HARPS
The Exoplanet Finder on La Silla

Florian Rodler (ESO)
HARPS = High Accuracy Radial velocity Planet Searcher

on the La Silla 3.6m telescope
Measure: **stellar absorption lines**!

They shift in the line of sight as the star wobbles due to gravitational pull of the unseen planet.
Finding exoplanets with the Radial Velocity technique

Doppler effect:  \( \nu_{\text{rad}} = c \, \frac{\Delta \lambda}{\lambda} \)

380 nm \( \rightarrow \) wavelength \( \lambda \) \( \rightarrow \) 700 nm
Solar spectrum on the detector of an Echelle spectrograph
(Courtesy Harvard-Smithsonian CfA)
Finding planets with the Radial Velocity technique

Zoom further in ...

571 nm

wavelength $\lambda$

572 nm

Florian Rodler - ESO La Silla Observing School
Try to detect Jupiter around the Sun:

i.e. an object of 318 Earth masses
with an orbital period of 11.9 yr
and causing a stellar RV variation of ±12.4 m/s
(a shift in \( \lambda \) of 0.000023 nm at 550 nm)
Requirements for such a spectrograph:

- very high **spectral resolving power** \( (R = \lambda/\Delta \lambda > 50 \, 000) \)

- very high **instrumental stability** over many years
  (error in RV \( \sim 1 \, \text{m/s} \) ... \( \sim 1/100 \) of a pixel ... over 10 years)
Finding planets with the Radial Velocity technique

Requirements for such a spectrograph:

- very high spectral resolving power \( R = \lambda / \Delta \lambda > 50 000 \)

- very high instrumental stability over many years
\( \text{error in RV} \sim 1 \text{ m/s} ... \sim 1/100 \) of a pixel ... over 10 years

Always know your instrument!
Think of possible error sources!

\( \text{(Murphy’s law applies: your nice planet signal just might turn out to be instrumental variations)} \)
Requirements for such a spectrograph:

- very high **spectral resolving power** \((R = \lambda/\Delta\lambda > 50\,000)\)

- very high **instrumental stability** over many years
  (error in RV \(\sim 1\) m/s ... \(\sim 1/100\) of a pixel ... over 10 years)

How to achieve such a stability?
What possible error sources do you see?
Finding planets with the Radial Velocity technique

Very high instrumental stability:

- **simultaneous wavelength calibration**

- **no moving parts** in the spectrograph, fixed spectral format, spectrograph not moving

- **in vacuum** (P and T stabilized)
- **build by a consortium led by Geneva Observatory**
- **commissioned in 2003**

- **wavelength range: 381 - 691 nm;**
  
  fixed spectral format, 72 orders,
  simultaneous wave calibration

- **spectral resolving power: 115,000** in HAM mode
  80,000 in EGGS mode

- Spectrograph in Coudé-room, connected via fibers to 3.6m telescope
- Pressure stability: $<10^{-3}$ mbar
- Temperature stability: 1 mK / day
Telescope

Guiding system
Calibration lamps (ThAr, Tun)
Fabry-Perot
Laser Frequency Comb

Spectrograph

Fibers A+B

Florian Rodler - ESO La Silla Observing School
Florian Rodler - ESO La Silla Observing School

HARPS

star

sky, wave calib

A

B

2'

Fibers A+B

Spectrograph
The Concept of Echelle Spectrograph

- **Fiber A**
- **X-Disperser**
- **Grating**
- **Detector (2x 2x4k)**

- Spectrum produced by grating
- Spectrum produced by X-Disp
Daily Calibrations (afternoon before the observations!)

Two long-term absolute wavelength references (only used during afternoon to preserve lifetime):
- ThAr lamp 1
- Laser Frequency comb
**Daily Calibrations (afternoon before the observations!)

Two long-term absolute wavelength references (only used during afternoon to preserve lifetime):
- ThAr lamp 1
- Laser Frequency comb

They are used to calibrate the nightly simultaneous wavelength reference:
- ThAr lamp 2
- Fabry-Perot (has a drift of <0.1 m/s per night)
Observing modes:

**HAM:** High accuracy mode,
R~115,000
RV precision 1 m/s, 1” fibers A+B
For faint targets (V>12) no simultaneous wave calib!

**EGGS:** High efficiency mode (faint targets),
R~80,000
RV precision 3 m/s, 1.4” fibers A+B

**Polarimetry:** 1” fibers A+B
Example: HAM mode, 240 sec, 1” seeing, X=1.1:

**HR810** (V=5.4 mag, G0V)
Observing with HARPS

Reduction Information Window

Information returned by Reduction Recipes

Flux correction not performed: no flux template available
Correlation fiber B: C=28.7[%] RV=14.27381[km/s] FWHM=1.6037[km/s]
On fiber B estimated RV accuracy on spectrum: 10.47[m/s]
On fiber B estimated RV accuracy on CCF : 144.30[m/s]
Recipe obj_TWO_harps is terminated

INSTRUMENT MODE: HARPS
Now processing Image TYPE: STAR,SKY,M1 with obj_TWO_harps recipe
OB target name:

Raw Frames

/data/raw/2019-09-30

HARPS.2019-10-01T00:20:36.984.fits : G, (STAR,SKY,M2
HARPS.2019-10-01T02:17:12.923.fits : G, (STAR,SKY,M1
HARPS.2019-10-01T02:36:04.394.fits : G, (STAR,SKY,M2
HARPS.2019-10-01T03:22:26.843.fits : TC, (STAR,SKY,M1
HARPS.2019-10-01T04:28:26.008.fits : G, T3 (STAR,SKY,M1
HARPS.2019-10-01T07:51:45.653.fits : TC, (STAR,SKY,M0
HARPS.2019-10-01T08:24:38.151.fits : G, (STAR,SKY,M2
HARPS.2019-10-01T08:58:21.730.fits : TC, (STAR,SKY,M0

Average CCF normalized with TPL= M2
C=24.2% RV=7.47443 km/s FWHM=3.0800 km/s
HARPS Pipeline (DRS)

- **standard steps:** bias, flat-field, cosmic-rays correction

- **extraction of spectral orders** from frame + **wavelength solution**

- **cross-correlation** with suitable reference mask (G2, K5, M2) to calculate radial velocity of target. Barycentric correction.

- Bi-sector analysis of stellar line-profile (star spots?)
- **cross-correlation** with suitable reference mask (G2, K5, M2) to calculate radial velocity of target.
Result: cross-correlation function (CCF):

\[ v_{\text{rad}} = c \frac{\Delta \lambda}{\lambda} \]

\[ C(v) = \frac{\sum_k (M_k(v)O_k)}{\sqrt{\sum_k M_k(v)^2 \sum_k O_k^2}} \]
Raw science frame:
/data/raw/<date>/HARPS*.fits

Reduced data products:
/data/reduced/<date>/

HARPS*_ccf_G2_A.fits ..... CCF
HARPS*_ccf_G2_A.tbl ..... extracted RV per spectral order (72 orders)
HARPS*_e2ds_A.fits ....... extracted spectrum, per order, fiber A
HARPS*_s1d_A.fits .......... extracted and merged spectrum, fiber A
HARPS*_bis_G2_A.fits ..... bi-sector analysis
HARPS*_INT_GUIDE.fits ... integrated image of the guide camera
OUTLOOK: HARPSP+NIRPS

HARPS

$\lambda = 381-691 \text{ nm}$
$R \sim 115,000$, 1 m/s
$80,000$

NIRPS

$\lambda = 970-1810 \text{ nm}$
$R \sim 100,000$, 1 m/s
$80,000$

+ 

Simultaneous operations (2021)!