The Role of Radial Velocities in the Quest for New Earths

Stéphane Udry
Geneva Observatory, Geneva University
Motivation and requirements

- scientific and technical

Challenges

- technical (stability, telescope, detector)
- astrophysical (star, dynamics)
- data analysis (aliases, interpretation)

On-going and developing facilities

- HARPS, HARPS-N, ESPRESSO, ...

Synergies with other methods

- transit (TESS, CHEOPS)
Mass distribution

Size distribution

M2sini distribution (complete sample)

HARPS+Coralie
Mayor et al. 2011

corrected
observed

# planets

0
100
200

M2sini [Earth Mass]

Howard 2013
Mayor et al. 2011

HARPS+Coralie

0.15
0.10
0.05

0.15
0.10
0.05

A

Size

Neptune
3.8 Earth radii

Earth

Jupiter
11.2 Earth radii

Kepler
Howard 2013

Kepler
Howard 2013

Planet size (relative to Earth)

1.0
1.4
2.0
2.8
4.0
5.7
8.0
11.3
16.0
22.6
We need the mass $\leq$
Planetary mass - 1st basic aspect

RV Amplitude 10cm/s for Earth analog

<table>
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<tr>
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<th>RV Amp. (m/s)</th>
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<tbody>
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Radial velocity: photon starving

![Graph showing relationship between telescope diameter and star magnitude]
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Radial velocity: photon starving
Higher RV precision = .... ????

Earth effect on the Sun = 9 cm/s
Higher RV precision = .... ????

Earth effect on the Sun = 9 cm/s

Earth atmosphere \hspace{1cm} \text{interstellar medium}

\Rightarrow \text{Need to control EVERYTHING from the star to the detector (both included)}
Higher RV precision = .... ????

Earth effect on the Sun = 9 cm/s

=> Need to control EVERYTHING from the star to the detector (both included)
Higher RV precision = .... ????

Earth effect on the Sun = 9 cm/s

Earth atmosphere               interstellar medium

=> Need to control EVERYTHING
from the star to the detector (both included)

Challenges:
- Technical aspects: telescope, fibers, detector
- Astrophysics: star, atmosphere, system dynamics
- Observational aspects: coordinates, contamination, ...
- Data analysis: alias, confidence level, ...
Instrumental effects

I) Instrumental error
   - stability and repeatability

Instrumental stability

Astroclimatic

T variation

P variation

Variation of refractive index

Unstable

Telescope Guiding

Focus

Seeing

Affect the spectrum location on CCD

Wavelength drift

PSF change
Instrumental effects

1) Instrumental error
   - stability and repeatability
   - calibration and wavelength solution
**HARPS**: stability $< 1$ m/s

$\Delta RV = 1$ m/s

$\Delta \lambda = 0.00001$ Å

15 nm

1/10000 pixel

Thorium simultaneous calibration

2-fiber fed

$\Delta RV = 1$ m/s

$\Delta T = 0.01$ K

$\Delta p = 0.01$ mBar

Pressure controlled

Temperature controlled

- Observatoire de Genève
- Physikalisches Institut, Bern
- Observatoire Haute-Provence
- Service d’Aéronomie, Paris
- ESO
Instrumental effects

1) Instrumental error
   - stability and repeatability
   - calibration and wavelength solution

Replace ThAr lamp by laser comb or Fabry-Perot

Steinmetz et al. 2008
Instrumental effects

1) Instrumental error
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   - calibration and wavelength solution

Steinmetz et al. 2008
FPCS Spectrum with HARPS

Allows to check for pixel regular spacing/size

=> possibly responsible for 1-year signals

Wildi, Pepe, Chazelas 2011
Instrumental effects

1) Instrumental error
   - stability and repeatability
   - calibration and wavelength solution
   - Optimum guiding, centering
   - Uniform illumination of the spectrograph

minimize photocenter effect
   • importance of using fibers
   • additional scramblers
   • => octagonal fibers
Illustration of the improved scrambling by octagonal optical fibres.

An extreme example: Sophie spectrograph (OHP)
Fibre diameter 3 arcsecs!

...telescope focus, bad guiding, variable seeing

>>> normal fibres
RMS 7.8 m/s

octagonal fibres
RMS 1.2 m/s

Perruchot et al. 2011, SPIE
HARPS-N
HARPS-N

Consortium

Geneva Observatory (Head),
CfA, Harvard University.
INAF-TNG,
University of St. Andrews,
University of Edinburgh,
Queens University Belfast
HARPS-N

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Queens University Belfast
The HARPS-N LFC

David Phillips
CfA
The HARPS-N LFC

David Phillips
CfA
The first season of the HARPS-N programs

- Start: summer 2012
  - still "young"
  - Precision: ~1 m/s

- GTO: 80 nights/yr
  - kepler candidate FU
  - Rocky Planet Search

- RPS GTO Survey
  - ~40 stars
  - very precise observations
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\[ \text{rms} = 1.2 \text{ m/s} \]
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Overview of the RPS HARPS-N GTO program

Number of measurements (nightly averaged)

RMS [m/s]

N

0 1 2 3 4 5 6 7 8

0 1 2 3 4 5 6
Overview of the RPS HARPS-N GTO Program

![Graphs showing the distribution of measurements and RV dispersion](image)

- **Numbers**
  - Distribution of measurements (nightly averaged)
  - RMS distribution

- **HARPS-south**
  - Number of nights: 16
ESPRESSO on ESO VLT

«Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations»

- Ultra-stable spectrograph for the VLT
- R=120’000
- Calibration: laser comb
- visible: blue + red arms
- can use any of the UTs (coudé train)

- Consortium: CH, Italy, Portugal, Spain
- FDR: passed last week
- On the sky: 2016

- Precision in RV: < 10 cm/s
- Goal: Very low-mass planets

- Sample: 50-100 quiet dwarfs
- GTO: 200 nights
- Expected: 25-50 planets
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**ESPERESSO on ESO VLT**

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Stellar intrinsic limitations
Stellar effects

1) high-frequency stellar intrinsic variations
   - accoustics modes: a few minute timescale
   - (super-)granulation: timescale up to several hours
Stellar effects

1) high-frequency stellar intrinsic variations
   - acoustics modes: a few minute timescale
   - (super-)granulation: timescale up to several hours

Choice of the target is very important for ultra-high precision
Simulations
- real asteroseismology observations
- noise model => synthetic observations

Beat the stellar limitations with
- good target selection
- clever observational strategy

Dumusque et al. 2010a

strategy
- RV rms

- detection limits
Stellar effects

1) high-frequency stellar intrinsic variations
   - **acoustics modes**: a few minute timescale
   - (super-)granulation: timescale up to several hours

2) “short-period” activity-related variations
   - **spots**: effet over the rotation period of the star
3) effect of realistic spot models: case for $\log(R'_{HK})=-4.9$
Simulations of spot effects on radial velocities

3) effect of realistic spot models: \( \text{case for } \log(R'_{\text{HK}})=-4.9 \)

- 40 days
- 1 m/s
- RV
- 3 yr
- Filling factor: 0.001
- Spot #: \( \sim 90 \)
Simulations of spot effects on radial velocities

3) effect of realistic spot models: case for log(R’HK)=-4.9

Spot #: ~90
Filling factor: 0.001
Spot #: ~90
Filling factor: 0.001
Longer periods => larger possible bins for average => small effect of the period on detection capability
Ultra high-precision radial velocities

...Beat the stellar noise (quiet stars, obs strategy)
...Large collecting area (VLT)
...Ultra-stable spectrograph (ESPRESSO/VLT, 2016)

A 2.5 Earth-mass planet in the HZ of a K star (P=200 days)

(Dumusque et al., 2010b)
HD 69830 >>>>> 0.35 m/s

Log($R'_{HK}$) = -5, Spec type K0V

Over 5 seasons ...
- Residuals as function of the binning on .... days

Lovis et al. 2006
Over 5 seasons …

- Residuals as function of the binning on …. days

Lovis et al. 2006

\( \log(R'_{\text{HK}}) = -5 \), Spec type K0V
HD 85512 b (Pepe et al. 2011)
P = 58.4 days, m₂sini= 3.6 M Earth
185 measurements

Fig. 13. Phase-folded RV data of HD 85512 and fitted Keplerian solution. The dispersion of the residuals is 0.75 m s⁻¹ rms.
MAGNETIC CYCLES

Radial velocity

Activity indicator
Another example

HARPS: ~30% of low-activity stars show magnetic cycles

Importance of diagnostics
Stellar effects

1) high-frequency stellar intrinsic variations
   - acoustics modes: a few minute timescale
   - (super-)granulation: timescale up to several hours

2) “short-period” activity-related variations
   - spots: effect over the rotation period of the star

3) long-term activity-related variations
   - magnetic cycles: several years timescale

Question: low-level stellar intrinsic variation with a 6 month - 1.5 year timescale?
Data analysis challenges => syst. characterisation
(do not forget Dynamics)

1) sampling effects
   - *aliases*: 55 Cnc e is the best example *(Dawson & Fabrycky 2010)*
   - *multi-planet systems*: all periods need to be covered
Data analysis challenges => syst. characterisation (do not forget Dynamics)

1) sampling effects
   - aliases: 55 Cnc e is the best example (Dawson & Fabrycky 2010)
   - multi-planet systems: all periods need to be covered

2) Confidence level
   - different statistical approaches and detection thresholds

![Graph of HD10700 and Tau Ceti](image)

10 years, 375 nights
rms = 1 m/s

Tuomi et al. 2013
5 planets!!!!

=> none with our detection threshold
An Earth-mass planet around Alpha Cen B

Dumusque, et al. 2012 (Nature)

Textbook system with all the previously mentioned effects .... and more
Binary Star

Orbital parameters: Pourbaix et al. 2002

Orbit of Alpha Centauri B
[compared with the orbits of Mars, Jupiter, Saturn, and Uranus]

- Alpha Centauri B
- Proxima Centauri [outside the scale]
- Sun [for comparison]
Binary Star

Orbital parameters: Pourbaix et al. 2002

[Graphs showing RV vs JD and RV vs \phi]

[Graph showing normalized power vs period]
Removing the Magnetic Cycle

Variation from -5 (solar minimum) to -4.85 (solar max) in 40 days !!!
Residuals after removing magn cycle + Binary
+ remove observations polluted by Alpha Cen A
+ granulation noise (error bars)
+ instrumental noise (error bars) \[ \Rightarrow \] 90 cm/s
Corrected RVs

Harmonic filtering of rotation-induced effect: 1.93 m/s -> 1.09 m/s
Harmonic filtering of rotation-induced effect: 1.93 m/s -> 1.09 m/s
Alpha Centauri B b

- $P = 3.236$ days
- $K = 51$ cm/s
- $M_{pl} = 1.1 M_{\text{Earth}}$
Radial velocities in the space-transit era

=> confirmation + mass + non transiting
Radial velocities in the space-transit era

=> confirmation + mass + non transiting

1-2 m/s Instruments
- HARPS/ESO 3.6m
- HIRES/KECK
- HARPS-N/TNG
- SOPHIE/OHP
- HET
- ....

+ TESS (2017)
+ CHEOPS (2017)

- ESPRESSO/VLT
- SPIROU/CFHT
- ....
- Space-based high-precision photometry
- Pointing satellite
- 33 cm on-axis telescope
- Follow-up of known systems
- Bright stars (V=6-12 mag)
- Transit detection down to Earth size planets
- First ESA S-class mission
- Joint Swiss-ESA mission + European partners
- Selection 2012, launch 2017
.... and he will always be welcome in my office, in my house, and in my cellar.