Scientific impact of PSF knowledge for AO assisted spectrographs

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(on behalf of HARMONI Science Team)
HARMONI – spatial setup

For non-AO & visible observations

- 60 mas × 30 mas

For optimal sensitivity (faint targets)

- 20 mas
- 10 mas
- 4 mas

Best combination of sensitivity and spatial resolution

Highest spatial resolution (diffraction limited)

- 4 mas

Equivalent slit length:

- 16 arcmin
- 3.2 metres in ELT focal plane

6.42” × 9.12”

3.04” × 4.28”

1.52” × 2.14”

0.61” × 0.86”

~152 × 214 (32000) spaxels at all scales
## HARMONI spectral setup

<table>
<thead>
<tr>
<th>Bands</th>
<th>Wavelengths (µm)</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>“V+R” or “I+z+J” or “H+K”</td>
<td>0.45-0.8, 0.8-1.35, 1.45-2.45</td>
<td>~3000</td>
</tr>
<tr>
<td>“I+z” or “J” or “H” or “K”</td>
<td>0.8-1.05, 1.05-1.35, 1.45-1.85, 1.95-2.45</td>
<td>~7500</td>
</tr>
<tr>
<td>“Z” or “J_high” or “H_high” or “K_high”</td>
<td>0.9, 1.2, 1.65, 2.2 (TBD)</td>
<td>~20000</td>
</tr>
</tbody>
</table>
HARMONI Adaptive Optics Flavours

<table>
<thead>
<tr>
<th>SCAO</th>
<th>NOAO</th>
<th>LTAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1% sky coverage</td>
<td>100% sky coverage</td>
<td>30-50% sky coverage</td>
</tr>
<tr>
<td>Diffraction limited (0.01&quot;)</td>
<td>Seeing limited (0.7&quot;)</td>
<td>Diffraction limited (0.01&quot;)</td>
</tr>
</tbody>
</table>
ELT AO PSF varies strongly with $\lambda$

S. Zieleniewski et al. (MNRAS 2015)
Titan at many wavelengths
Motivation for PSF reconstruction

- Create mock observations of sources with simulated PSF, using HSIM
- Analyse (noisy) data using Original PSF, and ”wrong” PSFs, with different Strehl, jitter, and elongation.
- Quantify dependence of extracted parameters on PSF knowledge required accuracy
HARMONI Simulator Scheme

- HARMONI design + throughput
- Sky transmission + radiance
- Noise model
- Atmospheric differential refraction (ADR)
- AO PSF
- Science input cube
- DIT x NDIT

HARMONI observed cube

Institutional logos present at the bottom of the image.
PSF effects

- Strong variation of PSF with wavelength
- Parameterize PSF (axi-symmetric) with a few parameters, which vary smoothly with wavelength.
- Allows quick computation of PSF at any wavelength, with high accuracy.
- Extended to allow user defined PSF, interpolated in $\lambda$
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## PSFs used in simulations

<table>
<thead>
<tr>
<th>PSF name</th>
<th>LGS asterism diam.</th>
<th>Residual jitter</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>2.2 arcmin</td>
<td>3 mas rms</td>
<td>N/A</td>
</tr>
<tr>
<td>New_PSF1</td>
<td>1 arcmin</td>
<td>2 mas rms</td>
<td>N/A</td>
</tr>
<tr>
<td>New_PSF2</td>
<td>1 arcmin</td>
<td>4 mas rms</td>
<td>N/A</td>
</tr>
<tr>
<td>New_PSF3</td>
<td>1 arcmin</td>
<td>4 mas × 2 mas rms</td>
<td>45 degrees</td>
</tr>
<tr>
<td>New_PSF4</td>
<td>1 arcmin</td>
<td>4 mas × 2 mas rms</td>
<td>0 degrees</td>
</tr>
</tbody>
</table>
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Study three science cases

• Effective radius of high-z star forming galaxy (with S. Kendrew, B. Haußler, M. Richardson)

• Rotation curves of high-z galaxies (long slit and IFS) (with L. Routledge, M. Richardson, M. Pereira)

• Stellar kinematic signatures of intermediate mass black holes in nuclear stellar clusters (with T. Yasin, R. Houghton, J. Magorrian)
NUTFB simulation@ z=3

- $M_{DM} = 5 \times 10^4 \, M_\odot$
- $M_{\text{star}} = 2 \times 10^4 \, M_\odot$
- $n_{\text{th}} = 400 \, \text{cm}^{-3}$
- $z_{\text{end}} = 3$
- $z_{\text{UV}} = 8.5$
- $\text{SFE} = 1\%$
- SN Type II feedback

- Zoom-in sim from the NUT suite (Powell+ 2011; Kimm + 2011) using RAMSES (Teyssier 02)
- Terminates @ $z=3$ (@ ~2.2 Gyr), physical spatial resolution of 12 pc
Every star particle represents a simple stellar population (SSP)

- Age
- Metallicities
- \([x, y, z]\) velocity (rest-frame)
- Mass

Star particle (SSP) spectrum

Library of model spectra
Compare star formation history deduced from fit to absorption line spectra with input

Compare observed metallicity & gradients with intrinsic ones

Use stellar kinematics to infer a dynamical mass, and compare with DM and baryonic mass

Look at dependence of observed features on IMF, to determine diagnostics

Important to disentangle PSF effects!

S. Kendrew et al. (2016)
Effective radius of the galaxy

Galaxy 1: faint, almost round, $R_{\text{eff}}$ (actual) = 40 mas (0.3 kpc at $z = 3$)
Observed (with no PSF effect taken into account): $R_{\text{eff}} = 140$ mas

<table>
<thead>
<tr>
<th>PSF used</th>
<th>$R_{\text{eff}}$ (PSF deconvolved)</th>
</tr>
</thead>
<tbody>
<tr>
<td>original</td>
<td>$43.4 \pm 3.9$ mas</td>
</tr>
<tr>
<td>Higher Strehl, round (2mas rms jitter)</td>
<td>$71.8 \pm 8.8$ mas</td>
</tr>
<tr>
<td>Higher Strehl, elongated, rotated (4 x 2 mas)</td>
<td>$162.4 \pm 40.7$ mas</td>
</tr>
</tbody>
</table>

Galaxy 2: brighter, not round

<table>
<thead>
<tr>
<th>PSF used</th>
<th>$R_{\text{eff}}$ (PSF deconvolved)</th>
</tr>
</thead>
<tbody>
<tr>
<td>original</td>
<td>$85.8 \pm 0.6$ mas</td>
</tr>
<tr>
<td>Higher Strehl, round (2mas rms jitter)</td>
<td>$189.2 \pm 1.2$ mas</td>
</tr>
<tr>
<td>Higher Strehl, elongated, rotated (4 x 2 mas)</td>
<td>$189.4 \pm 1.2$ mas</td>
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Gas kinematics at $z = 1.44$
Velocity fields & warps

1’-2mas-0

1’-4mas-0

1’-4x2mas-45

1’-4x2mas-0

2.2’-3mas-0 (original)

Input cube
Extracted rotation curves

Different methods for obtaining a rotation curve.

- Simulation
- Input
- Original PSF
- 2mas Round PSF
- 4mas Round PSF
- 4x2mas 45° PSF
- 4x2mas 0° PSF

Radius (")

Rotation Speed (km/s)

Radius (kpc)
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Plummer model of NSC

• Observed at 4 mas spaxels
• 900s × 40 (5 hours)
• LTAO PSF
• K band (2.25 μm, single abs. line)
• R = 7500
• 0.7” seeing, 10 deg ZD
• Rₕ = 3.5 pc
• 10 Mpc distance
• M_BH/M_NS = 0.1
• M/L = 1
Fit using forward modelling
Impact of PSF knowledge

!! Work in progress !!

Signature of Intermediate Mass Black Hole

Velocity dispersion (km/s) vs. Radius (milli-arcsec)
PSF effects 🔄 "Fake News"

- The Donald will be happy!