Future of Giant Planet Imaging: Requirements

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Direct imaging of exoplanets

• Access to long period planets
• Rates of planets, systems architectures
• Planets properties: log(g), Teff, R, atmosphere composition (non-irradiated planets)
• Formation processes, link with disks
1990': Adonis
50 act., 60Hz
ESO T3.6m

2000': NaCo
185 act., upto400Hz
ESO VLT8.2m

2015: SPHERE XAO
1600 act., 1.2 kHz
ESO VLT8.2m

Classical AO on 3m
CFHT/PUE'O, etc

Classical AO on 10m nIR/LM
VLT, Keck, GEMINI, SUBARU, LBT, Magellan

Neuhauesser et al, 1995

Neuhauesser et al, 2005

Beuzit et al, 2015

XAO on 10m nIR/LM
SPHERE, GPI, SCEXAO
LBTAO, 1640 PALM
VLT/ERIS (project)
Extreme AO-fed instruments

**GPI (Gemini South)**
- Compact & light
- Cassegrain focus
- SH WFS at 2.5kHz max
- TTM +4096 act. MEMS DM
- IR interferometric cal. system for NCPA compensation
- IFS and integral field polarimeter

**SPHERE (VLT)**
* Spectro-Polarimeter High-contrast Exoplanet REsearch
- Heavy & stable at Nasmyth
- HODM: 41*41 act (NAOS: 185)
- SH WFS 40x40 lensless at 1.38kHz, spatial filtering (NAOS: 180; 400Hz)
- Off-line phase diversity for NCPA
- Control of star centering behind mask
- Near-IR Imager, IFS, optical imager/polarimeter
XAO-fed instruments

P3K - P1640 (Hales telescope, Palomar)
TTM + LODM + HODM of 3000 actuators
SH WFS at 2kHz

MagAO (Clay telescope)
Adaptive Secondary (ASM; 585 actuators)
Pyramid WFS 378 modes controlled at 1KHz

AO188 (Stacked array + curvature WFS)
+ MEMS DM of 1000 act.
pyramid WHS

Scexao (Subaru, Mauna Kea)

LBT
PyWFS
Secondary DM
672 actuators
• Improved AO XAO Planet-imagers
• Improved coronagraphs
• Improved algorithms for star halo subtraction
  => improved contrast performances % previous systems

best performances (not representative)
Vigan+ 2015

more representative (Langlois+, 2018)
Mass conversion with Baraffe et al. models (Baraffe+ 2003, 2015)
+ Monte-Carlo analysis with MESS tool (Bonavita+ 2013)

Some sensitivity down to 2-3 au

Major sensitivity gain in 10-50 au
Table 1

<table>
<thead>
<tr>
<th>Reference</th>
<th>Nb</th>
<th>Mass range</th>
<th>Sep range</th>
<th>Age</th>
<th>F</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>of targets</td>
<td>au</td>
<td>MYr–Gyr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metchev et al. 2009</td>
<td>266</td>
<td>12-72</td>
<td>28-1590</td>
<td>3 Myr–3 Gyr</td>
<td>0.5-6.3 (FGK)</td>
<td>2 sigma</td>
</tr>
<tr>
<td>Galicher et al. 2016</td>
<td>356</td>
<td>0.5-14</td>
<td>20-300</td>
<td>&lt; 200 Myr</td>
<td>0.3-3.85 (BAFGKM)</td>
<td>95 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.25-4.95 (GM)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.35-7.15 (AF)</td>
<td></td>
</tr>
<tr>
<td>Bowler et al. 2016</td>
<td>384</td>
<td>1.-100</td>
<td>0.5-100</td>
<td>5-300 Myr</td>
<td>0.1-1.3 (BAFGKM)</td>
<td>68 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.5-6.5 BA</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt;4.1% FGK (95%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt;3.9% M (95%)</td>
<td></td>
</tr>
<tr>
<td>Vigan et al. 2016</td>
<td>199</td>
<td>5.-75</td>
<td>5.-300</td>
<td>&lt; 200 Myr</td>
<td>0.8-3.4 / 0.3-5.75</td>
<td>68/95 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.-75</td>
<td>5.-300</td>
<td></td>
<td>1.6-4.4 / 0.85-6.45</td>
<td>68/95 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5-14</td>
<td>20-300</td>
<td></td>
<td>0.7-3.0 / 0.25-5.05</td>
<td>68/95 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5-75</td>
<td>20-300</td>
<td></td>
<td>1.4-3.85 / 0.75-5.7</td>
<td>68/95 %</td>
</tr>
</tbody>
</table>

Massive (> 5 MJup) GPs further than ~10-20 au are not common. GPs more common around early type stars than late-type stars.
# GPIES & SPHERE/SHINE planet surveys

<table>
<thead>
<tr>
<th>GEMINI/GPI</th>
<th>VLT/SPHERE</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFS Y-K (+polar)</td>
<td>IRDIS DBI (+polar)</td>
</tr>
<tr>
<td>890 hours over 3 yrs</td>
<td>200 nights over 5 yrs (SHINE)</td>
</tr>
<tr>
<td>(GPIES)</td>
<td>20 nights disks</td>
</tr>
<tr>
<td>600 stars</td>
<td>~800</td>
</tr>
<tr>
<td>Young (&lt;100 Myr), Close &lt;75 pc</td>
<td>Young (&lt; 150 pc) + &lt;1 Gyr</td>
</tr>
<tr>
<td>A to M stars</td>
<td>A to M stars</td>
</tr>
<tr>
<td>Started: nov 2014</td>
<td>Started: Feb 2015</td>
</tr>
</tbody>
</table>

- **2 new planets**
- **planets characterisation**
- **several new disks**

[SPHERE/IRDIS Image](#)  
**FoV 11*12”**

[SPHERE/IFS FoV](#)  
**1.7*1.7”**

[GPI FoV](#)  
**1.7*1.7”**
Known bright young debris disks with SPHERE

Disks close to the stars — morphology at sub-AU scale — multiple belts — asymmetries
New young debris disks with SPHERE - The Sco Cen 'niche'

HD111520
LCC, F; Ld/L* ~ 1e-3
30-100AU

HD106906
LCC, F, Ld/L*~ 1.e-3
~ 65 AU

HD115600 GPI
LCC, F2V; Ld/L*=1.3e-3
22-48 AU
Currie+ 2015

HD131835
UCL, A2V; Ld/L*>1.e-3
75-210 AU

Tens of AU scales -- ring structures – side asymmetries
More to come
Protoplanetary disks with SPHERE

Spirals & gaps
Planets to explain spirals in transition disks?

HD model (6MJ)
Dong +2015

Observations
Benisty +2015

HD model
Dong+ 2016

Observations
Langlois+, 2018
PDS70

- **SPHERE/IRDIS DPI observations**
  - Young transition disk
  - Inner and outer belts detected
  - Large 65 au sized gap; Flared Geometry;

- **Exoplanet candidate**
  - Separation = 200 mas (25 au)
  - $\Delta H_2 = 9.2 \pm 0.2$ mag
  - Mass = 5-10 $M_{\text{Jup}}$; $T_{\text{eff}} = 800 - 1100$ K
  - IRDIS H2, H3, K1 and K2 + NaCo L’

Keppler et al. 2018, submitted
Status

- Very few planet-mass companions detected despite XAO
- Distribution of giant planets:
  - massive giant planets are not numerous, at separations > 5-10au
  - directly imaged planets so far belong to a small category of planets
- Many disks detected
- Planets in protoplanetary disks still debated
- Studies of individual cases very informative: confirms that DI is a powerful tool for planet characterisation and studies of planet-disk interactions
GP Exploration in Direct Imaging

• Detection
  - Still very limited in (mass, sep): ~5 MJup, 10 au
  we still lack most of the 5-10 Mjup in the 5-10 au range
  and by far the SS young GP analogs
  - Still very limited in age (a few 10-100 Myr)
=> Need to improve contrast, sensitivity, IWA

• Spectral characterisation
  - Mostly limited to R<100
  - Few cases of “molecular” detections and velocity-based measurements (Planet rot, orbital vel) (Snellen et al) with no/moderate AO correction
Coupling (high resolution) spectroscopy and AO

- Beta Pic b rotation period (Snellen et al, 2014)

- GQ Lup B rotation period (Schwarz et al, 2016)

R~100000 CRIRES + MACAO

- Coupling ESPRESSO+SPHERE for aCen b (Pepe+ 2018)
Spectroscopy coupled with AO

Hoeijmaker+, 2018, subm
Coupling (high resolution) spectroscopy and AO

R5000 SINFONI  
(Hoeijmaker+, 2018, subm.)
Improve XAO
10m class telescopes
near-mid-IR

Disks & lighter young GP around ~ 5 AU

E-ELT 1st gen. instruments
MICADO, HARMONI, METIS

Disks & young GP tens of AU in SFR
Inner components of disks
sub-Jup GP a few AU

JWST (mid-IR)
Light (0.2MJ) young GP, 10au
>2MJ GP around < 2Gyr close M

WFIRST (optical)
Detection down to super Earths
LR spectra
Disks

LUVOIR, HabEx
Earth in HZ atmospheres, Habitability
Exoplanets Imaging with JWST

Complementarity ground & space
• JWST: light planets further than 1"
• Ground AO: planets within 1"

Niche for JWST
• Light, young giant planets (0.2 MJup, 10 AU)
• >2MJup planets few au from <2Gyr, close (<10pc) M dwarfs

Beichman, 2010
Improving current systems on 10m

There is a spectrum of possibilities, with different levels of complexity and costs

• More sensitive WFS
• Faster correction
• Improved correction of NCPA
• Improved instrumental stability
• Improved coronagraphs (Vortex, APP and derivatives are not yet used routinely !)
• Coupling spectroscopy and XAO (various flavors)

Such improvements will serve as test benches for ELTs
Improving current systems on 10m

Basic Requirements

- IWA down to 0.1"
- $C=10^{-5}$ (goal a few $10^{-6}$) at 0.1-0.2" (5-20 au at 50-100 pc: e.g. Sco -Cen) under median conditions
- Spectral Resolutions: 2 interesting domains: 5000-10000 for detection and 100000 for Doppler charac.
- Wavelength domains: H, K, (L-M)
- For targets brighter than $R\sim 13$ (// Sphere)
- Access targets fainter than $R\sim 13$ (P2)