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MICADO, THE ELT FIRST-LIGHT IMAGER

Y. Clénet[1], P. Baudoz[1], R. Davies[2], E. Tolstoy[3], K. Leschinski[4] and the MICADO consortium

Abstract. The MICADO instrument is the first light imager of the European ELT. It will work in the near-infrared (0.8-2.4 μm), over a large field (up to 50″) and high sensitivity (similar to JWST).

MICADO will benefit from two modes of adaptive optics correction: a MCAO correction, uniform on the field of MICADO and developed by the MAORY consortium, and a classic correction of the SCAO type, with high performance in the direction of the star guide and developed under the responsibility of the MICADO consortium. In a phased approach of the integration of adaptive optics to the ELT, MICADO will first be operational in SCAO mode.

Offering four observing modes (imaging mode, astrometry, long-slit spectroscopy with R$\sim$20000 and high contrast imaging), MICADO aims to scan a wide range of scientific objectives: small bodies and planets of the solar system, exoplanets and exo-disks, stellar populations in distant galaxies, black holes and the center of our galaxy, evolution and dynamics of galaxies.

Keywords: MICADO, ELT, SCAO, MCAO, observing modes, science cases

1 MICADO: the project and its French contribution

MICADO (Multi-AO Imaging Camera for Deep Observations) is the European Extremely Large Telescope (ELT) first-light imager, working at the telescope diffraction limit in the near-infrared (Davies et al. 2018).

The consortium is lead by R. Davies, from the Max Planck Institute for Extraterrestrial Physics (MPE), and comprises, in addition to MPE, the Max Planck Institute for Astronomy (MPIA), the University Observatory Munich (USM), the Institute for Astrophysics of Göttingen, the Netherlands Research School for Astronomy (NOVA), the Institut National des Sciences de l'Univers (INSU, acting on behalf of LESIA, GEPI, IPAG, Observatoire de Besançon and the INSU Technical Division), the A* Austrian partnership and the Instituto Nazionale di Astrofisica (INAF).

The project started in October 2015, with the signature of the contract between ESO and the MPE, representing the consortium. The Preliminary Design Review occurred as planned after three years, in November 2018, and has been successful. The Final Design Review is planned in late 2020. It will be followed for 3.5 years by the Manufacturing, Assembly, Integration and Test phase, ending with the Preliminary Acceptance in Europe, mid 2024. The instrument will then be shipped to Chile, integrated and commissioned after the technical first light of the telescope, now planned in November 2025.

In the project, INSU is responsible for the development of the Single Conjugate Adaptive Optics (SCAO) mode, made of a wavefront sensor, a real-time computer, a dedicated calibration unit as well as their corresponding, either non real-time or real-time, software (see Sect. 3). INSU is also responsible for the development of the MICADO high contrast imaging mode (see Sect. 2).

[1] LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris, 5 place Jules Janssen, 92195 Meudon, France
[2] Max Planck Institute for extraterrestrial Physics, 85748 Garching, Germany
[3] Kapteyn Astronomical Institute, 9700 AV Groningen, The Netherlands
[4] Institute for Astrophysics, University of Vienna, Türkenschanzstrasse 17, 1180 Vienna, Austria

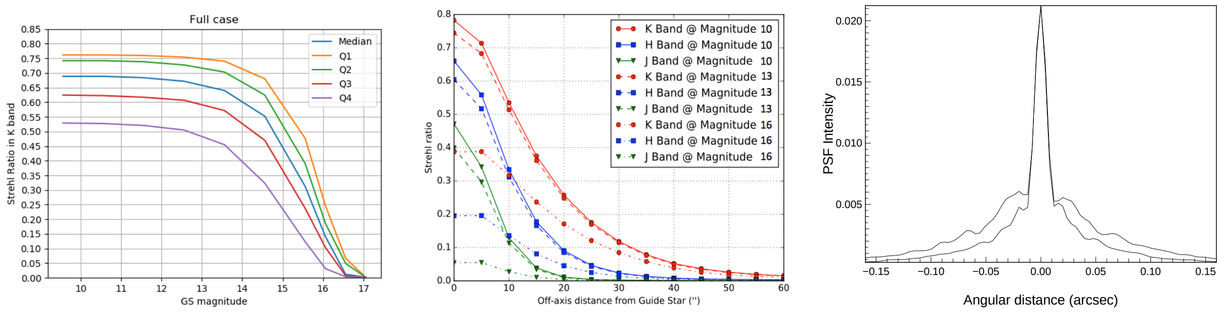

Fig. 1. Left: K-band SCAO performance vs. the guide star magnitude for the different ESO atmospheric conditions. Note that the complete SCAO performance is obtained from these end-to-end AO simulations results and additional instrumental error terms (130 nm rms left for these instrumental contributors to fulfil the SCAO performance specifications of SR=60%). Middle: Off-axis SCAO performance under Q2 seeing conditions for magnitudes R=10, 13 and 16. Right: SCAO PSF radial and transversal cuts obtained for L_0=25 m and 60 arcsec off-axis distance. The maximum intensity is equal to the K-band Strehl ratio, i.e. about 2%.

2 MICADO observing modes

MICADO is being designed to provide four observing modes: imaging, astrometric imaging, spectroscopy and high contrast imaging.

MICADO will provide images in the near-infrared, between 0.8 and 2.4 μm. More than 30 broad-band and narrow-band filters will be available to cover the numerous science cases that such an ELT first-light instrument will address. The default pixel size will be 4 mas, with a corresponding field of view of $\sim$50$''\times$50$''$, allowing the instrument to work at the diffraction limit of the telescope in the H and K bands. A zoom mode, with a 1.5 mas pixel size over a field of view of $\sim$19$''\times$19$''$, will be available to work at the telescope diffraction limit over the whole MICADO bandpass as well as to increase the instrument astrometric precision. Hence, MICADO will have a sensitivity similar to JWST with a six times better spatial resolution.

MICADO aims at bringing astrometry into mainstream. The instrument is being designed for that purpose: in a gravity-invariant configuration, it will make use of only fixed mirrors and specific calibration procedures will be developed. The goal is hence to reach 50 microarcsecond precision anywhere in MICADO field of view, which translates into 10 microarcseconds per year after 3-4 years of observation, i.e. 5 km/s at 100 kpc distance. From Fritz et al. (2015), the absolute proper motion measurement errors with MICADO could be reduced down to 1 km/s at a distance of 100 kpc for 5 year observation baseline.

MICADO will also come with spectroscopic capabilities. This mode will provide coverage of a wide wavelength range simultaneously (1.15-1.345 μm, 1.48-2.45 μm or 0.845-1.48 μm) at a resolution of $\sim$20000 on faint compact or unresolved sources. Three slits will be available: 3$''\times$16 mas, 15$''\times$20 mas (for sky subtraction along the slit), 3$''\times$48 mas (ÒwideÓ).

The high contrast imaging mode will use the central detector and will be enabled via a classical configuration of focal plane coronagraphs and Lyot stops, as well as pupil plane vAPP coronagraphs and sparse aperture masking (Baudoz et al. 2019). Pupil tracking will be available for angular differential imaging.

3 Adaptive optics for MICADO

MICADO will benefit from two modes of adaptive optics (AO). The first one is a Multi-Conjugate AO (MCAO) correction, uniform over the field of MICADO (Strehl ratio at K of $\sim$30-40% on 50% of the sky), developed by the MAORY consortium, and for which the design of MICADO is optimized. See Ciliegi et al. (2018) and Douté et al. (2019) for additional information, in particular regarding AO performance.

MICADO will also benefit from a SCAO correction developed under MICADO's responsibility and jointly by MICADO and MAORY(Clénet et al. 2018, 2019). The AO performance is expected to reach SR(K)$\sim$60% nearby the reference source (Fig. 1, left), degrading with the distance to it (Fig. 1, middle). One has to remember that at the ELT, with a telescope diameter larger than the outer scale L_0, the coherent core in the PSF is preserved even at low Strehl ratio (Fig. 1, right, Clénet et al. 2015), making possible to address astrometry over a large field even in SCAO.

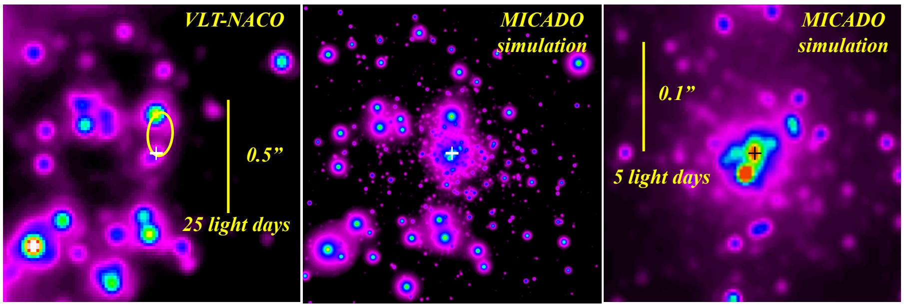

Fig. 2. Simulated MICADO image of the central cusp in the Galactic Centre (middle and zoomed on the right), compared to a current high-quality VLT/NACO K-image (left).

In a phased approach of the AO integration at the ELT, SCAO will be the first AO mode to be tested with MICADO at the telescope and will be ultimately offered as a MAORY mode.

4 MICADO science

4.1 Main science objectives

MICADO has the potential to address a large number of science topics that span the key elements of modern astrophysics. The science drivers focus on several main themes: the dynamics of dense stellar systems, black holes in galaxies and the centre of the Milky Way, the star formation history of galaxies through resolved stellar populations, the formation and evolution of galaxies in the early universe, planets and planet formation, and the solar system. To address these, MICADO will exploit its key capabilities of sensitivity and resolution, which are in turn leveraged by its observing modes of imaging, astrometry, coronagraphy, and spectroscopy. With a point-source sensitivity that is comparable to JWST and a resolution about a factor 6 better, MICADO is well suited to numerous science cases. Two examples of these, in the extragalactic field, are highlighted below. The MICADO science cases related to the exoplanet characterization and to the solar system study are described in Baudoz et al. (2019) and Merlin et al. (2019), respectively.

4.2 Galaxy evolution, structure of high-z galaxies

We now have a fairly robust outline of the cosmic evolution of global galaxy properties, and hence the first pieces of evidence about how galaxies assembled and transformed into the present day Hubble sequence. An obvious next step is to resolve the faint distant galaxies on sufficiently small scales to assess their sub-galactic components including disk structures, nascent bulges, clumps, and globular cluster progenitors.

The current view is limited by spatial resolution, which corresponds to ∼1 kpc in the best cases (space-based telescopes or adaptive optics on 8-m class ground-based telescopes). In particular, relatively unexplored regimes include lower mass galaxies, comprising the bulk (by number) of the galaxy population, and galaxies at early cosmic times, when they were building their first stars.

An alternative probe of galaxy evolution is via the relic populations in local galaxies, by performing photometry on individual stars to generate a color magnitude diagram (CMD). The various features of a CMD relate to stars formed at different cosmic times. In particular, detecting stars on the horizontal branch enables one to trace the star formation history of galaxies to $z>6$, to the reionization epoch. The ultimate goal for resolved stellar populations is to probe the central regions of elliptical galaxies in the Virgo Cluster. The high surface brightness, due to extreme stellar crowding, makes this very challenging. JWST will only be able to probe the outskirts of these galaxies, while the higher resolution of MICADO will enable it to reach almost to the centre where the bulk of the stars are to be found.

4.3 Black holes near & far

All reasonably massive galaxies appear to host supermassive black holes in their centres ranging in mass from several million to several billion solar masses (e.g., Kormendy & Ho 2013). Understanding why this is so and

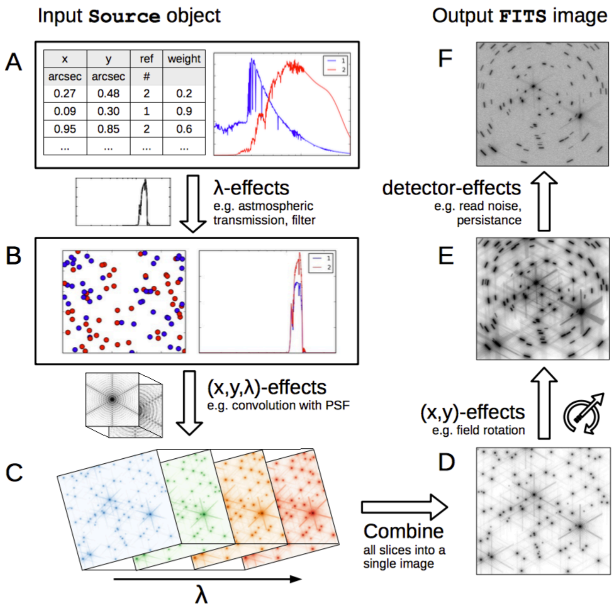

Fig. 3. SimCADO data model, representing the flow of events from the creation of the source object (here a mock open cluster) to the output FITS image. More details in Leschinski et al. (2016)

what is the link with galactic evolution processes, and how their properties depend on, or are affected by their environment are long standing and important issues.

We still need to understand the formation of galaxy cores, central star clusters and supermassive black holes, and the mechanisms of mass transport into these central regions and the influence of and on the galaxy-scale and larger environment. A suite of different mechanisms is expected to be at work, spanning nine orders of magnitude in linear scales from galaxy environment down to the sphere of influence of a central black hole.

So far, the fundamental limiting factor has been that of spatial resolution of current imaging and spectroscopic instrumentation. The highest fidelity measurements of supermassive black hole masses are obtained either through the observation of quasi-Keplerian orbits of stars around the black hole in our own Milky Way (e.g., Gillessen et al. 2017) or from the measurements of the circular motions of water masers (e.g., Kuo et al. 2011). But such measurements are only possible for a very few cases. The size of the spatial region where black holes directly influence the motions of stars and gas through their gravity – the sphere of influence – ranges from 1 pc (for $M_{BH} \sim 10^6\, M_{\odot}$) to 1 kpc (for the most massive $M_{BH} \sim 10^{10}\, M_{\odot}$ black holes). To obtain accurate measurements this sphere of influence must be at least marginally resolved.

MICADO will reach 10 mas spatial resolution, and consequently the observable volume will increase by a factor of >300 over what is possible today. With this, MICADO will be the first instrument able to probe core properties and nuclear morphologies for a large number of objects over a range of distance. MICADO will be able to determine black hole masses down to $\sim 10^6\, M_{\odot}$ and out to redshifts, z$\sim$3. This will increase the number of direct stellar dynamical black hole mass measurements from the current few hundred to several tens of thousands. MICADO will also deliver superior sky subtraction compared to small IFUs, such as on HARMONI. This is crucial for the study of extended objects where the surface brightness typically lies below that of the night sky.

5 MICADO data simulation software packages: SimCADO & SpecCADO

SimCADO is a python package designed to simulate the effects of the atmosphere, ELT, and MICADO instrument on incoming light (Leschinski et al. 2016). It provides a framework for simulating raw output images based on the most recent design of the instrument. SimCADO is also highly configurable. The user is able to simulate various observational scenarios, e.g. the use of different adaptive optics (AO) systems, or set the effectiveness of different subsystems along the optical train, e.g. the performance of the derotator or atmospheric dispersion corrector (ADC). SimCADO is available on GitHub.

While SimCADO only provides functionality for imaging in the wide-field and zoom modes, a similar simulation package exists for the MICADO spectroscopic mode: SpecCADO. Soon available on GitHub, SpecCADO currently only simulates point sources (represented by the PSF) and background sources (that fill the slit homogeneously). It produces 2D spectra, accounting for various instrumental effects, and reproduces in the end the spectral layout on the MICADO's detectors.

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