



FACULTY
OF MATHEMATICS
AND PHYSICS
Charles University



Astronomický
ústav
AV ČR

High resolution spectroscopy of exoplanets - tool for characterization

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Prague 2019

1. Introduction to exoplanets
2. Radial velocity measurements
3. The instrumentation
4. Observational data set
5. Data reduction
6. Results
7. Summary



Dome of the 2m Perek Telescope at Ondrejov observatory

What is an extrasolar planet?

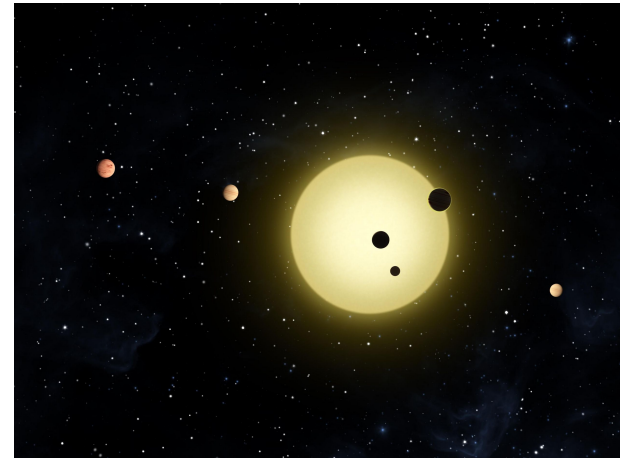
- A planet outside of the Solar system, orbiting a different star or moving through the space without a parent star

When was the first exoplanet discovered?

- 51 Pegasi b in 1994 (Mayor and Queloz by the RV measurements, the first to the main sequence star)

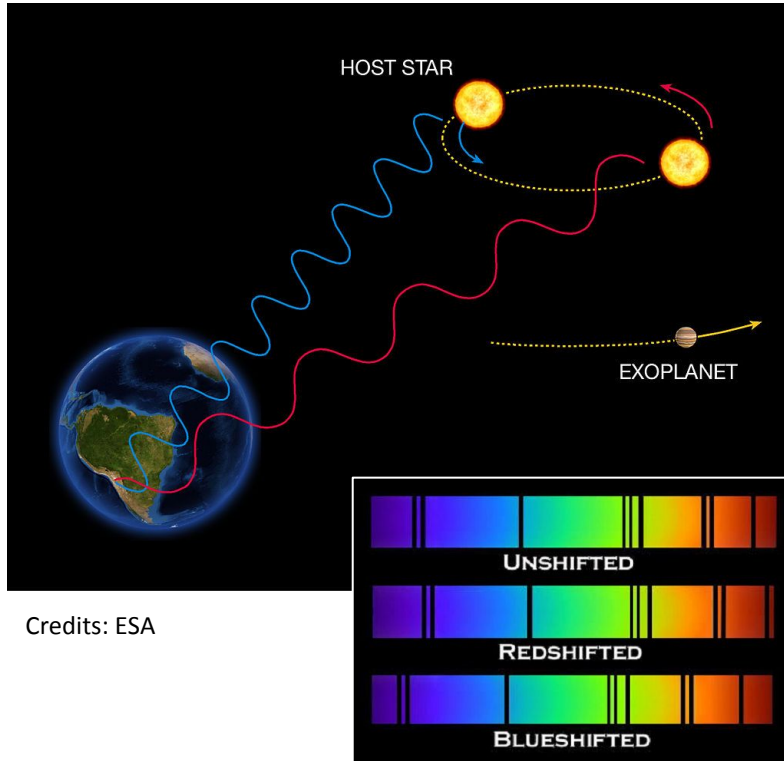
Current number of the known exoplanets?

- 4019 exoplanets in 3059 planetary systems, from which 667 are multi planet systems (Source: exoplanet.eu, September 2, 2019)



Credits: NASA/T. Pyle

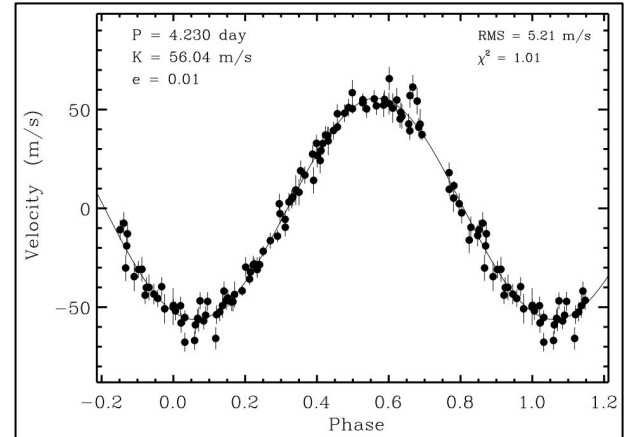
Radial Velocity Measurements



Credits: ESA

Credits: NASA

Radial velocity curve of 51 Pegasi b

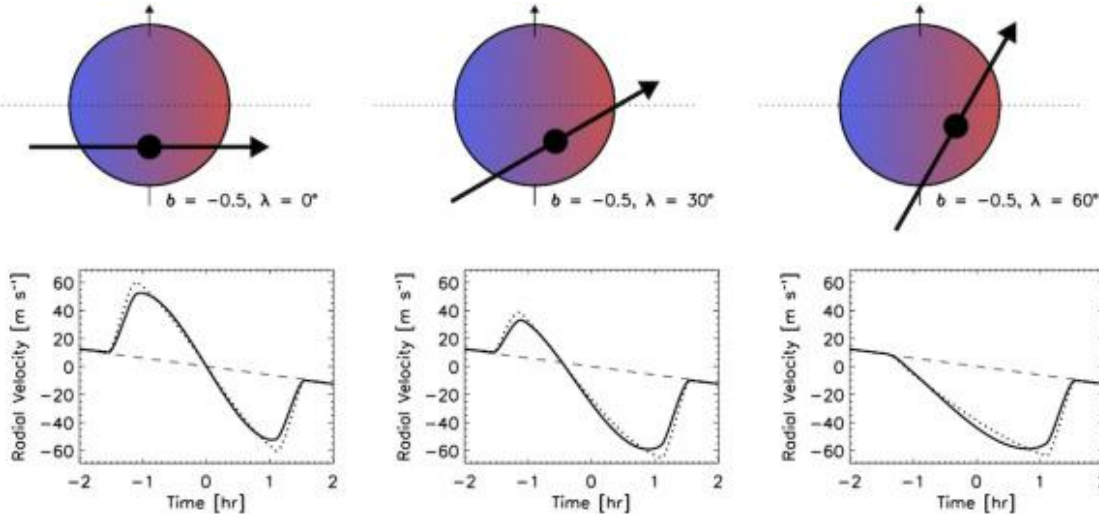


Source: Marcy et al. 1997 [4]

Radial velocity amplitude K ,
 $M_p \sin i$ is mass of the exoplanet

$$K = \left(\frac{2\pi G}{P} \right)^{\frac{1}{3}} \frac{M_p \sin i}{(M_p + M_*)^{\frac{2}{3}}} \frac{1}{(1 - e^2)^{\frac{1}{2}}}$$

Rossiter-McLaughlin Effect



RM effect for exoplanets WASP-66b, WASP-87b and WASP-103b. The color on the star disk corresponds to the RVs of the various parts of the surface.

RM effect mainly depends on speed of the stellar rotation and inclination of the planetary orbit.

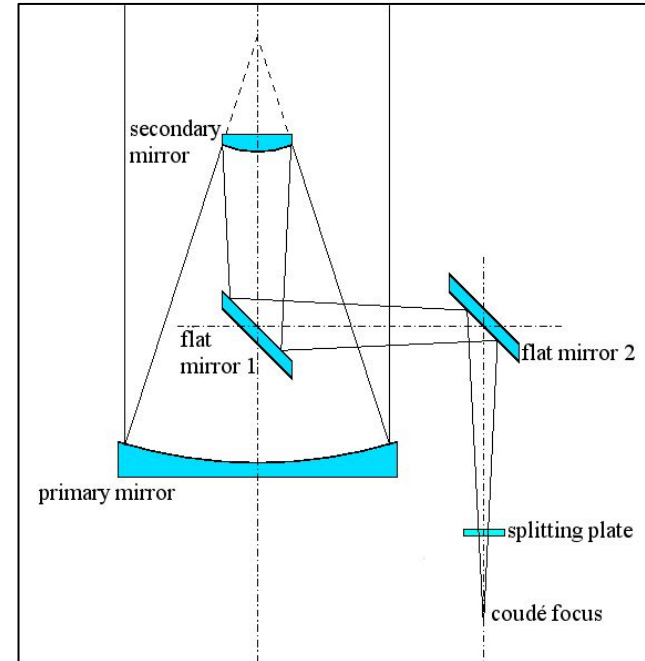
The Instrumentation - 2m Perek Telescope



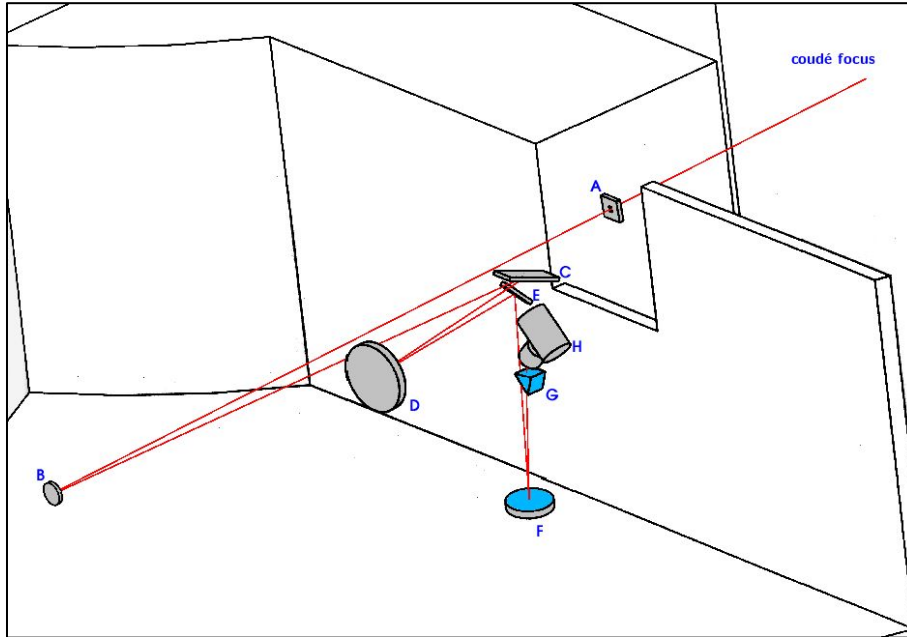
Telescope specification

Mounting:	equatorial
Optical system:	coudé focus
Primary mirror:	diameter 2m, parabolical, focal ratio 1:4.5
Secondary mirror:	diameter 58cm, convex hyperbolical
Effective focal length:	63.5m
Effective focal ratio:	1:32

Scheme of 2m Perek Telescope



The Instrumentation - OES Spectrograph



Scheme of the Ondrejov Echelle Spectrograph

Echelle grating, crossdisperser and the detector



Spectrograph specification

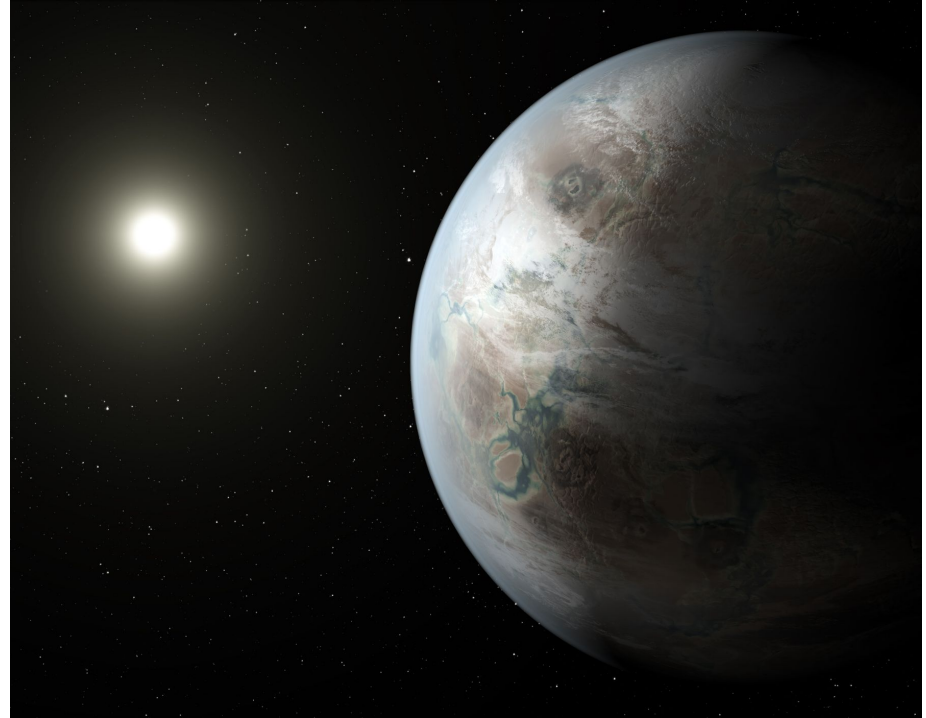
Spectral range:	360-950 nm
Echelle grating:	54.5 g/mm
Spectral resolution:	50,000 (500 nm)
Blaze angle:	69°
Limiting magnitude:	13 mag

Observational Data Set - Target Selection

Main criteria in the target selection process:

- **Visibility** (suitable for a long term observations)
- **Brightness** (brighter than 10 mag)
- **Confirmed exoplanet** (or a candidate)
(examination of limits for our instrumentation)
- **Transiting** exoplanet (or a predicted transit)
(detection of the Rossiter-McLaughlin effect)
- **Short orbital period** (transit observations)
- Possibility of existence of **an exo-atmosphere**
(hot Jupiters for the exo-atmosphere detection)

Star chosen as the main target: **MASCARA-2**



Credits: NASA Ames/JPL-Caltech/T. Pyle

Other designations - HD 185603, KELT-20

Parameters of target star MASCARA-2

Parameter	Symbol	Unit	Value	Ref.
Right Ascension	RA		19 38 38.73	1
Declination	DE		+31 13 09.21	1
V-band magnitude	m_V		7.58	1
Spectral Type			A2V	2
Parallax	π	mas	7.41 ± 0.39	2
Stellar mass	M_*	M_\odot	1.89 ± 0.06	3
Stellar radius	R_*	R_\odot	1.60 ± 0.06	3
Effective temperature	T_{eff}	K	8980 ± 130	3
Projected rotation speed	$v \sin i_*$	$\text{km} \cdot \text{s}^{-1}$	114 ± 3	3

Parameters of exoplanet MASCARA-2b

Parameter	Symbol	Unit	Lund et al. 2017	Talens et al. 2018
Epoch	T_0	BJD	$2\,457\,485.749\,65 \pm 0.000\,20$	$2\,457\,909.5906 \pm 0.0003$
Orbital period	P	h	$3.474\,108\,5 \pm 0.000\,001\,9$	$3.474\,199 \pm 0.000\,006$
Transit duration	T_{14}	h	3.57 ± 0.03	3.55 ± 0.03
Transit depth	δ	-	$0.013\,06 \pm 0.000\,14$	0.013
Planet-to-star ratio	R_p/R_*	-	$0.114\,26 \pm 0.000\,62$	0.115 ± 0.001
Inclination	i	$^\circ$	86.15 ± 0.28	86.4 ± 0.5
Impact parameter	b	-	0.500 ± 0.029	0.47 ± 0.06
Semi-major axis	a	AU	0.0542 ± 0.0021	0.057 ± 0.006
Planet radius	R_p	R_J	1.735 ± 0.075	1.83 ± 0.07
Planet mass ^a	M_p	M_J	< 3.518	< 17
Equil. temperature	T_{eq}	K	2261 ± 73	2260 ± 50

Observational Data Set - Target Spectra

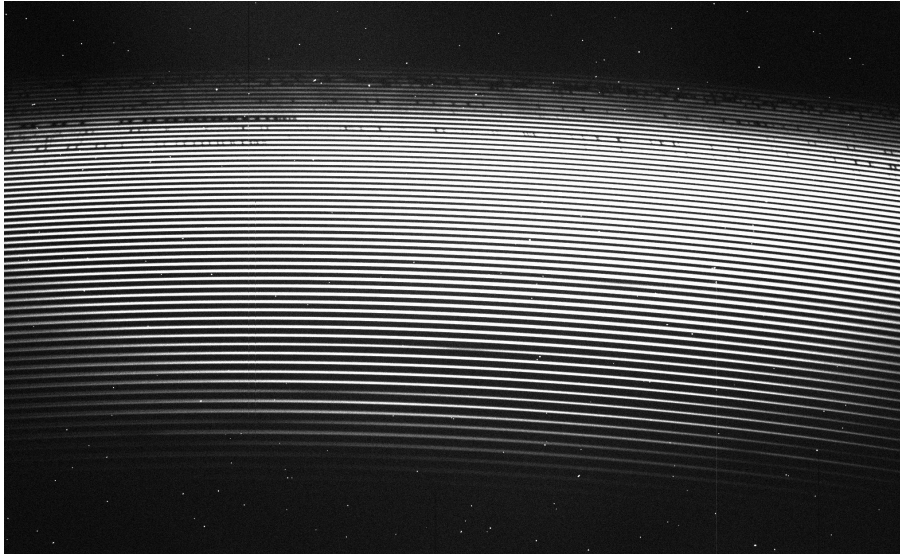


- Observational period from March to October 2018
- In sum 211 spectra from 28 different nights
- 8 full-nights observing campaigns
- 5 full-night campaigns taken during transit phase

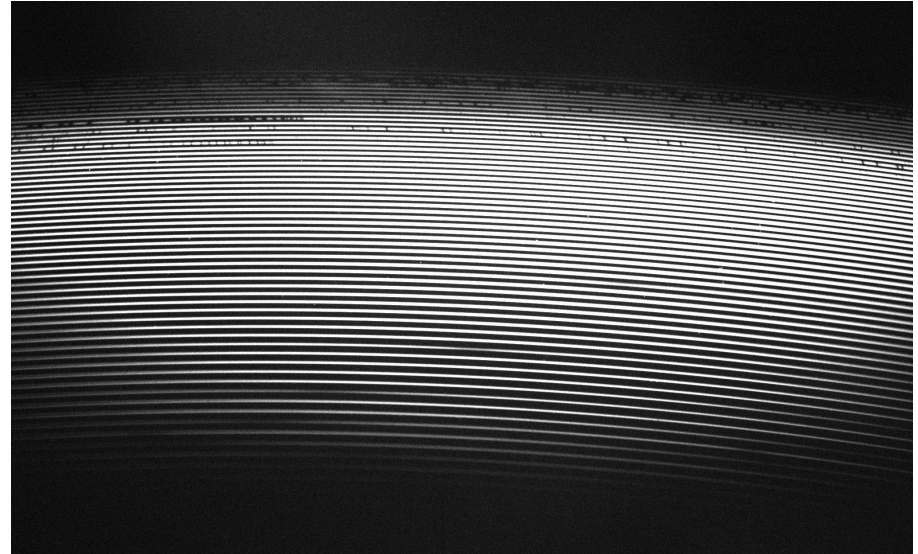
No.	Night	Spectra	Exposure time (s)	Template	Notes
1	2018-03-21	2	1800	1	
2	2018-03-25	1	600	1	
3	2018-04-11	1	1800	1	
4	2018-04-14	1	1800	1	
5	2018-04-17	1	1800	1	
6	2018-04-18	1	1800	1	
7	2018-05-18	3	1800	2	
8	2018-05-19	3	1800	2	
9	2018-05-26	2	1800	2	
10	2018-05-28	4	1800	2	
11	2018-05-30	4	1800	2	
12	2018-07-14	7	600	3	
13	2018-07-15	2	600	3	
14	2018-07-18	2	1200	3	
15	2018-07-19	24	600	3	transit campaign
16	2018-07-20	4	600	3	
17	2018-07-26	16	600	3	transit campaign
18	2018-08-03	3	600	3	
19	2018-08-16	16	600	4	transit campaign
20	2018-08-17	17	600	4	
21	2018-08-20	13	600	4	
22	2018-08-26	16	600	4	transit campaign
23	2018-08-29	16	600	4	
24	2018-09-04	6	600	4	
25	2018-10-11	6	600	5	
26	2018-10-17	6	600	5	
27	2018-10-18	6	600	5	
28	2018-10-21	28	600	5	transit campaign

Echelle Spectra of MASCARA-2

Raw spectrum

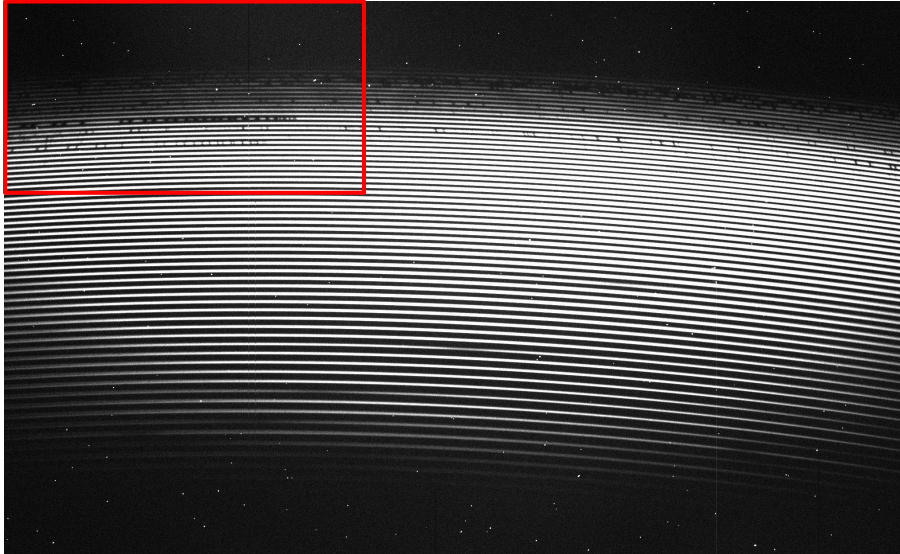


Clear spectrum

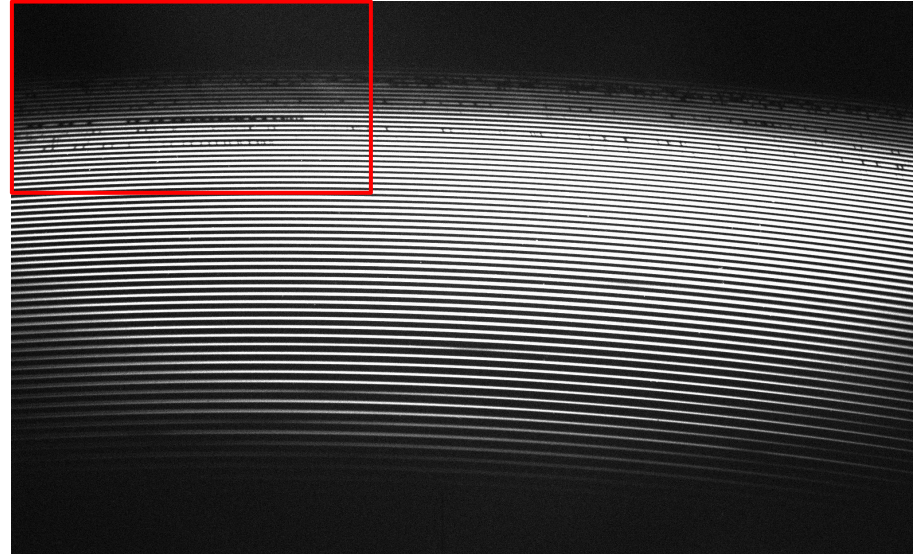


Echelle Spectra of MASCARA-2

Raw spectrum

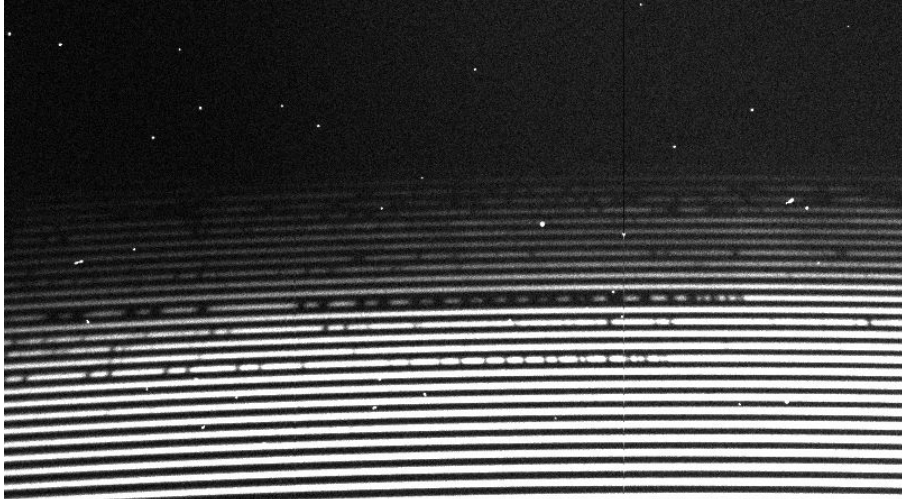


Clear spectrum

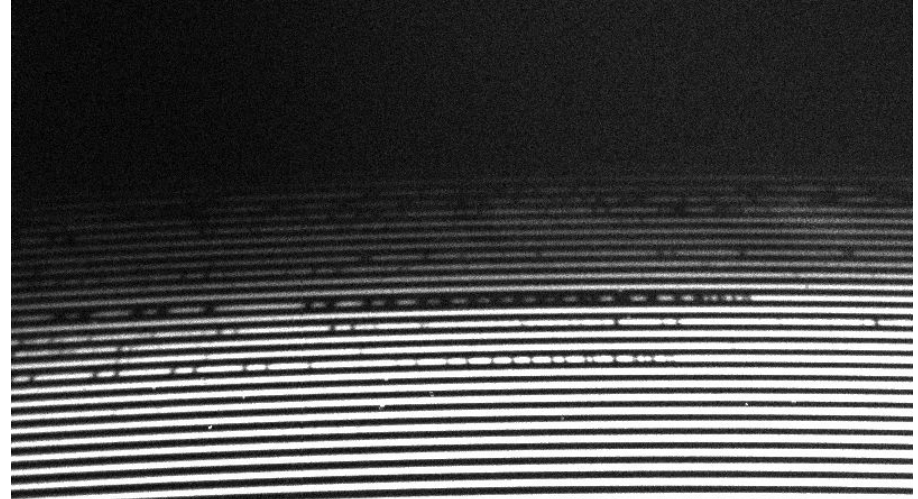


Echelle Spectra of MASCARA-2

Raw spectrum

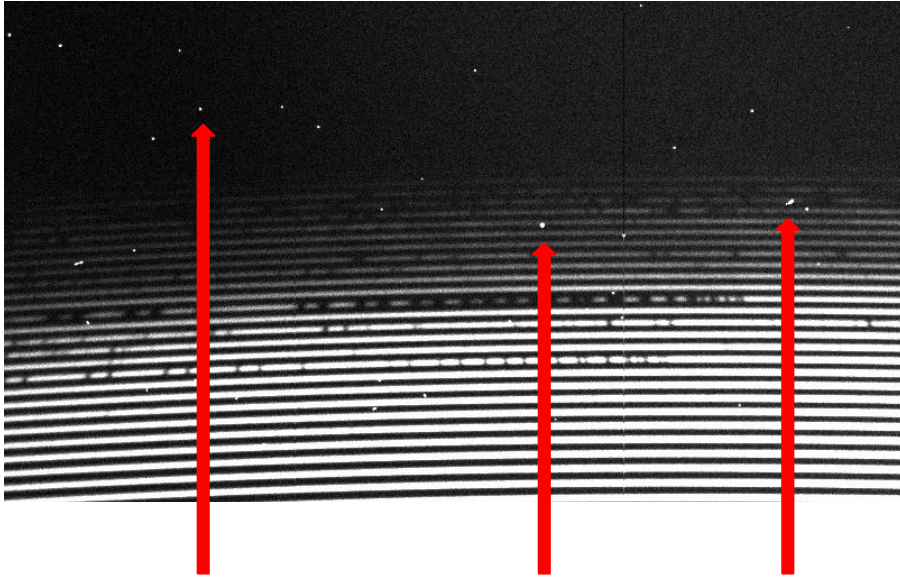


Clear spectrum



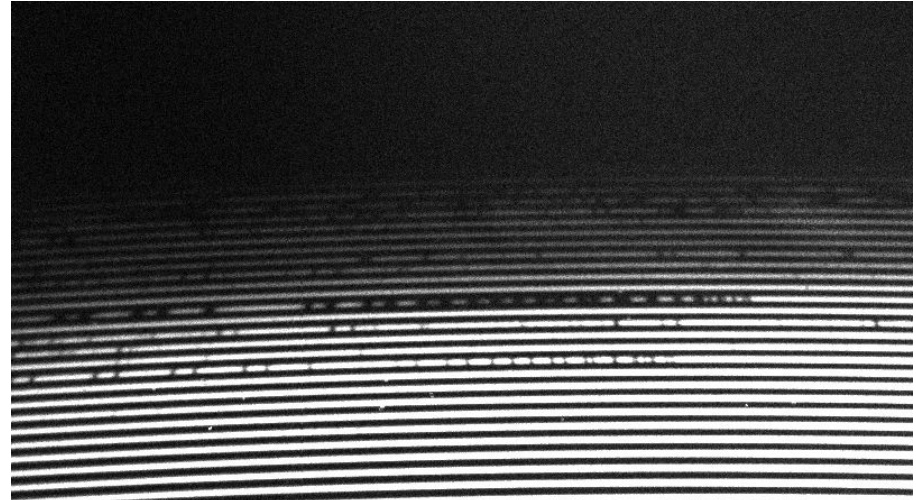
Echelle Spectra of MASCARA-2

Raw spectrum



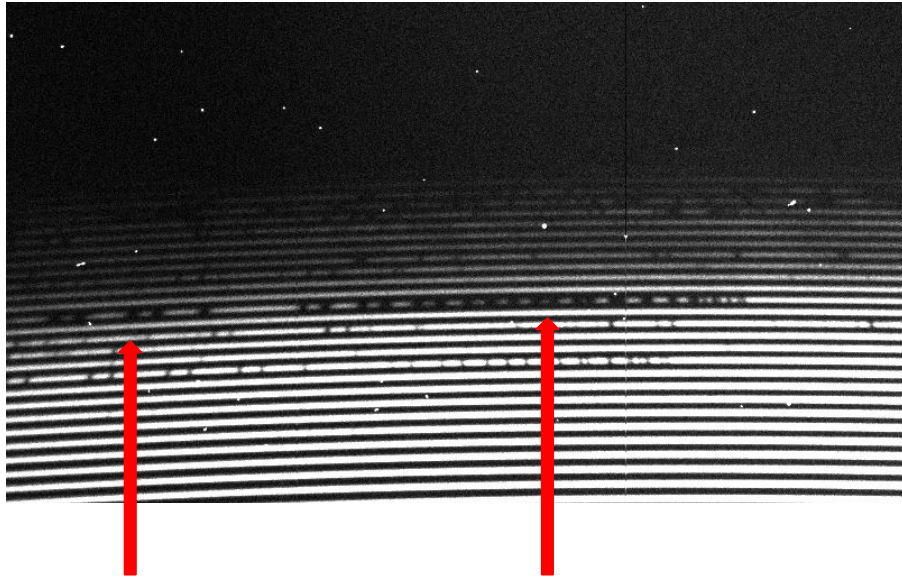
Cosmic rays to be removed from the spectrum

Clear spectrum



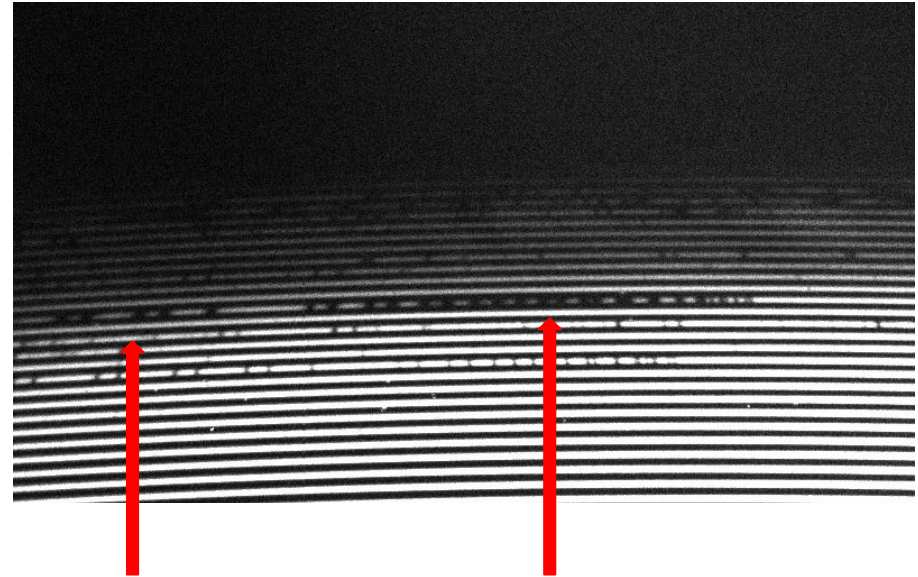
Echelle Spectra of MASCARA-2

Raw spectrum



Telluric lines

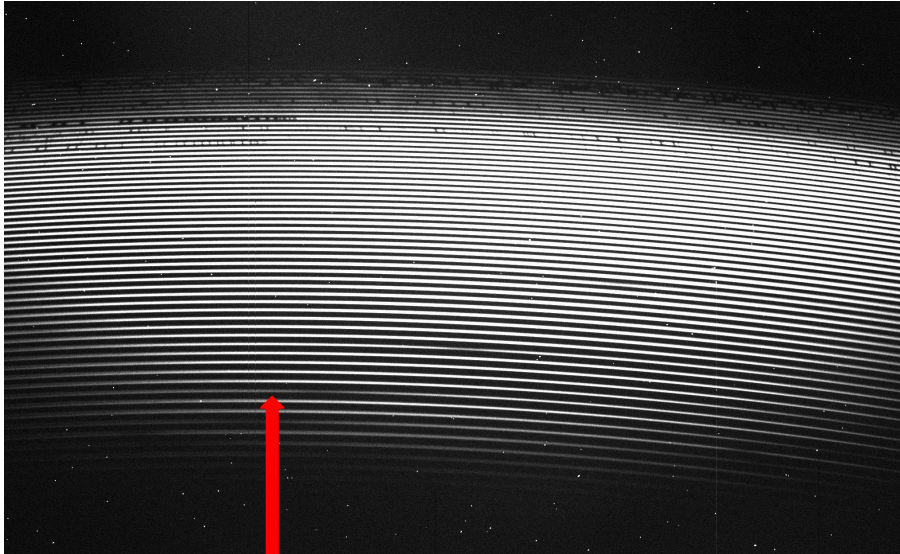
Clear spectrum



Telluric lines

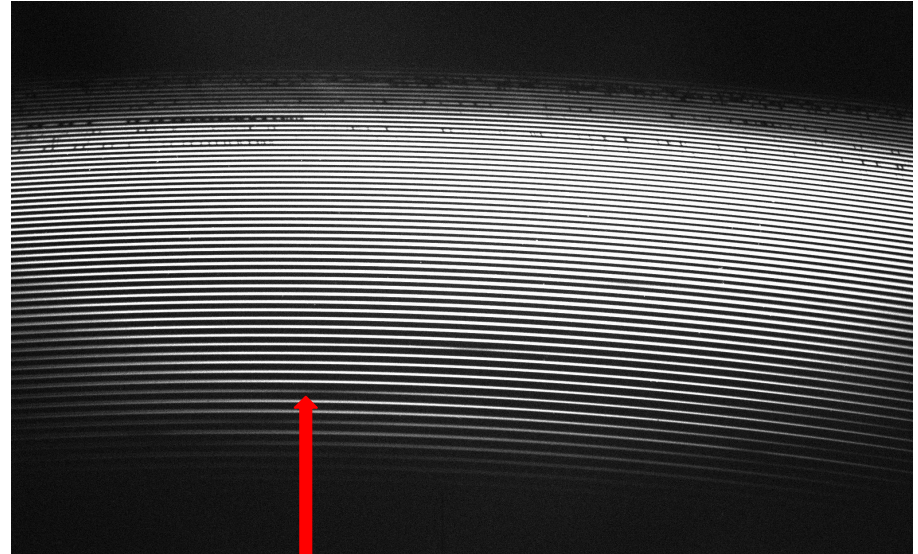
Echelle Spectra of MASCARA-2

Raw spectrum



Balmer line

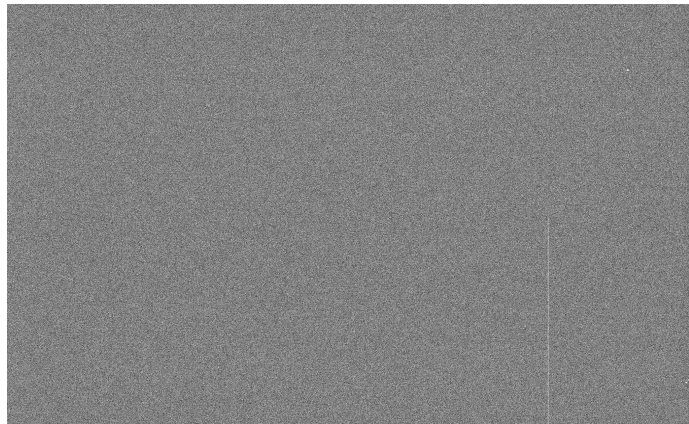
Clear spectrum



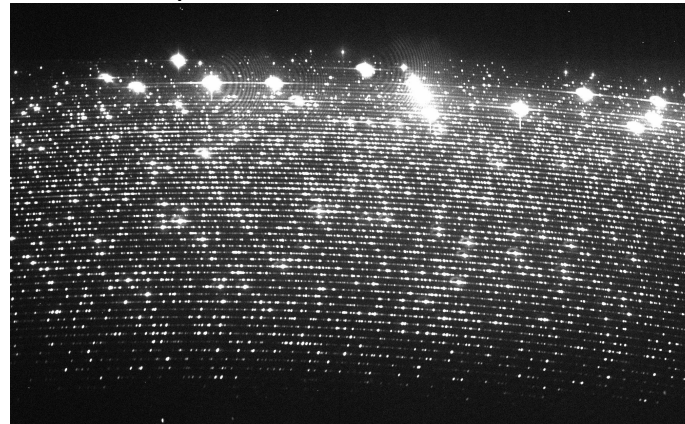
Balmer line

Correction and Calibration Frames

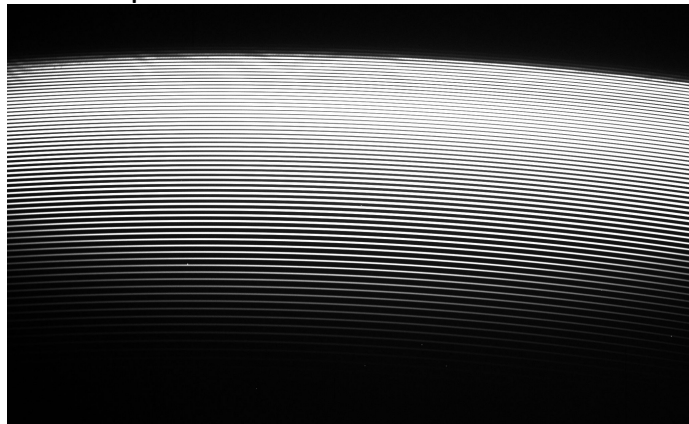
Bias correction frame



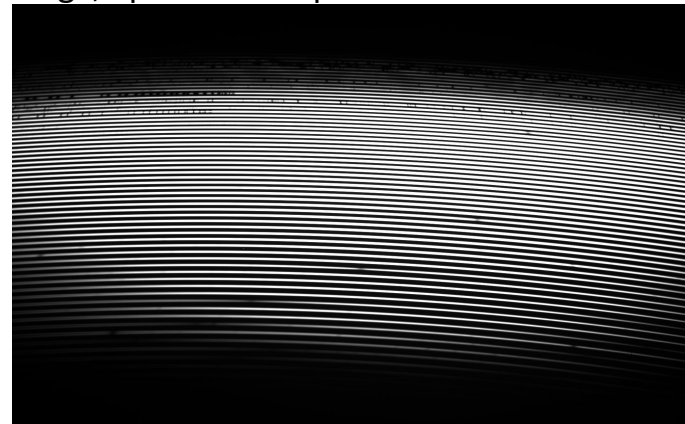
Th-Ar comparison frame



Flat lamp correction frame

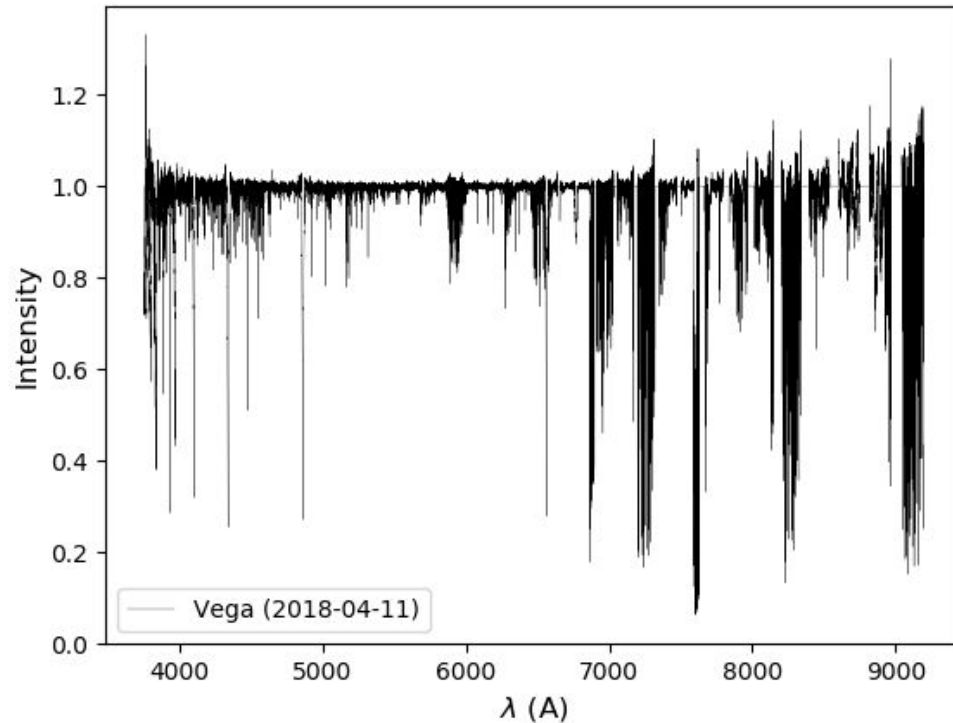


Vega, aperture template frame



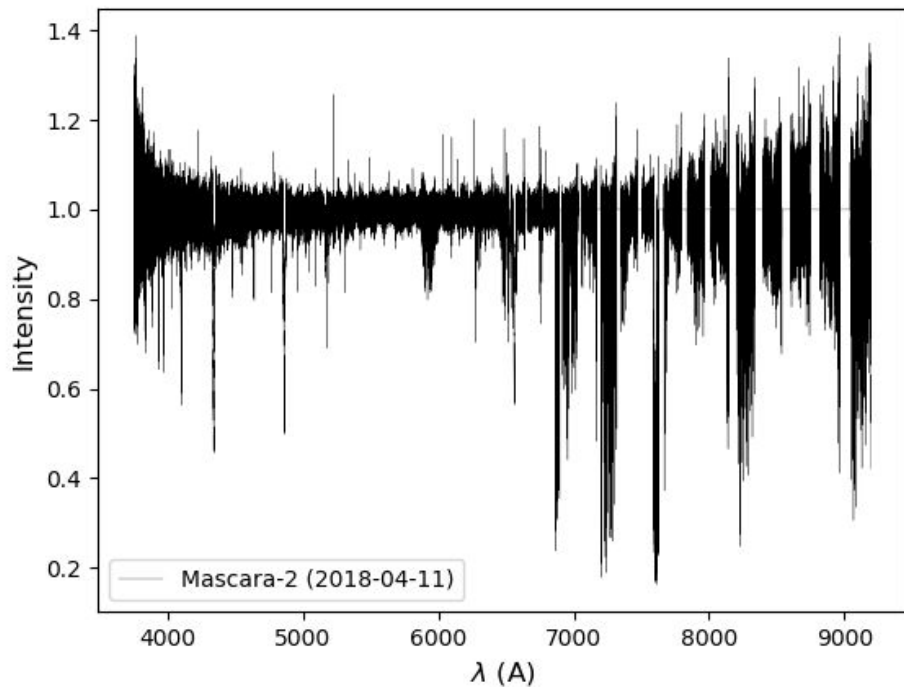
1. Image reduction
2. Spectra identification
3. Radial velocity determination
 - a. Telluric lines correction
 - b. Heliocentric correction
 - c. Cross-correlation

Vega (2018-04-11), exposure 120 sec

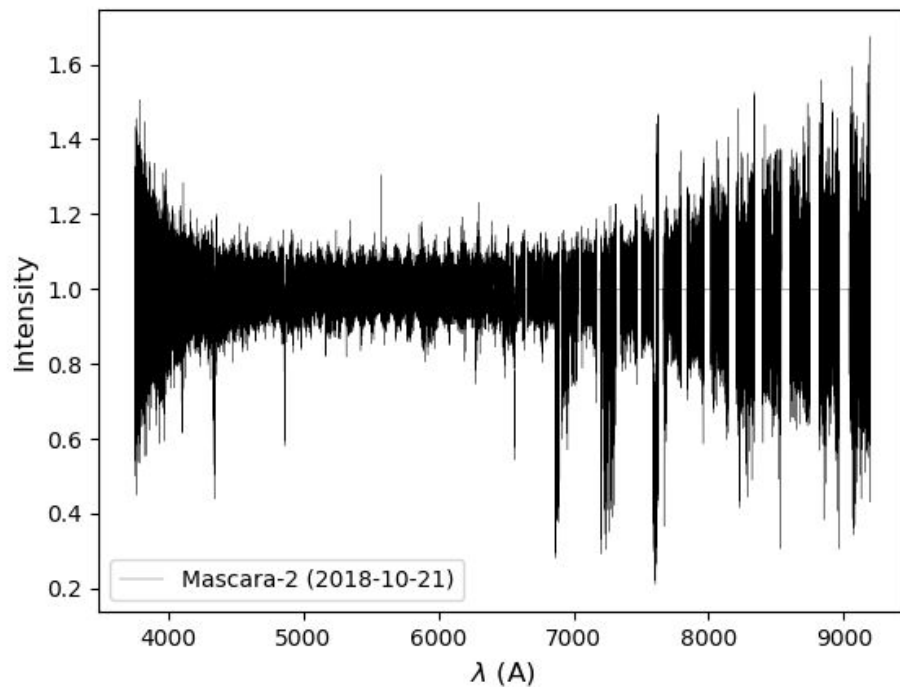


Final Spectra of MASCARA-2

MASCARA-2 (2018-04-11), exposure 1800 sec



MASCARA-2 (2018-10-21), exposure 600 sec



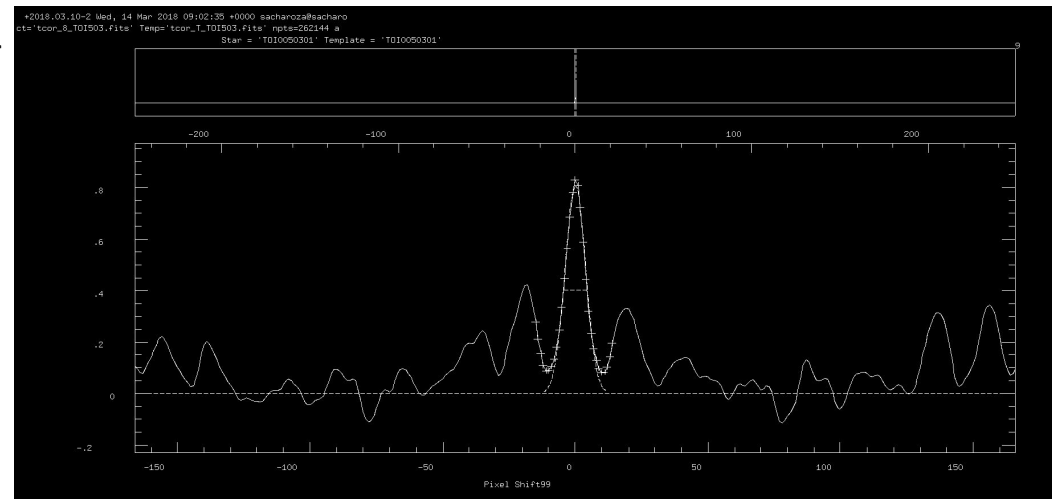
- For cross-correlation a **template spectrum** is chosen (with the best SNR)
- RVs are determined relatively to the template spectrum
- Region of **4900 - 6300 Å** is used (minimal number of telluric lines and significant spectral lines e.g. H β line etc.)
- This region is divided into **10 overlapping intervals of 500 Å** (for better precision and elimination of the deviations)
- The final RV of the spectrum is calculated as an average of RVs obtained from these intervals
- Gained precision is **~ 0.3 km/s** per when SNR is approximately 35

$$s = \frac{1}{\sqrt{N}} \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2}$$

The errors are calculated as the standard deviations of final RVs divided by the square root of number of the intervals

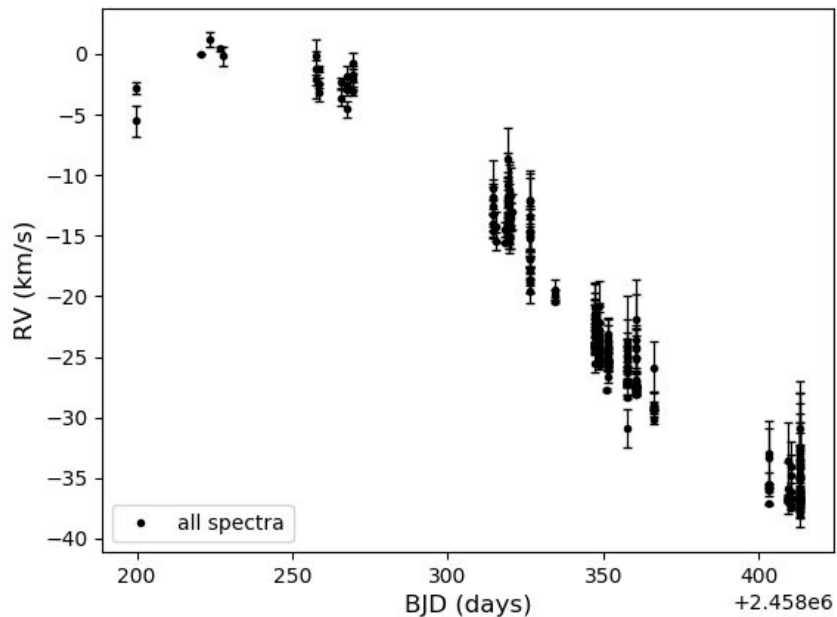
Cross-correlation in IRAF (fxcor task)

Gauss function is used to fit of the highest peak, its mean value corresponds to the shift of spectra

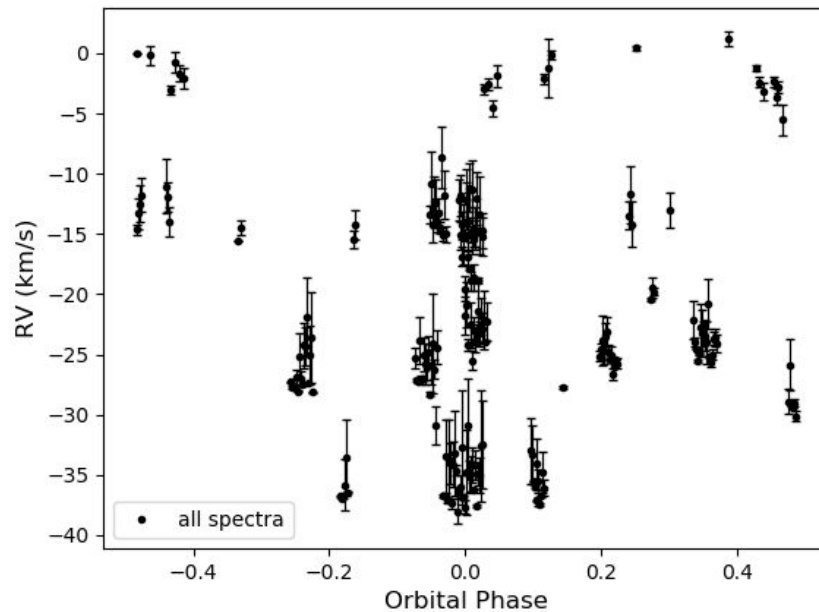


Results - RV Curve

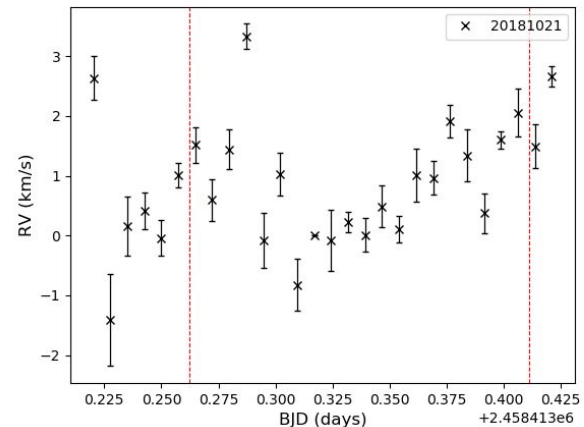
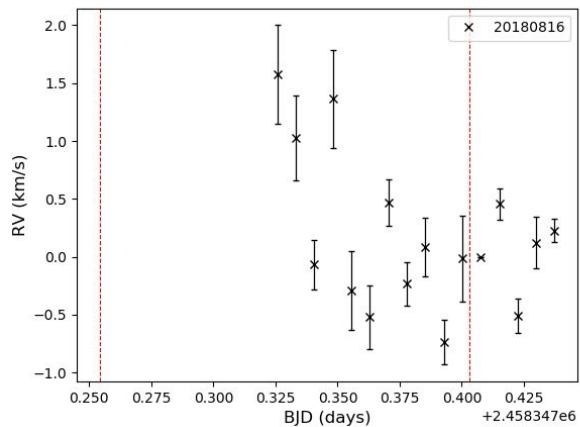
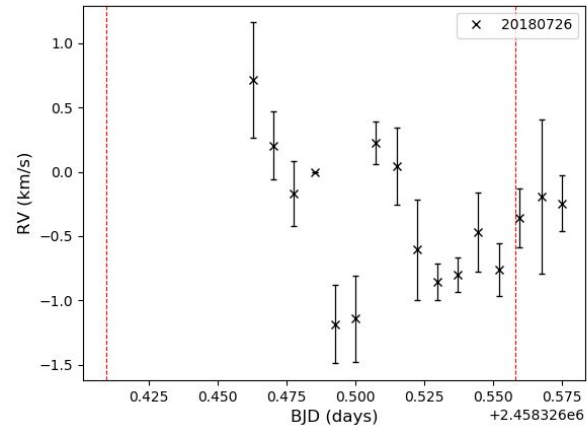
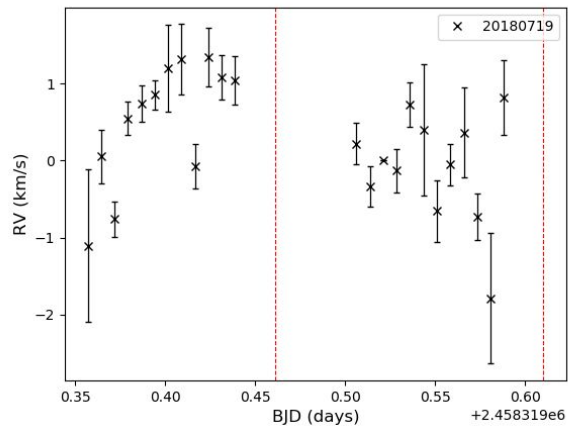
Change of RVs in time



Phase diagram of MASCARA-2b

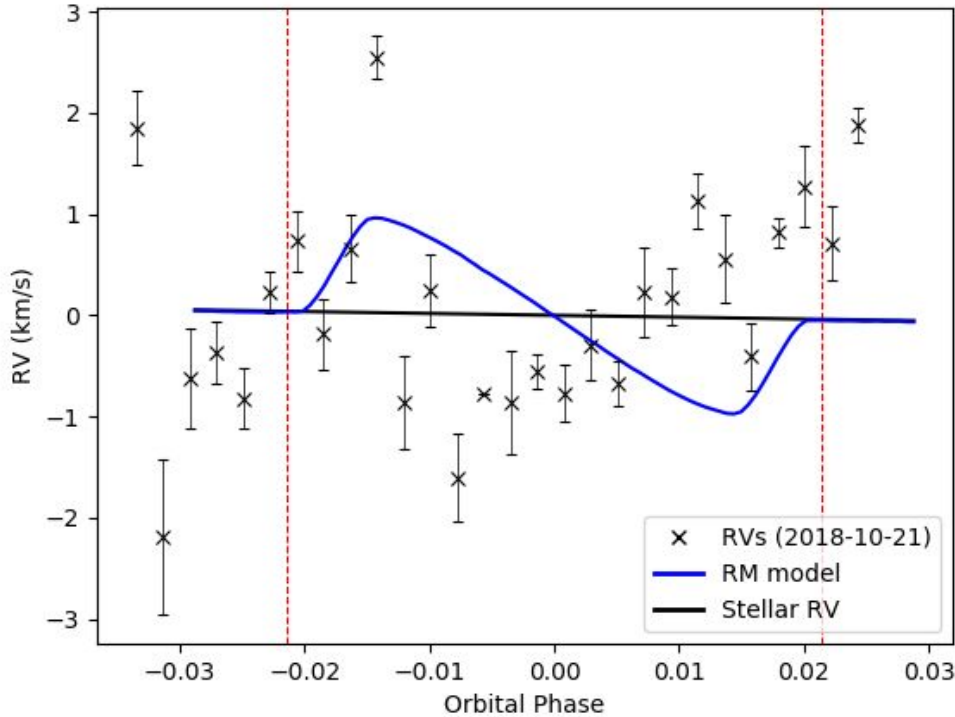


Results - Transit Nights



Red lines indicate begin and end of the transit

Results - RV spectroscopy - RM Effect



Indication of variations in RVs
(data from 2018-10-21)

Red lines indicate begin and end of the transit

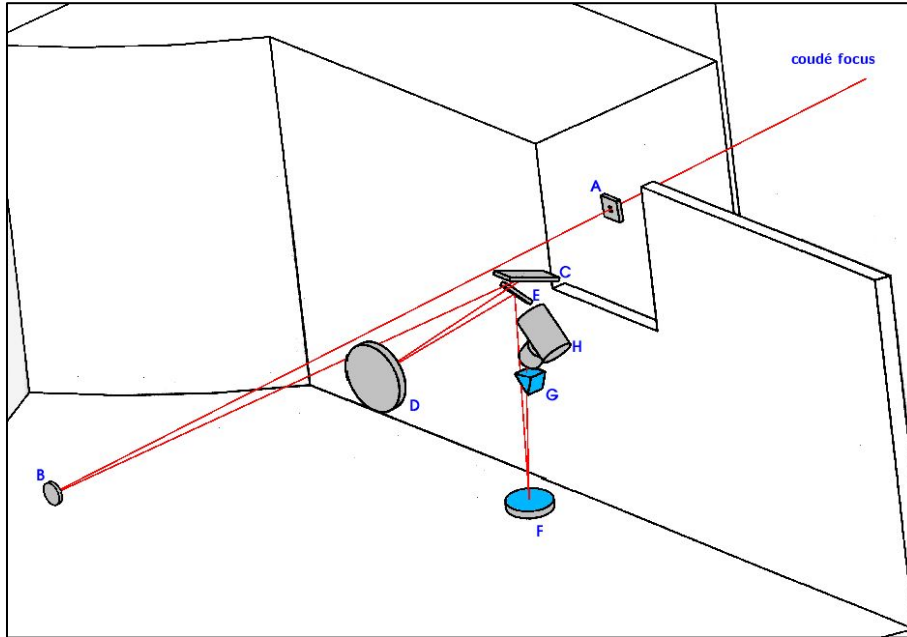
- **Follow-up observations of MASCARA-2**
 - 211 spectra of MASCARA-2 from 28 different
 - 5 full-night observing campaigns of MASCARA-2b transits
- **Processing and analysis of the acquired data**
 - The semi-automatic scripts created for data processing
 - 1D normalized spectra of MASCARA-2 obtained
 - Radial velocities determined
- **Analysis of the radial velocities for long term observations**
 - Hypothesis for the cause of RV shift in time
- **Analysis of the full-night transit observations**
 - An indication of the variations in RVs during the transit
 - For the confirmation of Rossiter-McLaughlin effect more thorough analysis is needed
- **Limits of the 2m Perek telescope with OES Spectrograph were studied**
 - Adjustments of the observation strategy for better SNR
 - Use of the different exposure times for the RM effect detection / long term RV analysis



- [1] HD 185603. [online] SIMBAD, Centre de données astronomiques de Strasbourg. Retrieved 2019-05-02 from <http://simbad.u-strasbg.fr/simbad/sim-id?protocol=html&Ident=HD%20185603>
- [2] Lund M.B., Rodriguez J.E., Zhou G., et al. (2017): KELT-20b: A giant planet with a period of $P \sim 3.5$ days transiting $V \sim 7.6$ early A star HD 185603. AJ 154, 194
- [3] Talens G.J.J., Justesen A.B., Albrecht S., et al. (2018): MASCARA-2b A hot Jupiter transiting the $m V = 7.6$ A-star HD 185603. A&A 612, A57
- [4] Marcy G.W., Butler R.P., Williams E., et al. (1997): The planet around 51 Pegasi. ApJ 481, 926–935

Thank you for your attention.
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The Instrumentation - OES Spectrograph



Scheme of the OES: A the slit, B first collimator, C echelle grating, D parabolic mirror, E small flat mirror, F secondary colimator, G crossdisperser, H camera with the CCD chip (Source: Šlechta, Stellar department of AI CAV)

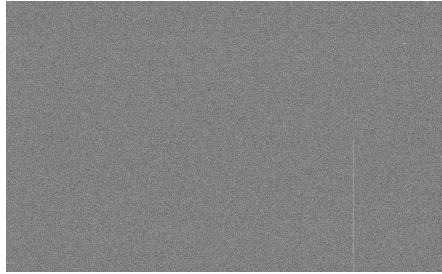
Echelle grating, crossdisperser and the detector



Spectrograph specification

Spectral range:	360-950 nm
Echelle grating:	54.5 g/mm
Spectral resolution:	50,000 (500 nm)
Blaze angle:	69°
Limiting magnitude:	13 Vmag

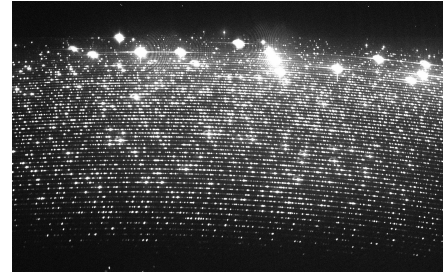
Correction and Calibration Frames



Bias correction frame

raw image (2018-04-11)
exposure time 0 seconds

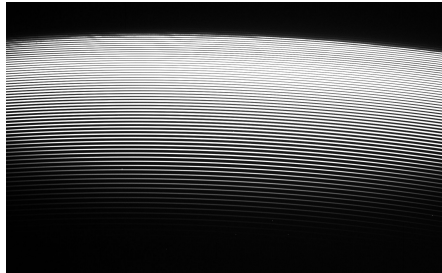
Bias frames are used for removing of the readout signal detected from the camera sensor. A median image of 10 images is used.



Th-Ar comparison frame

raw image (2018-04-11)
exposure time 140 seconds

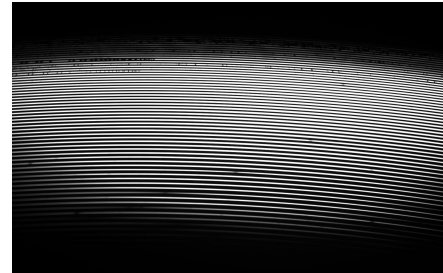
Images of Thorium-Argon comparison spectrum are used for identification of spectral lines in the star spectra. Th-Ar lamp is used as the light source (its spectrum is known with high accuracy). From series of 5-6 images only the last (the best) image is used.



Flat lamp correction frame

raw image (2018-04-11)
exposure time 40 seconds

Flat lamp images are used for correction of different pixel sensitivity of the camera sensor and the imperfections in the optical path of the light. A median image of 10 images is used.

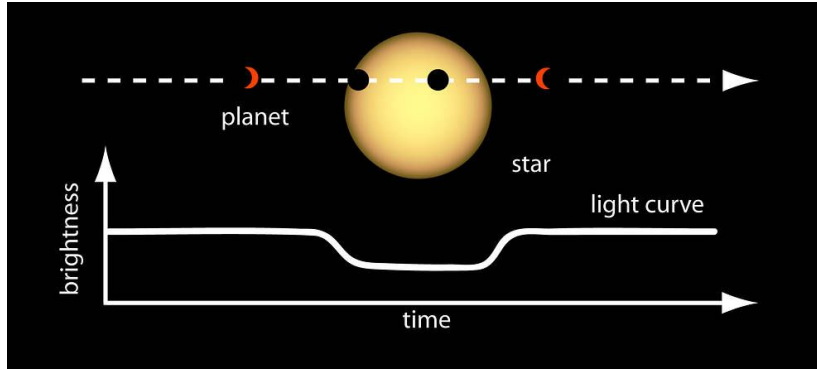


Vega (alp Lyr), aperture template frame

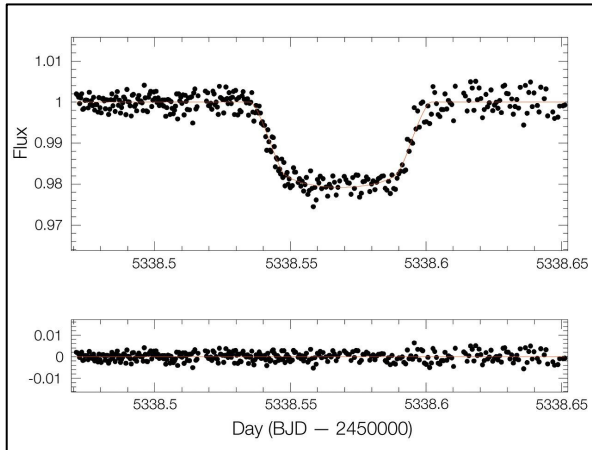
raw image (2018-04-11)
exposure time 120 seconds

Usually, it is a bright star with the light intensity high on a wide spectral range. Each night 2 spectra are taken with exposure times 30 - 120 seconds depending on the weather conditions.

Transit Photometry



Credits: NASA Ames



Light curve of WASP-19b

Credits: TRAPPIST/M. Gillon/ESO

Semi-major axis

$$a^3 = \frac{GM_*}{4\pi} P^2$$

Luminosity drop

$$\frac{\Delta L}{L_*} \simeq \left(\frac{R_p}{R_*} \right)^2 = \delta$$

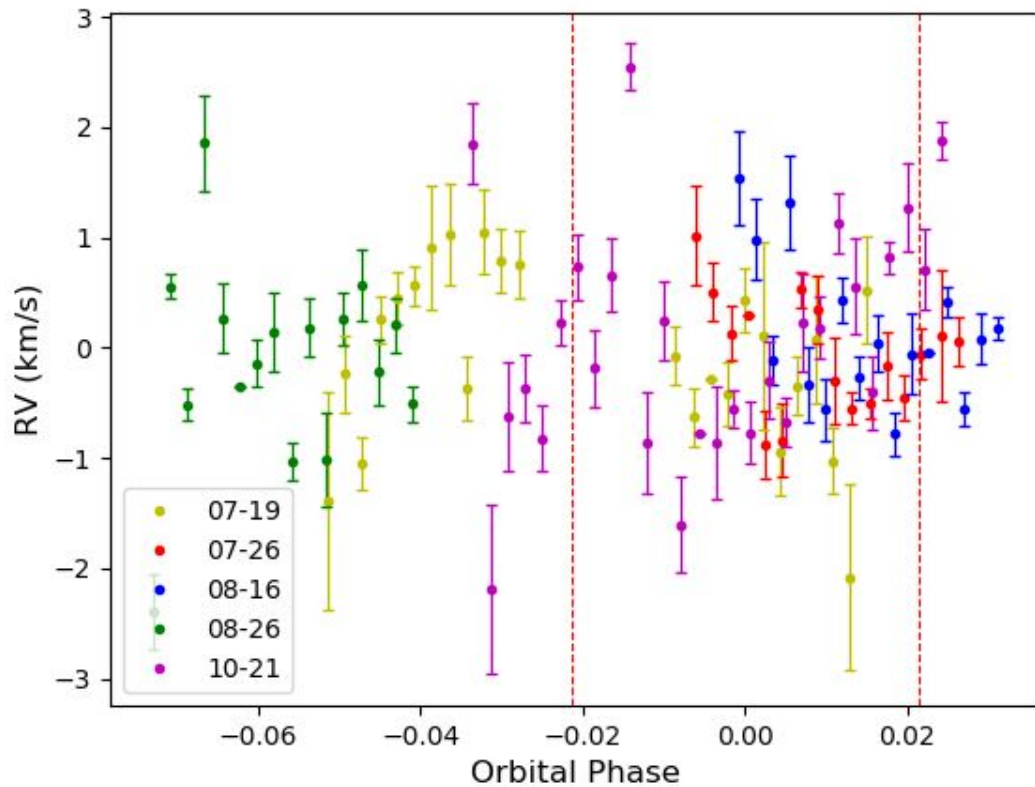
Transit duration

$$\tau = \frac{P}{\pi} \left(\frac{R_* \cos d + R_p}{a} \right)$$

Orbital inclination

$$\cos i = \frac{R_* \sin d}{a}$$

MASCARA-2b - Combined Transit Nights



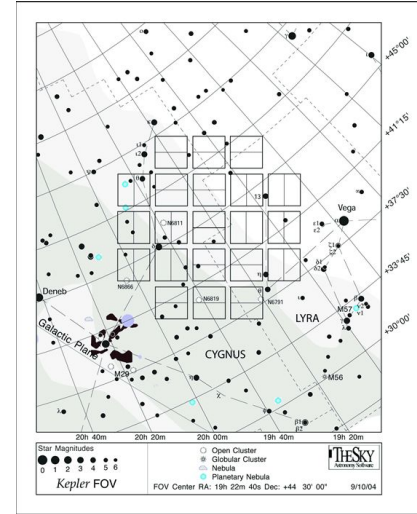
Introduction - Space Telescopes



Credits: CNES / D. Ducros

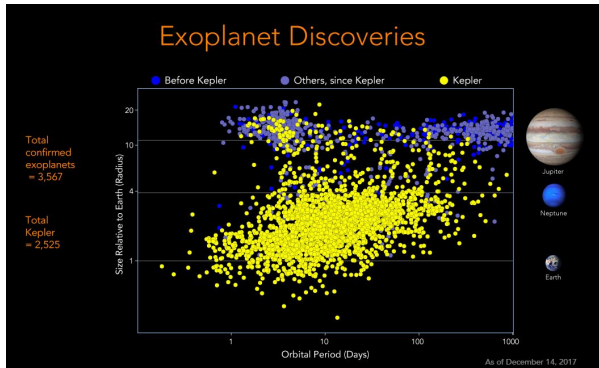


Credits: NASA Ames, T. Trower



Kepler specification

- Kepler Mission: May 2009 - May 2013
- K2 Mission: May 2014 - November 2018
- Primary mirror: diameter 0.95m
- Target stars: In sum more than 500,000



Source: NASA/Ames Research Center/J. Dotson, W. Stenzel
As of December 14, 2017