Imaging the high redshift universe with MICADO on the ELT

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on behalf of the MICADO consortium in Germany, France, Netherlands, Austria, Italy and at ESO

- MICADO the Instrument
- Galaxy Evolution at high redshift
- Galactic Archaeology
- Spectroscopy
MICADO "stand-alone"

Stand-alone phase with just SCAO during initial operations.

Long term operation with MAORY (LGS-MCAO, & keeping SCAO).

MAORY: project led by INAF, uses 4-6 LGS and up to 3 NGS to provide uniform AO correction over full MICADO field.

-> talk by P. Ciliegi this afternoon
Key Capabilities

MICADO will be used with the MAORY system to provide:

| Imaging          | • 0.8-2.4µm with 30 broad/narrow filters  
|                  | • 1.5 & 4mas pixels for 19” & 51” FoV at 6-12mas  
|                  | • Similar sensitivity to JWST, and 6× better resolution |
| Astrometric imaging | • 10-50µas precision anywhere in the field  
|                   | • 10µas/yr = 5km/s at 100 kpc after only a few years |
| High Contrast imaging | • focal & pupil plane coronagraphs  
|                    | • angular differential imaging  
|                    | • small inner working angle |
| Spectroscopy      | • for compact sources  
|                  | • fixed configuration for 0.84-1.48µm & 1.48-2.46µm  
|                  | • R ~ 20000 for point sources (R ~ 10000 across slit) |
Inside MICADO

- **SPE** (Spectroscopy): 2 gratings
- **PIM** (Pupil Imager): 2 mirrors + 1 lens
- **LRI** (Low Resolution Imager): 4 mas imager (2 flat fold mirrors)
- **HRI** (High Resolution Imager): 1.5 mas imager (4 fixed mirrors)

**Cryostat**
- Diameter: 2 m
- Mass: 4800 kg

**Focal Plane Array**
- 3×3 HAWAII 4RG detectors
MICADO Science Themes

- Potential to address a large number of science topics
- Science Report focus is on themes where MICADO can make major progress:
  - Dynamics of dense stellar systems,
  - Black holes in galaxies and the centre of the Milky Way,
  - Formation and evolution of galaxies in the early universe,
  - Star formation history of galaxies through resolved stellar populations,
  - Planets and planet formation,
  - The solar system.
Galaxy Evolution with MICADO

GOODS-S 150 arcmin²
- ~3000 log(M_/M☉) > 9  z=1-4
- ~150 log(M_/M☉) > 11  z=1-4
- ~300 z > 8

MICADO 0.7 arcmin²
- ~15 log(M_/M☉) > 9  z=1-4
- ~0.7 log(M_/M☉) > 11  z=1-4
- ~1.5 z > 8

HUDF 6 arcmin²
- ~120 log(M_/M☉) > 9  z=1-4
- ~6 log(M_/M☉) > 11  z=1-4
- ~12 z > 8

814 HST orbits, ACS+WFC3
UV - V  R - Y  J - H

HUDF 2014
NASA Release 14-151 / STScI Release 2014-27
Structure of high-z Galaxies

Spatial resolution
Order of magnitude gain in resolution from 1 kpc- to 100 pc-scale at z > 1.
6-12 mas ~ 50-100 pc matches seeing limited scale for Virgo cluster galaxies.

JWST will select samples & measure basic galaxy properties.

MICADO will trace stellar continuum & provide detailed structure.

Synergies with ALMA, HARMONI, etc.

combined JHK images of local templates (BVR bands) shifted to z=2 (top) and z=1 (bottom), with $R_{\text{eff}}=0.5''$ and $M_V=-21$; 5hrs integration.
Structure of high-z Galaxies

Key science drivers at $z > 1$
- Resolving disks, bulges, clumps.
- Characterising SSCs.
- Resolving compact galaxies at $z > 1$.
- Massive ETG progenitors in dense environments.
- QSO host properties.
- Structure of lensed galaxies on $<100$ pc scales.
- The first galaxies.
- Substructure of DM halos to $\sim 10^7 M_{\odot}$.

SimCADO simulations
https://simcado.readthedocs.io

Based on HUDF source catalog with additional clump and cluster populations.
MICADO, 10hrs each on IJH bands.

Cut-out size in main field: □

Courtesy of N.M. Förster Schreiber
Galaxy Evolution: Archaeology

- Spatially resolved stellar populations -> cosmic star formation history
- Resolution -> galaxy centres
- Horizontal branch -> oldest populations
- Virgo cluster -> tip of RGB

Compilation from Madau & Dickinson (2014)
Galaxy Evolution: Archaeology

SimCADO simulations:
- 1" x 1" fields
- matching NGC 4472
- 18 Mpc in Virgo Cluster

HST / WFC3  JWST / NIRCam  ELT / MICADO

\[ \mu = 19.6 \quad (10^6 \text{ stars/arcsec}^2) \]

\[ \mu = 22.0 \quad (10^5 \text{ stars/arcsec}^2) \]

\[ \mu = 25.2 \quad (10^4 \text{ stars/arcsec}^2) \]
SCAO for initial operations - an example

The structure of lensed Lyman-α absorbers/emitters at 4 < z < 5
(courtesy of G. Caminha & K. Caputi)

Cluster CL0102 (El Gordo):

- 4 spectroscopically confirmed Lyα emitters/absorbers at z=4.3, within ~8” of a star with $H_{AB} = 15.6$ mag & Gaia G =15.9 mag. (Caminha et al. 2019)
- Even with lensing magnification, HST resolution of 90mas is insufficient to resolve morphology.

ID3-b
Highest magnification of 10
Observed magnitude $H_{AB} = 23.6$
SCAO for initial operations - an example

The structure of lensed Lyman-α absorbers/emitters at 4 < z < 5
(courtesy of G. Caminha & K. Caputi)

Question: can clumpy star-forming regions be resolved in ID3-b?

- SimCADO simulations: 2-hr integration of sources based on size & total flux in ID3-b.
- MICADO can easily distinguish clumpy and smooth distributions.
- Clumps with $K_{AB} < 29.5$ can be detected for all sizes considered in range 3-600pc; small fainter clumps can also be detected.
- Lensing in ID3-b allows one to detect structures to 10-20pc scales in K-band.
Sensitivity

- Depends on:
  - AO performance; nominal Strehl for MCAO 40% / 18% / 6% for K / H / J band
  - ambient temperature (warm telescope; AO cooling)
  - how flux is measured (e.g. aperture vs PSF fitting)
  - source structure
  - location in field for SCAO (note MCAO is uniform)
- Real numbers can vary by 1mag either way

<table>
<thead>
<tr>
<th></th>
<th>FWHM mas</th>
<th>1hr, $\sigma$ AB mag</th>
<th>5hr, $\sigma$ AB mag</th>
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<tr>
<td>Ks</td>
<td>11</td>
<td>28.2</td>
<td>29.0</td>
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<tr>
<td>H</td>
<td>8</td>
<td>28.6</td>
<td>29.5</td>
</tr>
<tr>
<td>J</td>
<td>6</td>
<td>27.7</td>
<td>28.5</td>
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![PSF profile graph](image_url)
Empirical vs Reconstructed PSF

How many stars in the field?

- On average, ~3 stars / sq. arcmin for \( K_{AB} < 27 \) mag in classical deep fields.
- Would be well detected in integrations > 1 hr, so could be used as PSF reference (for MCAO).
- \textit{But} MICADO field is 0.7arcmin\(^2\), so 35-45% chance there is \( \leq 1 \) star in a pointing.
- PSF reconstruction is mandatory – and is part of MICADO project.

\[
K_{AB} = 23 \text{ mag} \quad \text{and} \quad K_{AB} = 27 \text{ mag}
\]

Simulation of 3 hr integration
Spectroscopy

Purpose

- Large simultaneous wavelength coverage at high spectral resolution, optimized for point sources.

Characteristics

- Fixed single configuration: order sorting filters switch between options of 1.48 - 2.46 µm, 1.15 - 1.35 µm, & 0.84 - 1.48 µm.
- Slit width: narrowest is 16mas (60µm);
- Slit length: 15” for HK and J-bands, 3” for IzJ band.
- Resolution: 10000 integrated across slit; 20000 for point sources.
- Operationally: default alignment along parallactic angle (ADC is after the slit); also option for user to choose position angle
High-z science cases include:

- Dynamical mass of compact & early type galaxies in the early universe via velocity dispersion of stellar absorption features.
- Star formation rates, dust, metallicities, excitation, kinematics, in star forming galaxies via multiple line ratios.
MICADO and JWST

MICADO & JWST have similar sensitivity, but MICADO will resolve structures that JWST cannot detect.

In crowded fields, resolution gives an effective sensitivity gain of ~3mag wrt JWST, allowing MICADO to probe regions where JWST cannot reach.

MICADO will achieve astrometric measurements ~6 times faster, or for objects ~6 times more distant, than JWST.
MICADO will be a first light instrument for the ELT

It will work with the MAORY adaptive optics system.

It’ll do imaging at 6-12mas resolution over a 50” field to J/H/K ~ 29 mag AB,
R~20000 spectroscopy covering H & K simultaneously,
(also astrometric & high contrast imaging).

It’ll use SCAO for initial operations, &
MCAO, providing uniform correction over the field.

It’ll provide the user with a reconstructed PSF reference.

Try out SimCADO and see what it can do for you.