Direct imaging characterisation of (exo-) planets with METIS

Wolfgang Brandner (MPIA) with contributions by Ian Crossfield, Lisa Kaltenegger (MPIA), Sascha Quanz (ETH), Eric Pantin (CEA Saclay) and the METIS science team

Jupiter
VLT/ISAAC

HR8799
VLT/NACO

Saturn
Cassini/VIMS

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Outline

1. Motivation and Challenge
2. eXtreme Adaptive Optics (XAO) at the E-ELT
3. Giant planet characterization
4. Prospects for detection and characterisation of Super-Earths and exo-Neptunes
Direct Imaging - Why bother?

<= Talk by Gael Chauvin

• derive orbital parameters and constraints on outward migration

• study exoplanet atmospheres not subject to strong irradiation

• young systems: study interaction between planet and disk

Why extend studies of exoplanets to the MIR?
Exoplanet characterisation - the challenge

Key requirements for direct detection:

- high angular resolution $\ll 1''$
- high contrast $>1:10^7$
- high signal-to-noise ratio

Flux ratio Jupiter/Sun:

- **optical** to J-band: reflected star light probing upper cloud layers
- **mid-IR**: intrinsic thermal emission of exoplanet, probing deeper atmospheric layers + optimal contrast planet/star
2. eXtreme Adaptive Optics (XAO) at the E-ELT

eXtreme AO operational at the VLT since late 2001: NACO in L&M-band

Eps Eridani at $\lambda=4 \, \mu m$ (NB4.05)

NACO
SR = 85% ($t_{exp}=1160s$)

Field of View: 27”x27”

inner ~50 Airy rings detected

E-ELT adaptive M4 has actuator density projected on the primary mirror of 1/0.5m (~6000 actuator on ~40m mirror) <= comparably to VLT/NACO

E-ELT/METIS with NGS AO is capable of achieving SR >75% in L-band, >80% in M-, and >90% in N-band on bright stars (I=10 to 12 mag)
3. Giant planet characterisation

Spectral features of ultra-cool brown dwarf ULAS J0034-00 ($T_{\text{eff}} \sim 550$K)

$T=550 \text{ g}=300 \text{ m/H}=+0.3$

$\text{H}_2\text{O}$

$\text{CH}_4$

$K_{zz}=10^4$

$\Rightarrow$ models (red) reproduce spectral features (black) of cool brown dwarfs reasonably well

Leggett et al. 2009
3. Giant planet characterization

**Standard model of cool, cloudy atmospheres**

- stratification (absence of pronounced vertical mixing)
- deeper layers are hotter (no temperature inversion)
- chemical equilibrium
- local thermal equilibrium

**Model assumptions**

- ~125 K
- 600 - 1200 K
- 1200 - 2000 K
- ~2200 K

Cloud condensations remove species from the higher atmospheric layers (no metal-oxides in L-dwarfs, no Li in T-dwarfs, etc.)

=> MIR observations probe deeper atmospheric layers, and constrain and test atmospheric models

Katharina Lodders 2004 (Science)
SPITZER (red): 3.6 to 8.0 μm secondary transit observations of TrES-4

Atmospheric models can be “degenerate” in the NIR
MIR observations allow to distinguish between model parameters

=> temperature inversion in exoplanet atmosphere (Knutson et al. 2009)
one possible explanation of the observations

=> broad wavelength coverage is essential for studying exoplanets
Chemical characteristics of exoplanet atmospheres

HR 8799: 4 exoplanets with masses in the range ~7 to ~12 M$_{\text{Jupiter}}$. L’-band spectroscopy of the directly imaged exoplanet HR 8799c (Janson et al. 2010)

Strategy:
- Use long-slit, place both the star and one of the planets in the slit (monitor telluric features simultaneously with obtaining science data)
- Nod along the slit every 100s, integrate for 10000s per half night

HR 8799c, 10 M$_{\text{Jup}}$, $T_{\text{eff}} = 1100$K

L’=15.6mag (0.14 mJy, S/N ≈ 30)  
L’=14.7mag  
L’=5.2mag

Planets detected in 300s imaging ($\pm0.4$ s with E-ELT/METIS)

Spectral trace of exoplanet
3. Giant planet characterization

Chemical characteristics of exoplanet atmospheres

- More CO, less CH$_4$ than expected
- $CH_4 + H_2O \leftrightarrow CO + 3H_2$

Sign for i) non-equilibrium chemistry, or ii) smaller atmospheric scale heights, or iii) temperature inversion, or iv) young age, or ...
3. Giant planet characterization

**METIS imaging sensitivity**

METIS in LMN-bands: sensitivity gain ~500 compared to VLT

E-ELT/METIS facilitates detailed (low-res) spectral characterization of directly imaged exoplanets detected in the NIR at separations closer than what JWST could resolve

Extrapolation of current sample ~10 to 20 directly imaged exoplanets to the year 2024:

**Prospects for spectral characterization of ~100s of directly imaged giant exoplanets**
4. Super-Earth and exo-Neptunes in the Solar Neighbourhood

**SCR 1845-6537** has ~40 to 50 M\(_{\text{Jup}}\) (Biller et al. 2006; Kasper et al. 2007)

**Eps Indi B** has a binary brown dwarf as companion with a system mass ~120 M\(_{\text{Jup}}\) (McCaughrean et al. 2004, Cardoso et al. 2009, King et al. 2010)

**Eps Eri** is suspected to house multiple giant planets

**Alp Cen Bb** with $\geq$ 1.1 Earth masses
Direct Imaging observations of Alpha Cen Bb

Bb

\[ M \star \sin i = 1.13 \, M_{\text{Earth}} \]

\[ a = 6 \, \text{Mio km} \]

\[ T_{\text{Planet}} \leq 1180K \]

For comp.: Lava 1000 – 1500K

something amiss with the artist's impression?
4. Super-Earth and exo-Neptunes

J-band detection of known exoplanets

Known Targets for E-ELT High-contrast Observations:

Crossfield 2013, in press; arXiv:1301.5884

4. Super-Earth and exo-Neptunes

=> strong science case for PCS (see talk by Markus Kasper) and TMT/GMT equivalents

Wolfgang Brandner (MPIA)

Shaping E-ELT science and instrumentation, Ismaning, 26. February 2013
L-band detection of known exoplanets

Known Extrasolar Planets: 39 m, 3.50 \( \mu \)m

Crossfield 2013, in press; arXiv:1301.5884

=> METIS could detect some of the wider and cooler exoplanets below the detection threshold of MICADO/PCS, and provide complementary long-wavelength spectral characterisation for sources detected by PCS at shorter wavelength

=> detection of “lava” planet Alpha Cen Bb at 1\( \lambda / D \) in MIR “challenging” => see poster by Olivier Absil on MIR vector vortex coronagraph
M-band detection of cool and “distant” exoplanets identified by radial velocity (RV) studies

RV detected planets within METIS IWA

**4. Super-Earth and exo-Neptunes**

16 of the presently known RV (giant) planets could be imaged by E-ELT/METIS in M-band in 1 hr of integration time each. Detection of exo-Neptunes in M-band requires longer integration times

=> see poster by Sascha Quanz for more details
4. Super-Earth and exo-Neptunes

**N-band detection prospects**

Simulated planet population (based on Kepler results) expected to be detectable by METIS direct imaging as a function of planetary radius and equilibrium temperature.

METIS is particularly sensitive to planets that are relatively small (2-4 Earth radii) and quite cool (equilibrium temperature 200-350 K), i.e. planets located close to the habitable zone.

=> see poster by Ian Crossfield for more details

Wolfgang Brandner (MPIA)

Crossfield 2013, in press; arXiv:1301.5884
Summary: MIR exoplanet imaging and characterisation

mid-IR: optimal contrast planet/star + study of intrinsic thermal emission of exoplanets

Scientific topics:

* Atmospheric composition and chemistry
* Atmospheric temperature profile
* Weather and seasons
* Exoplanet orbital parameters (astrometry)
* Formation of giant planets (core accretion, disk instability)
* Detection and characterisation of Super-Earths and Neptunes in the habitable zone around nearby stars