SPHERE Early & Expected Results

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IPAG, MPIA, LAM, ONERA, LESIA, INAF, Geneva Observatory, Lagrange, ASTRON, ETH-Z, UvA, ESO

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1. Introduction to DI
2. Description & Status
3. Key early-Results & Expectations
4. Conclusions & Perspectives
I- Introduction

Observational success

Two decades of exoplanet studies

✿ Hot-Jupiters Discoveries
✿ First glimpse of Exoplanetary atmospheres
✿ Images & revolution of Super-Jupiters
✿ Diversity of planetary architectures
✿ Super-Earths in Habitable Zone
✿ Discovery of Earth-mass planets...

Mayor et al. 11; Triaud et al. 10; Swain et al. 08; Desert et al. 12; Bonfils et al. 09; Udry & Santos 07
Batalha et al. 13; Howard 12
I- Introduction

Hunting Techniques

http://exoplanet.eu/
I- Introduction

Why Imaging?

Direct detection of planetary photons

I/ Orbital & Physical properties

> Giant planets at wide orbits (>10 AU)
> Luminosity, a, e, i, ω, T0

Hd95086 b (5 Mjup at 56AU, Contrast = $10^4$, $\Delta L = 9.6$mag)

Rameau et al. 13ab
I- Introduction

Why Imaging?

Direct detection of planetary photons

I/ Orbital & Physical properties
> Giant planets at wide orbits (>10 AU)
> Luminosity, a, e, i, ω, T0

II/ Atmosphere
> Non-strongly irradiated EGPs
> Low-gravity, clouds, non-LTE...

Janson et al. 10; Skemer et al. 12
Konopacky et al. 13; Bonnefoy et al. 13, 14
I- Introduction

Why Imaging?

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Janson et al. 10; Skemer et al. 12
Konopacky et al. 13; Bonnefoy et al. 13, 14

III/ Architecture
> Dynamical Stability & Evolution
> Planet – disk connection
Mouillet et al. 97; Kalas et al. 04, 08;
Buenzli et al. 10; Rameau et al. 12;
Grady et al. 12; Lagrange et al. 12;
Outline
SPHERE Early & Expected Results

1. Introduction to DI
2. Description & Status
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OHP 2015: 20 years of Giant Exoplanets
The VLT/SPHERE Project

VLT/SPHERE (Beuzit et al. 08)

- **Consortium:** 12 institutes, IPAG, MPIA, LAM, ONERA, LESIA, INAF, OAPD, Geneva Observatory, Lagrange, ASTRON, ETH-Z, UvA + ESO


- **Instruments:**
  - **SAXO**, Extreme AO system
  - NIR (YJHK): **IRDIS** (Dual imaging Spectrograph; 10” FoV) and **IFS** 3D-spectroscopy (1.8” FoV; Res ~30)
  - VIS: **ZIMPOL** (Imaging Polarimeter; Visible; 3.5” FoV)
  - **Coronagraphs:** Classical Lyot, A4P and ALC
VLT/SPHERE – Description & Status

Design

- CPI
- IRDIS
- IFS
- ZIMPOL
- ITTM
- PTTM
- DM
- De-rotator
- HWP2
- Focus 1
- HWP1
- Polar Cal
- Focus 2
- Focus 3
- Focus 4
- NIR corono
- VIS corono
- HWP1
- HWP2
- Polar Cal
- Focus 4
- ZIMPOL
- NIR corono
- VIS corono
- WFS
- NIR corono
- VIS corono
- IRDIS
- DTTS
- PTTM
- NIR corono
- VIS corono
- Focus 2
- Focus 3
- Focus 4
- NIR corono
- VIS corono
- VIS corono
- ZIMPOL
- NIR corono
- VIS corono
### Overview

<table>
<thead>
<tr>
<th></th>
<th>ZIMPOL</th>
<th>IRDIS</th>
<th>IFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>FoV</td>
<td>Sq 3.5″ (instantaneous) Up to 4″ radius (mosaic)</td>
<td>Sq 11″</td>
<td>Sq 1.77″</td>
</tr>
<tr>
<td>Spectral Range</td>
<td>0.5 – 0.9 μm</td>
<td>0.95 – 2.32 μm</td>
<td>0.95 – 1.35/1.65 μm</td>
</tr>
<tr>
<td>Spectral information</td>
<td>BB, NB</td>
<td>BB, NB</td>
<td>50 / 30</td>
</tr>
<tr>
<td>Linear Polarisation</td>
<td>Simultaneous on same detector, x 2 arms, exchangeable</td>
<td>Simultaneous dual beam, exchangeable</td>
<td>x</td>
</tr>
</tbody>
</table>

**Coronography**: no /4Q / Lyot

**Rotation at Nasmyth**:  
Pupil-stab. (instrument fixed wrt tel.)  
Field-stab (slit spectro, long DIT...)  
No rotation: minimize crosstalk...

**AO sensitivity for high contrast**:  
R=9.5 for NIR; R=9 for R; R=7.8 for whole VIS

**Separation range where improved contrast**:  
2 - 20 λ/D, ie 30-300 mas in R,  
or 80 – 800 mas in H

**Mode switching**: not VIS and NIR in same night
Path for Exoplanet Imaging

1. High angular resolution

SAXO Extreme-Adaptive Optics
90% Strehl in H-band;
(Coherent energy In PSF core)

- **Deformable Mirror:**
  High orders; 41 x 41 actuators

- **Wave Front Sensing:**
  Shack-Hartmann, 40x40 lenslets,
  Red-sensitive sub-e CCD
  Frequency = 1.2kHz
  Anti-aliasing spatial filtering

- **Sparta Real-Time Computer**
  Command; non-common path
  aberration corrections
1. High angular resolution

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**Contrast = 10^{-3}**

**median seeing 0.8”**

**1”**
1. High angular resolution
Exquisite PSF temporal stability

IRDIS: 2 images separated by 20 min in time
H-band
Path for Exoplanet Imaging

1. High angular resolution
   XAO works, also in visible!

IRDIS/Comm-1
May 2014
Path for Exoplanet Imaging

1. High angular resolution
2. Stellar-light attenuation

Coronagraphy (B. Lyot)

- Pupil and Image Control
  - PTTM, ITTM/HODM
  - Low-aberrations/Centering control (DTTS)

- Pupil Masks:
  - Apodizer or/and Lyot Stop

- Focal plane masks:
  - Classical Lyot Coronograph
  - Apodized Classical-Lyot
  - Apodized 4QP Mask, Boccaletti et al. 08

Contrast = $10^{-4}$

median seeing 0.8”

SPHERE/Comm-1
May 2014

VLT/SPHERE – Description & Status
Path for Exoplanet Imaging

1. High angular resolution
2. Stellar-light attenuation

IRDIS Coronography in H-band
3-20 lambda/D
H-band, 120 – 800mas
30pc, 4 – 26 AU
Path for Exoplanet Imaging

1. High angular resolution
2. Stellar-light attenuation
3. Speckles subtraction

Main limitation (<1.0’’):
Residual Turbulent/quasi-statics speckles

- Differential Imaging techniques
  . Polarimetric (PDI)
  . Spectral (SDI), Close et al. 05
  . Angular (ADI), Marois et al. 06

- Minimizing WFE (Coffee, ZELDA...)

- Post-processing tools
  . LOCI, Lafrenière et al. 07
  . ANDROMEDA, Mugnier et al. 10
  . KLIP/PCA, Soummer et al. 12

SPHERE@IPAG
Sr = 90%  
DBI: H2-H3  
Apo+Stop

median seeing 0.8”
Contrast = 10^-6
1”
Detection performances
VLT/SPHERE – Description & Status

Detection performances

![Graph showing detection performances](image)

1 Mjup @6 AU
(10 Myr star at 30pc)
Since $1^{st}$ Light...

• **Science Verification in Dec. 2014**  
  - Fully operated by ESO team, validating actual operations of various modes  
  - Public data, covering a variety of science topics

• **Open time with SPHERE:**  
  - 1$^{st}$ Call in Sep. 2014 (from instrument validation after 2 commissionning runs only): for observations Apr – Sept 2015  
  - 2$^{nd}$ call in March 2015: 204 night proposed, covering all SPHERE modes  
  - **Now, 3$^{rd}$ call in Oct. 1$^{st}$, 2015**

• **Guarantee Time Observations:**  
  - 260 nights over 5 years, started in Feb 2015  
  - Organised as a project in its own, with 4 science programs:  
    ✓ NIRSUR (200 nights): Survey for Exoplanets of 400-600 stars in NIR  
    ✓ DISK (20 nights): Survey for Proto-planetary & Debris Disks Study  
    ✓ REFPLANETS (18 nights): Planets in Visible/Reflected Light  
    ✓ OSCIENCE (12 nights): Solar systems, Evolved stard, Clusters, X-Gal...
Since 1\textsuperscript{st} Light...

Guaranteed Time Observations

• Observing runs in visitor mode
• Current status (Oct 2015)

<table>
<thead>
<tr>
<th>Category</th>
<th>Executed GTO nights</th>
<th>Future GTO nights</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIRSUR (200n)</td>
<td>37.5n</td>
<td>-&gt; 75 nights</td>
</tr>
<tr>
<td>DISK (20n)</td>
<td>5n</td>
<td>-&gt; 11 nights</td>
</tr>
<tr>
<td>REFPLANETS (18n)</td>
<td>2n</td>
<td>-&gt; 3 nights</td>
</tr>
<tr>
<td>OSCIENCE (12n)</td>
<td>3n</td>
<td>-&gt; 4.5 nights</td>
</tr>
</tbody>
</table>

• Downtime statistics

Weather loss (mostly humidity and wind) ~ 25%

SPHERE (+ VLT) technical loss < 5%

• Obtained data

NIRSUR: 120+ targets in good or very good conditions (known and new targets)
DISK: 10 targets (known disks)
REFPLANETS: 1 target (alpha Cen)
OSCIENCE: 10 targets (Ceres, clusters, evolved stars)
1. Introduction to DI
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OHP 2015: 20 years of Giant Exoplanets
4.1 Protoplanetary Disks
   - HD142527, MWC758

4.2 Debris disks
   - AU Mic, HD106906

4.3 Brown dwarfs
   - GJ758, 2M0122-2439

4.4 Exoplanetary systems
   - HR8799bcde, β Pic b

4.4 Evolved stars, Solar Systems...
   - Betelgeuse, Titan, R Aquarii

R Aquarii, Symbiotic binary (42mas)
4.1 Proto-planetary Disks

Spirals & Planetary perturbers

**HD142527**
Herbig F6 star, 3-7 Myr
d = 145±15pc; Sco OB2-2 member

ALMA/NICI/NACO/HiCIAO
Huge continuum cavity
CO gas in Keplerian rotation
Cassasus et al. (2012, 2013) Rameau et al. (2012; Fujiwara et al. (2006)

Comm-2, July 2014; ZIMPOL
1 – 1.5hr Telescope time
Double-based-difference
R+I Color Polarimetry
4.1 Proto-planetary Disks

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VLT/SPHERE – 1st Light GTO Results
4.1 Proto-planetary Disks

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Ménard et al. 2015, A&A, in prep
4.1 Proto-planetary Disks

Spirals & Planetary perturbers

**MWC758**
Herbig A5 star, 3.5 Myr; d=240 pc
73-AU cavity seen in mm, 
i~21°, PA~65° (Isella et al. 2010)

SPHERE SVT (Dec 5th, 2014)
IRDIS –DPI, Y band (1.04µm),
ALC_YJH_S corono (185 mas φ)
18min on Target!

Spiral structures resolved
Contrast and pitch angle explained
by a marginally unstable disk with
embedded planets?
4.2 Debris Disks

Discovering new systems!

**HD106906AB**
Lowe Centaurus Cruxc Group Member
Age = 13+-2 Myr; d= 98.2pc
Resolved as a tight binary (VLTI/PIONIER)
11+-2Mjup Planetary Mass Companion
Located at 650 AU (Bailey et al. 2014)

IRDIS DBI_H23, NIRSUR, March 30th, 2015
4.2 Debris Disks

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Age = 13+/-2 Myr; d= 98.2pc
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Located at 650 AU (Bailey et al. 2014)

IRDIS DBI_H23, NIRSUR, March 30th, 2015

New edge-on & narrow ring resolved,
r0~66+/-1.8AU, i~85.4+/-0.1°,
PA~104.4+/-0.3°, g = 0.6+/-0.1
(HR4796, The Moth, HD15115 analogs)
Strong brightness asymmetry

Lagrange et al. 2015, A&A, accepted
4.2 Debris Disks

Discovering the unexpected!

**AU Mic**
M1Ve star
Beta Pictoris Moving Group Member
Age = 23+3 Myr; d = 9.94pc

Debris disk resolved by Kalas et al. (2004)

**Emblematic system** observed with HST, Keck, NaCo, NICI... see Liu et al. (2004); Krist et al. (2005); Fitzgerald et al. (2007); Graham et al. (2007); Schneider et al. (2014)

IRDIS coronographic sequence in BB-J
August 10th, 2014 (Comm-3)
VLT/SPHERE – 1st Light GTO Results

4.2 Debris Disks

13"

SPHERE 2014 rdl
SPHERE 2014 noadi
SPHERE 2014 adi
SPHERE 2014 klip
SPHERE 2014 loci
4.2 Debris Disks

A, B (E, C, D) are moving in time...
4.2 Debris Disks

VLT/SPHERE – 1st Light GTO Results

13"

[Graph showing elevation from midplane + constant vs. projected separation]
4.2 Debris Disks

Discovering the unexpected!

Origin?

• **Gaz-induced structures**: wind disk, photophoresis, jets...
  BUT, low content of gas (Roberge et al. (2005))

• **Interaction with another body?**
  - **Giant collisions**: (Kral et al. 2014): triggers eccentric rings. Clumps if edge-on but localized in the plane of collision. Timescale of ~ 100 yrs. Patterns on Keplerian orbits.
  - **spiral waves** triggered by self-gravity or planets: need gas ... but how much?
  - **outflow** (sporadic) from a planet:
    - **planet/disk interaction**: circumplanetary disk (Fendt et al. 2003). requires the planet axis to be tilted and again gas to form the disk
    - **star/planet/disk interaction**: plasma from a magnetosphere (Kivelson et al. 2005).

4.3 Brown Dwarfs

A super-solar metallicity atmosphere for GJ758 B?

GJ758, G9V, 15.8pc
metal-rich dwarf,
BD companion @46AU
(Thalmann et al. 2009)

IRDIS DBI
(Y23, H23, K12)
Aug 13-14th, 2014
(Comm-3)
4.3 Brown Dwarfs

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IRDIS DBI (Y23, H23, K12) Aug 13-14th, 2014 (Comm-3)
4.3 Brown Dwarfs

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IRDIS DBI (Y23, H23, K12) Aug 13-14th, 2014 (Comm-3)

3.2″
4.3 Brown Dwarfs

A super-solar metallicity atmosphere for GJ758 B?

GJ758, G9V, 15.8pc metal-rich dwarf, BD companion @46AU (Thalman et al. 2009)

IRDIS DBI (Y23, H23, K12) Aug 13-14th, 2014 (Comm-3)

SED Analysis (1-5 μm) Confirmed T8 SpT, but no good empirical Comparison.
Atmosphere fit: Teff = 600+/-100K, and probably metal-rich (but lack of grids).

4.3 Brown Dwarfs

Accessing higher resolution with IRDIS-LSS

2M0122-2439 M3.5V 120 Myr old star at 36pc
12-27 M\textsubscript{jup} young mid-L companion (Bowler et al. 2013)

IRDIS-LSS in LRS/MRS
Dec 6th, 2014 (SVT)
4.3 Brown Dwarfs

Accessing higher resolution with IRDIS-LSS

2M0122-2439 M3.5V 120 Myr old star at 36pc
12-27 $M_{\text{jup}}$ young mid-L companion (Bowler et al. 2013)

IRDIS-LSS in LRS/MRS
Dec 6th, 2014 (SVT)

Spectral indexes:
(FeH, VO, KI, H-band)
SpT L4+-1, INT-G

Atmospheric model:
$T_{\text{eff}} = 1600 \pm 100$ K
$log(g) = 4.5 \pm 0.5$ dex.

Hinkley et al. 2015,
ApJ, 805, 10
Revisiting HR8799bcde

A5V Columba member (30-40 Myr), d = 39.4pc
Planets bcde imaged (Marois et al. 2008, 2010)

IRDIS (+IFS) observations
Comm-2 and -3, SVT (Jul – Dec, 2014)
4.4 Exoplanets

Revisiting HR8799bcde

Combining SPHERE/IFS and IRDIS with GPI/OSIRIS/P1640/LBT

Planets b and c: reproduced by SED of peculiar or young, L9-T2 brown-dwarfs dereddened with Corundum grains.

Planets d and e: share similar properties with population of young, dusty L6-L8 dwarfs.

Atmospheric fits:
(BT-SETTL14, Exo-REM4, Cloud AE-60):
Teff = 1100 – 1300 K
Log(g) = 3.5-4.5
Bad fit for Planet b > clouds?
Revisiting HR8799bcde

Orbital fitting:
Planets @68, 42, 27 and 14 AU
Coplanarity and circular orbits for e, b and c; d non-coplanar and higher eccentricity (<0.3)

Dynamical Stability:
Unstable or chaotic solutions for d and e masses > 13 M_{jup}; Possible mean motion resonances:
- b – c: 5:2 or 3:1
- c – d: 2:1
- d – e: 3:2 or 2:1

Soummer et al. 11; Esposito et al. 13; Pueyo et al. 15

4.4 Exoplanets

Pushing the limit of Astrometric/Photometric monitoring

β Pic b monitoring
NaCo + SPHERE data since 2003
Planet@9AU, ecc < 0.2, (i = 88.9°)
Lagrange et al. 10; Chauvin et al. 12
Bonnefoy et al. 14;

Waffle Calibration: (2% stability - 2hrs)
β Pic b: 0.05 mag & 2mas precision

IRDIS-DBI (H23)
4.4 Exoplanets

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IRDIS-DBI (H23)
4.4 Exoplanets

Formation/Occurrence of Giant Planets at Wide Orbits

- **In-situ Core Accretion** does not work at > 20-30 AU
  - Gravo-turbulent fragmentation or Disk Gravitational Instability?
  - Alternatives: Pebble accretion or tidal downsizing?
    
    Hennebelel & Chabrier 11; Dodson –Robinson et al. 09; Lambrechts & Johansen 12

- **Dynamical evolution & stability**
  - outward migration (corotation torque), planet scattering & resonances
    
    Crida et al. 09; Scharf & Menou 09
4.4 Exoplanets

Formation/Occurrence of Giant Planets at Wide Orbits

• From previous DI surveys Occurrence (>40 AU): GI, not a dominant mechanism based on current predictions/observations Or need second steps of fragmentation?

• Bulk of the CA population not “currently” accessible in Direct Imaging with SPHERE and GPI!

(Rameau et al. 13)

Mordasini et al. simulations for 2Msun stars
Outline

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OHP 2015: 20 years of Giant Exoplanets
Conclusions/Perspectives

**SPHERE is now fully functional: it works well!**
- As in laboratory (calibrations, behaviour on internal source, DBI)
- And new validations possible only on sky (interfaces, atmosphere, UT, sensitivity, derotator, ADCs, DM shape control under external conditions, vibrations, configuration changes, polarization sequences and efficiency)

**Operation**
- Fully under ESO responsibility since December 2014
- Calibration scheme functional
- Minor corrections (observing templates, motor control, etc.)
- Pipeline: baseline under evolution to include on-sky feedback

**Performances are great!**

**Future plans**
- Deformable mirror mitigation plan (HODM2)
- Performance improvement: focal plane sensor, ZELDA, COFFEE, etc.
- New coronagraphs, SAM
Conclusions/Perspectives

GTO has now started (Feb 2015)

Impressive Early-Results

- **Proto-planetary & debris disks**
  Impressive structures revealed (HD142527, MWC758, AU Mic, HD106906...)
  A machine for circumstellar disk characterization and discovery
  Access to a wide spectral range, reasonable FoV, polarimetric modes...

- **Exoplanets & Brown dwarfs**
  First characterization results published (GJ758, HR8799, PZTel....)
  Already illustrate:
  - detection performances,
  - astrometric and photometric precision,
  - observing modes versatility (IFS, IRDIS-DBI, Hα-ASDI, LSS),
  Main NIRSUR Survey (200 nights) just started,
  but 40 nights of observations already obtained.~120 targets observed

- **Not only disks and exoplanets:**
  Symbiotic stars, R Aquarii (Schmid et al. 2015, A&A, in prep)
  Titan haze with ZIMPOL (Bazon et al. 2015, A&A, in prep)
Conclusions/Perspectives

GTO has now started (Feb 2015)

Impressive Early-Results

Exciting Perspectives

• Complete census of young, massive giant exoplanets beyond 5-10 AU (around young, nearby A-M stars)

• Physics of exoplanetary atmospheres, especially Young T and Y types
  Thick clouds, metal-enhancement, non-LTE, effect of low-gravity ...
  Photometric variability > Weather studies of Exoplanets

• Architecture of planetary systems: Planet – Disk, Planet - Planet interactions, dynamical stability studies & possible sites for telluric planets...

• Formation & Evolution to test predictions of Planetary Formation theories
  1/ using statistical output from systematic SPHERE survey
  2/ Deriving dynamical mass in combination with RV/Astrometry to get Mass – Luminosity & evolution relationship and test Physics of Accretion & Evolution of exoplanets (Hot/Warm/Cold Start models)