Planetary systems at ESO

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FEET ON THE GROUND  EYES ON THE SKY

60 years
Early days
• Methods of exoplanet detection (1960-1990)

• First exoplanets (indirect) detections
  
  • **Radial velocity** low mass companions to stars:
    
    • 51 Peg b *Mayor & Queloz, 1995*
    
    • Earth-mass planets around a **pulsar** *Wolszczan, 1993*
    
    • **Transiting** planet HD209458 b *Charbonneau et al, 2000*
    
    • **Micro-lensing** event OGLE 2003-BLG-235/MOA 2003-BLG-53 *Bond et al, 2004*

• First image of a planetary system (1984) at Las Campanas Observatory

*Smith & Terrile, 1984*
1986. Exocomets on Beta Pictoris

Vidal-Madjar, Ferlet, Lagrange, Lecavelier, Beust
1987,88,89,90 etc…

See also Kiefer et al, 2016
ESO PR1432

Beust et al, 1994
Beta Pic disk imaged at ESO
A planet is present

Inner depletion => planet?

Lagage et Pantin, 1994

Mouillet et al., 1997; Augereau et al, 2000
First survey for « dark objects »

Micro-lensing

40 cm GPO, La Silla
Aubourg et al, 1993 ESO Messenger 72

676 x 405 Thomson CCD chip (1 x 0.5 deg)

EROS-1 (1990-1995)
A high precision spectrograph at the 3.6m is recommended
Design the VLTI for narrow angle astrometry capabilities is highly recommended; most of AT time
A 2.5m telescope dedicated (1/3) to micro-lensing to search for Earth mass planets is recommended
High order AO system with modern coronagraphs and dark hole technics should be tried
A high resolution spectrograph (CRIRES) is highly desirable
Dedicate a 1m or part of a 100deg^2 Schmidt for transit is recommended
• Developed a few unique/game-changing facilities
  • High precision spectrograph *
  • Adaptive Optics & High Contrast Imaging
  • High precision astrometry Interferometry *
• Hosted dedicated infrastructures (e.g. for transit photometry) :
  • TRAPPIST, SPECULOOS, EXTRA, NGTS, etc
• Developed synergies with :
  • other ground facilities for micro-lensing & transits surveys
  • space missions (Corot, Kepler, TESS, Gaia, follow-ups)
First detection of a remote (P=10d) 5 Earth-mass planet

Planet population is plentiful
At least one planet per star

Beaulieu et al. 2006
ESO PR0603

PLANET network

Cassan et al. 2014
ESO PR1204
Hosting transit-team projects

Trappist-1bcdefg

Trappist

Trappist + Speculoos

Guillon et al 2017 PR1706

Grimm et al, 2018 ESO PR1805
2003. HARPS Revolution

Ideal survey instrument. Hundreds of planets, from giants to super-Earths (Msini = 1 - 10 M⊕) Super-Earths are super abundant: (50% for P = 10 - 100 d, HZ) around M dwarfs Bonfils et al, 2014. ESO PR1214. Conclusion shared with Cassan et al, 2014

51 Pegase b
Mayor et Queloz, 1995
Nobel Prize 2019

1.9m/Elodie (10m/s)

3.6m/HARPS (1m/s)

HD330075 b: 1st HARPS planet
Pepe et al, 2004
Proxima Cen planetary system

2016
3.6m/HARPS (1m/s)

Anglada-Escude et al, 2016

ESO PR1629

2020
VLT/ESPRESSO (25cm/s)

Suarez Mascareno et al, 2020

Faria et al, 2022

ESO PR 2202

M = 1.3 M\(_E\)
P = 11.2 d

M = 0.3 M\(_E\)
P = 5 d
Characterization of transiting planets with HARPS

- Test Corot candidates *Moutou et al, 2009*

- Characterize the planets structures

*Leger et al, 2009*

*Corot-7 b (5ME)*

*Queloz et al, 2009*

*ESO PR0933*

*Dorn et al, 2017*
Characterization of complex systems with ESPRESSO

Combining TESS, SPECULOOS, NGTS, ESPRESSO, and CHEOPS

TOI 178

Leleu et al., 2021

ESO PR2102
Imaging brown dwarfs with high contrast imagers at ESO

3.6m/Adonis (1993)

VLT/NACO (2001)

VLT/SINFONI (2004)

VLT/SPHERE (2014)

Neuhaueser et al, 1995

Neuhaueser et al, 2005

Angerhausen, 2008

Beuzit et al, 2015
2004: First images of exoplanets

**AB Pic b**
- $M \sim 13 \ M_{\text{jup}}$
- $\text{Sep} = 260 \ AU \ (\text{proj.})$
- 30 Myr

(Chauvin et al. 2005a)

**2Mass1207 b**
- $M \sim 5-8 \ M_{\text{jup}}$
- $\text{Sep} = 50 \ AU \ (\text{proj.})$
- 5 Myr

(Chauvin et al. 2004, 2005b)
2004: First images of exoplanets

- AB Pic b
  - M ~ 13 M\(_{\text{jup}}\)
  - Sep = 260 AU (proj.)
  - 30 Myr

Chauvin et al. 2005a

- ESO PR0515

Chauvin et al. 2004, 2005b
Planets detected with $M < 20$ MJ

Most discoveries made at ESO (surveys)
A giant planet imaged at Saturn distance

**β Pictoris b**

**Correlation techniques**

**VLT/NACO**

2003 2009

Lagrange+ 2009, 2010
ESO PR0842
ESO PR1024

Lagrange/Boccaletti/Chomez

**VLT/SINFONI**

Hoeijmaker+, 2018

Correlation techniques

**VLT/**

**VLT/**

Bonnefoy et al, in prep. Nowak et al, 2020

**Emission relative to continuum**

Fig. 5: Model templates of CO, H$_2$O, CH$_4$ and NH$_3$ at high ($R \sim 10^6$) spectral resolution (light colour) and convolved to a spectral resolution of $R = 5000$ (dark colour). The vertical dashed lines indicate the wavelength range of the data.

Fig. 6: Molecule maps of CO, H$_2$O, CH$_4$ and NH$_3$ at $v_{sys} = 0$ km s$^{-1}$. In all four panels, the colours scale linearly between cross-correlation of $-0.05$ (black) and $+0.2$ (white). The cross-correlation enhancement caused by the planet is detected at a significance of 14.5 and 17.0 in the maps of CO and H$_2$O respectively, but not in CH$_4$ and NH$_3$.

5.2. Planet characterization using molecule mapping

Variations in global atmospheric parameters such as the effective temperature, surface gravity, metallicity and abundances ratios affect the relative strength of individual absorption lines. This may significantly influence the cross-correlation function, which means that the analysis is potentially sensitive to underlying model parameters. Figure 9 shows the peak value of the 1D cross-correlation function with BT-Settl models with varying $T_e$ and log($g$).

The cross-correlation peak steeply decreases for temperatures below $\sim 1600$ K because the strength of the water
Beta Pictoris bc

HARPS

Radial Velocity [m/s]

B Pic c
M \sim 9 \, M_{\text{Jup}}
Sep = 2.7 \, \text{AU}
20 \, \text{Myr}

Lagrange et al, 2019

VLTI/GRAVITY

Full modeling:
HARPS, NACO, SPHERE, GRAVITY, Gaia

Nowak et al, 2020
Lagrange et al, 2020

Dynamical mass of bPic c

Lacour et al, 2021
PDS 70: a young (5Myr) forming planetary system

- PDS 70b
  - Proj. sep. ~ 25 au
  - Mass = 5-10 M_{Jup}

- PDS 70c
  - Proj. sep. ~ 30 au
  - Mass = 3-5 M_{Jup}

- Orbital configuration consistent with the planets in a 2:1 MMR (GRAVITY, Wang et al, 2021)

See also Benisty et al, 2021 ESO PR 2111
Structures of proto-planetary disks

SPHERE

Avenhaus et al, 2018
Sissa et al, 2018
ESO PR1811

ALMA

Andrews et al, 2018

Signposts of planets

Pinte et al, 2019, 2020

Complex organic molecules

Brunken et al. 2022 ESO PR2205

ESO PR1811
Exoplanetary systems
The future
ESO is now at the forefront of exoplanetology. Many questions remain:

- Detail of planetary formation processes
- Diversity of extrasolar systems. Is the Solar System unique/rare?
- How to find Earth twins? Signatures of life?
- Fully dedicated survey facilities: 3.6m, ESPRESSO, SPHERE(+), ERIS (?)

- Characterization facilities: same + GRAVITY(+), CRIRES+, + ELT (MICADO, HARMONI, METIS)

- Multitechnic approaches

- Complementarity with space missions (Gaia, TESS, JWST, PLATO, ARIEL..)

- Openness and reactivity to new ideas
ELT (39 m)
MICADO, HARMONI, METIS, PCS

Bourse du commerce, Paris (38m)