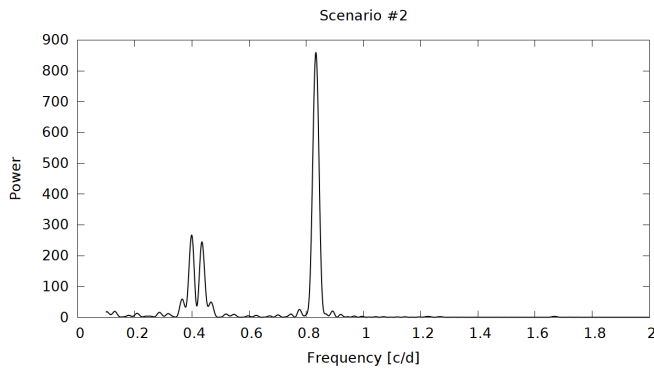| Parameter	Value
P_{rot} [d]	2.4
Δt [d]	0.01
t [d]	40
T_* [K]	4500
T_S [K]	4000
u []	0.7
i [deg]	0

	Spot 1	Spot 2
λ_S [deg]	340	270
φ_S [deg]	0	0
r_S [deg]	30	30

Scenario #2

- sharp change of amplitude is reflected in WWZ
- period in WWZ reacts dramatically when opposite spots

Parameter	Value
P_{rot} [d]	2.4
Δt [d]	0.01
t [d]	40
T_* [K]	4500
T_S [K]	4000
u []	0.7
i [deg]	0

	Spot 1	Spot 2
λ_S [deg]	340	160
φ_S [deg]	0	0
r_S [deg]	30	30

Scenario #3

Scenario #3

Scenario #3

Scenario #3

- smooth change of amplitude and period when close spots

Parameter	Value
P_{rot} [d]	2.4
Δt [d]	0.01
t [d]	40
T_* [K]	4500
T_S [K]	4000
u []	0.7
i [deg]	0

	Spot 1	Spot 2
λ_S [deg]	340	270
φ_S [deg]	0	0
r_S [deg]	30	30

31

Scenario #4

Scenario #4 — Normalized intensity vs Time [d]

Scenario #4 — Power vs Frequency [c/d]

Scenario #4 — Period [d] / Semi-amplitude [%] vs Time [d]
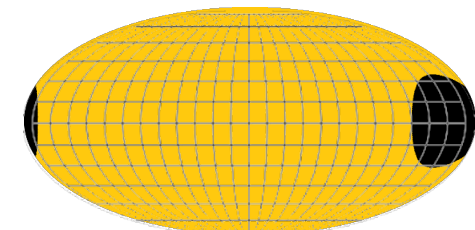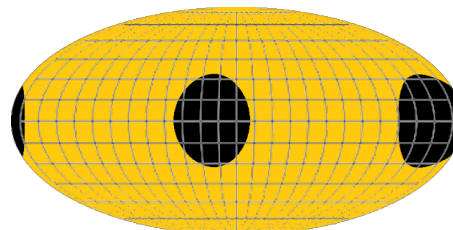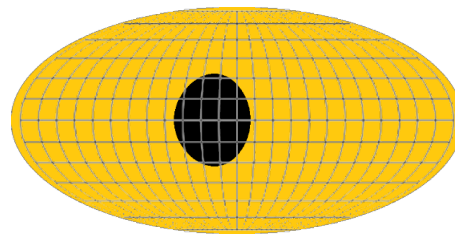
- sharp change of amplitude is edge effect
- period in WWZ reacts dramatically when opposite spots
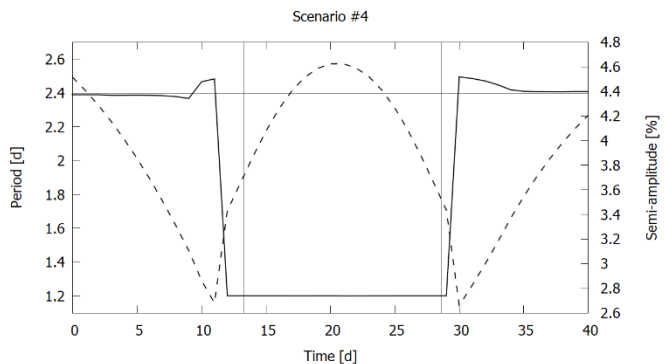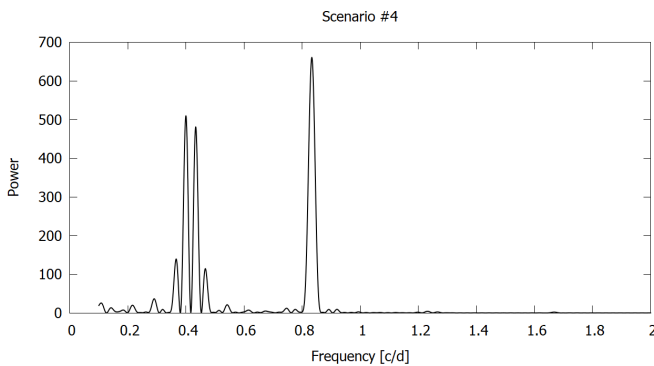
Parameter	Value
P_{rot} [d]	2.4
Δt [d]	0.01
t [d]	40
T_* [K]	4500
T_s [K]	4000
u []	0.7
i [deg]	0

	Spot 1	Spot 2
λ_s [deg]	340	160
φ_s [deg]	0	0
r_s [deg]	30	30

Test case HD 284496

Parameter	Value
P_{rot} [d]	2.71
Δt [d]	0.01
t [d]	80
T_* [K]	4500
T_S [K]	4000
u []	0.7
i [deg]	0
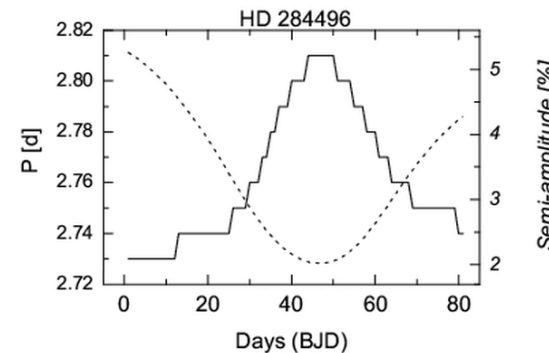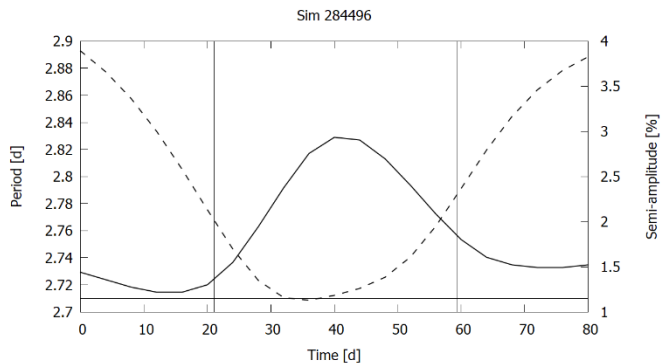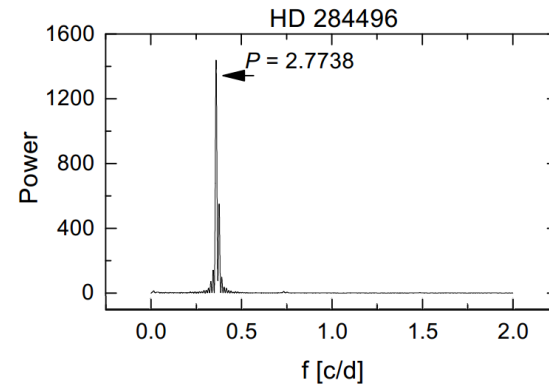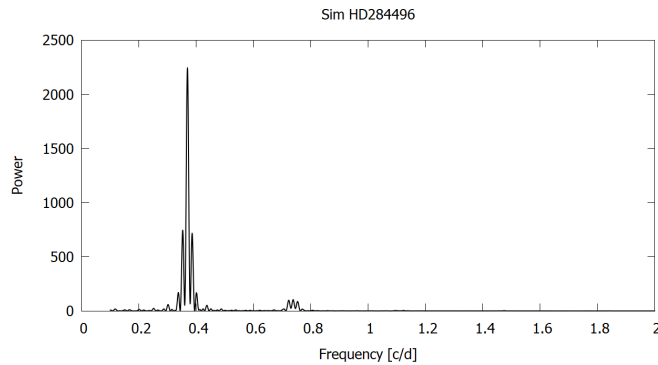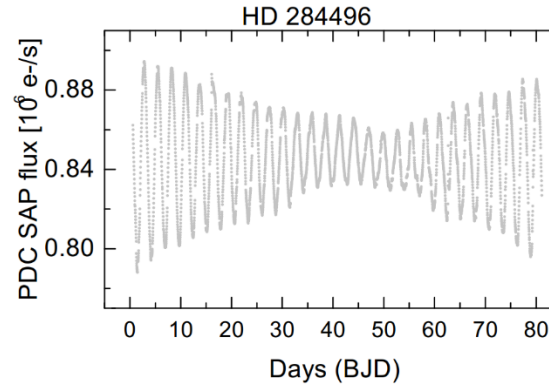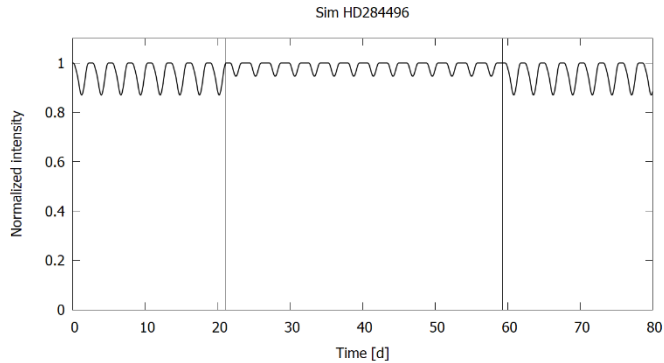
	Spot 1	Spot 2
λ_S [deg]	340	270
φ_S [deg]	0	0
r_S [deg]	20	30

Takeaway

- <u>Appearing/disappearing</u> spotted regions can explain visible changes of observed photometric period

- Period with more power is <u>not always</u> the one with longer duration in dataset

- Sharp change of period in WWZ means almost opposite spots

- Connection between WWZ and DC DFT is <u>unclear</u> (shorter/longer P_{rot})

- CPU heavy, no inversion
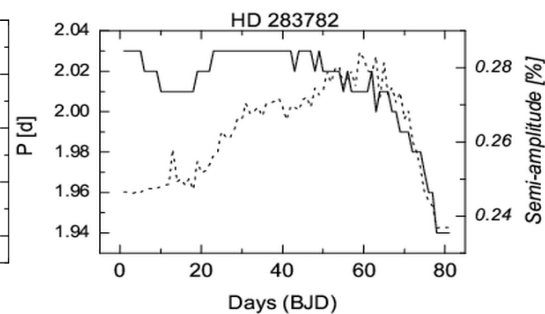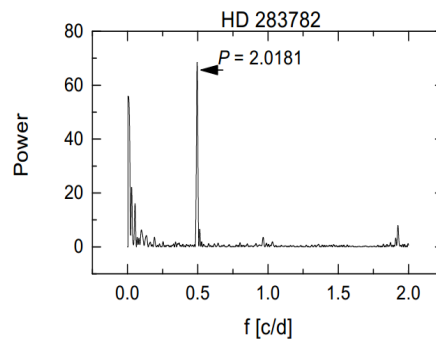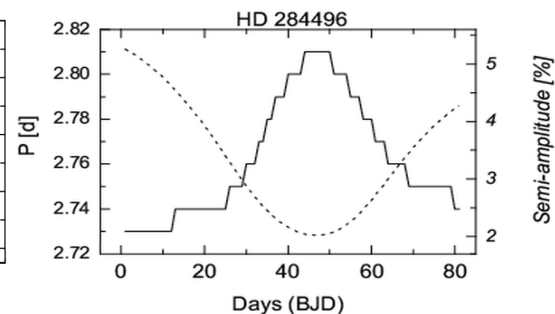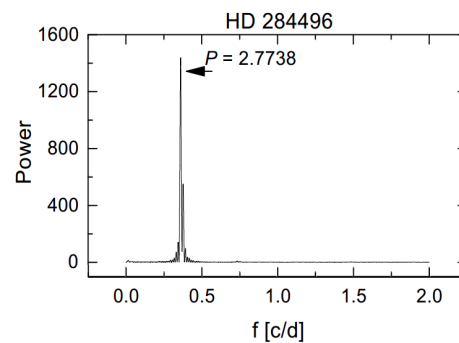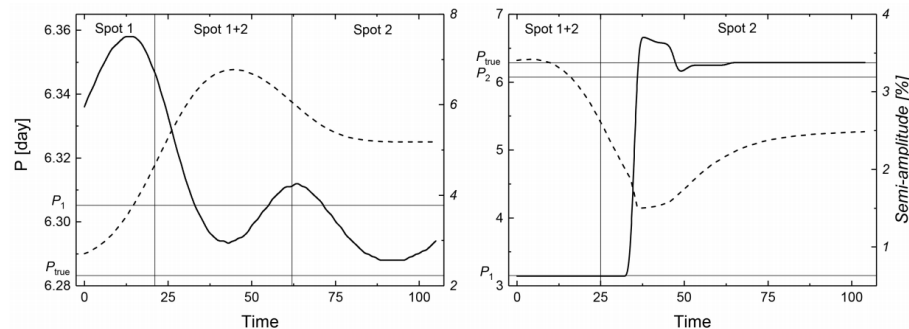
Ľ. Hambálek

Thank you!

T Tauri stars in the SuperWASP and NSVS surveys [*]

Ľ. Hambálek[1]†, M. Vaňko[1], E. Paunzen[2], B. Smalley[3]
[1] *Astronomical Institute, Slovak Academy of Sciences, 059 60 Tatranská Lomnica, Slovakia*
[2] *Department of Theoretical Physics and Astrophysics, Masaryk University, Kotlářska 2, 61137 Brno, Czech Republic*
[3] *Astrophysics Group, Keele University, Keele ST5 5BG, UK*

WIP

13.6.2018