Characterization of directly-imaged exoplanets at high spectral resolution: Coupling SPHERE and CRIRES+

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+ ESO Paranal support: A. Smette, L. Pallanca, L. Blanco, et al.
Direct imaging of exoplanets

PDS 70 - Keppler et al. (2018)
VLT/SPHERE

- 8 meter VLT mirror
- SAXO ExAO system
  - 40x40 DM
  - 1500Hz SHWFS
- IRDIS
- IFS
- Apodized-pupil
- Lyot coronagraph
- ZIMPOL
Direct imaging recipe

Seeing-limited PSF
- Adaptive optics
- Coronagraph

Diffraction-limited PSF
- Adaptive optics
- Coronagraph

Diffraction-limited PSF
- Adaptive optics
- Coronagraph

Coronagraphic image
- Adaptive optics
- Coronagraph

Diffraction limited within 20 $\lambda/D$

10^{-4}$-10^{-5}$ contrast in dark zone

$\sim$10^{-5}-10^{-6}$ contrast down to 0.2$

Enough to detect young giant exoplanets of a few Jupiter masses

Post-processing
SPHERE and GPI detections

GPI/H-band
51 Eri

HIP65426 (VLT/SPHERE)

Orbit of Neptune

500 mas
56 AU

PDS70

Broad Cavity
Inner belt
b (@21 au)
Outer belt

Macintosh et al. 2015

Chauvin et al. 2017

Keppler et al. 2018

Very low resolution spectroscopy!

→ First order characterisation

Go for high spectral resolution!
Detection boost at high-spectral resolution

\[ S/N = \frac{S_{\text{planet}}}{\sqrt{S_{\text{star}} + \sigma_{\text{bg}}^2 + \sigma_{\text{RN}}^2 + \sigma_{\text{Dark}}^2}} \sqrt{N_{\text{lines}}} \]

- Requires \( R \gg 10,000 \)

Cross-correlation function

Spectral information

- \( R=5000 \)
- \( R=10,000 \)
- \( R=20,000 \)
- \( R=50,000 \)
- \( R=80,000 \)

Cross-correlation function

Spectral + velocity information
Characterisation at high-spectral resolution

**IFS (Claudi+ 2008)**

**BT-Settl model**

2M$_{\text{Jup}}$ / 20 Myr

No noise

**Requires**

$R \gg 10\,000$

**CO features / K-band**
Exoplanet science at high resolution

**Abundances determination**

- **HR8799c**
  - Konopacky et al. (2013)
  - $C/O = 0.65$

**Isotopologues detection**

- Mollière & Snellen (2019)

**Formation, migration & evolution**

- Formation lines
  - $+$ CH$_4$ → H + H$_2$O → OH
  - OH + CH$_3$ → CH$_2$
  - $H_2$OH + M → H +
  - $C_2$CO + H → HC
  - $C_2$O + M → H

**Atmospheric chemistry & dynamics**

**Orbital and rotational velocity**

- **$\beta$ Pictoris b**
  - Snellen et al. (2014)

**Variability & Doppler imaging**

- Luhman 16B (Crossfield et al. 2014)

**Accretion lines**

- PDS70 in Hα

**Molecules detection**

- HR8799c
  - Konopacky et al. (2013)

**Model Atmosphere**

- H$_2$O lines
- CO lines
- CH$_4$ lines
- Speckle

**Wavelength (μm)**

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<td>3.09</td>
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</table>

**Opacity (cm$^2$ g$^{-2}$)**

- H$_2$O
- HDO

**Luhman 16B** (Crossfield et al. 2014)
Young exoplanets characterisation in near-IR

High-contrast imaging with coronagraphy

- PDS70 b
- PDS70 c
- HR2562 B
- β Pictoris b (H)
- HR8799 c
- HR8799 b
- 51 Eri b

High-resolution spectroscopy

- HIP65426 b
- HR8799 e

Characterisation

- 10-15 companions already known at separation < 1"
- contrast < $10^{-4}$

Companions detected by other means

- Imaging
- ESA/Gaia
- RV?

High-Resolution Imaging and Spectroscopy of Exoplanets

$x1000$
A unique window of opportunity

- **High-contrast exoplanet imager**
  - SPHERE

- **High-resolution spectrograph**
  - CRIRES+

- **VLT/UT3**

- **Extreme adaptive optics**
  - ✔

- **Coronagraphy**
  - ✔

- **Spectral coverage**
  - Y J H K
  - 50 - 350

- **Spectral resolution**
  - 50 000 - 100 000

- **Fiber coupling**
Implementation

Fiber injection module (FIM)

Fiber extraction module (FEM)

Fiber bundle
Fiber injection module in SPHERE
FIM conceptual design

- Removable pick-off mirror
- Tip-tilt in closed loop for positioning
- Long wavelengths to single-mode fibre
- At least 2 fibres
  - science
  - reference

(Very bright) planet!
Optical design

- Injection
  - ~30 nm rms on axis

- Tracking
  - ~60 nm rms on axis

F/3.5

Tip-tilt mirror
Fiber injection lens
Tracking camera lens

Dichroic filter
Fiber bundle

Recollimating lens
Dichroic
Fiber bundle plane (tilted)

Last lens of the SPHERE optics
Off-the-shelf pupil relay lens

Tracking camera CCD
HiRISE injection efficiency

How much stellar/planetary light can you inject into an SMF?

- Single-mode fiber:
  - $E_{M00}$ mode is quasi-Gaussian

- Telescope PSF:
  - Obstructed pupil + spiders
  - Complicated pattern

Mismatch!

Jovanovic et al. (2017)
HiRISE injection efficiency

Fiber coupling efficiency for VLT-like pupil

\[
\frac{\lambda}{10D} \text{ jitter}
\]

- VLT pupil
- VLT pupil + turbulence
- VLT pupil + turbulence + Lyot mask
- VLT pupil + turbulence + NCPA + Lyot mask
- VLT pupil + turbulence + NCPA + Lyot mask + Apodizer

Coupling efficiency vs. Displacement between PSF core and optimal Gaussian \(\lambda/D\)
Fiber injection module in SPHERE
Fiber injection module in SPHERE Enclosure
Fiber bundle

SPHERE section
~5 m

CRIRES+ section
~5 m

Long section
~50 m

Science fibers (Nufern 1310M-HP)
- s Science fiber, planet, 1.4-1.8 µm
- r Reference fiber, star, 1.4-1.8 µm

Calibration fibers (Nufern 1310M-HP)
- f SPHERE feedback fiber, max 1.4 µm
- c CRIRES+ calib fibers, 0.8-1.6 µm

2d assembly, AR coating

SPHERE

CRIRES+

HiRISE cabinet

Connectors

FIM feedback source

Science fiber, planet, 1.4-1.8 µm
Reference fiber, star, 1.4-1.8 µm
SPHERE feedback fiber, max 1.4 µm
CRIRES+ calib fibers, 0.8-1.6 µm
Fiber bundle with connectors

- White fibre stubs to complete hexagonal packing
- Hexagonal packed input AR coated 1200-1850 nm
- Calibration fibres (purple, green, red) get in/out at the level of the connector
- Single fibre connectors, format: FC/PC
- 2 multi-connectors
- Single fibre connectors, format: FC/PC
- Mechanical center
- Linear output, interface TBD, but likely a fixed mount
  AR coating:
  - science = 1450-1850 nm
  - calibration = 800-1450 nm
- Again, stubs included for packing symmetry
Fiber bundle without connectors

White fibre stubs to complete hexagonal packing

Hexagonal packed input AR coated 1200-1850 nm

Calibration fibres (purple, green, red) get in/out at the level of the connector

Single fibre connectors, format: FC/PC

Single fibre connectors, format: FC/PC

Mechanical center

Mechanical center

Linear output, interface TBD, but likely a fixed mount AR coating:
- science = 1450-1850 nm
- calibration = 800-1450 nm

Again, stubs included for packing symmetry
Low-loss connectors

• Throughput is a key driver of the performance
• Problem: single-mode fibres have very small cores! Typically 4-8 µm

![Diagram showing cladding and core with a graph indicating -0.1 dB loss specification for Nufern 1310M-HP → 6.5 µm core.](image)
Low-loss connectors

- Rugged connectors with repeatable connection exist...

- ... but they need properly aligned fibres in the first place

- Only solution on the market: Diamond SA, Active Core Alignment

Fiber bundle around UT3
Fiber extraction module in CRIRES+

CRIRES+ carriage selector unit

FEM optics
Fiber extraction module in CRIRES+

- Fiber bundle
- Cable wrap
- HiRISE FEM
- CSU
- CRIRES+ warm bench
CRIRES+: improving CRIRES

- NIR infrared echelle spectrograph
- New cross-dispersion gratings stage
- New Hawaii-2RG detectors
- Improved polarimetric unit

Covers ~70% of the H-band in a single observation
Spectropolarimetry with HiRISE?

- Not possible!
- Spectropolarimetric unit located inside the CSU

Already photon-starved regime... **every single photon counts!**
Transmission budget

End-to-end model from Otten et al. (2021)
Do we really want a coronagraph?

• Baseline in SPHERE ➔ apodized pupil Lyot coronagraph
• YES, from the injection efficiency point-of-view...

... but certainly not from the throughput point-of-view!

<40% of the total flux is transmitted!!
Performance estimation

Types of noise:
- Total
- Planet
- Dark noise
- Thermal
- Atmosphere
- Read noise

CRIRES+ standalone
- Total
- Stellar halo

CRIRES+ H

HiRISE H

CRIRES+ K

HiRISE K

End-to-end model from Otten et al. (2021)
Performance estimation

**H-band**

**K-band**

CRIRES+ standalone outperforms HiRISE
Expected performance

Gain in observing time

H-band

Star
A5V, 19.0 pc, 12.0 Myr
H = 3.5, K = 3.5

Companion
Teff = 1200K
log(g) = 4.0

Observation
Texp = 2.0 h
Test molecule → all12
Expected performance

**Major discovery potential**

**H-band**

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**Observation**

- Texp = 2.0 h
- Test molecule → all12

CRIRES+

HiRISE

- $\beta$ Pic b
- HIP 65426 b
- 51 Eri b
- PDS 70 b
- HR 8799 c
- HR 8799 d
- HR 8799 e
- HD 95086 b
- Mordasini+ 2017
- 10 Myr - hot start
- SPHERE/IFS, $5\sigma$
- SHINE best 20%

Gaia, 50 μas

Angular separation [mas]

Contrast [mag]
Status of HiRISE

• Many discussions with ESO over the past 2 years
• Science case validated by the OPC: strong support!
• Technical proposal validated by STC and Council: strong support!
  • HiRISE accepted as a visitor instrument by Paranal
• Current activities:
  • Final design
  • Identification of manufacturers
  • Procurement of some hardware
  • Laboratory validations
  • Design review with ESO Paranal
• Schedule:

![Schedule Diagram]
Technical activities

Laboratory validation on MITHiC

Fiber injection map

$\varnothing \ 11.44^\circ C (\Delta T)$

FIM tracking camera testing
Conclusions

1. High spectral resolution on exoplanets
   - Improved characterization
   - Detection boost
   - Opens new opportunities for understanding of exoplanets

2. HiRISE: high-spectral resolution of directly-imaged exoplanets
   - Unique opportunity on VLT/UT3!
   - Couling between SPHERE and CRIRES+
   - Final design on-going
   - Accepted by ESO/Paranal as a visitor instrument
   - On sky probably mid-2022
   - Demonstrator for future instrumentation ELT/PCS or post-JWST exoplanet imagers

https://astro.vigan.fr/hirise.html