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EXOPLANETARY SYSTEMS STUDY WITH MICADO

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Abstract. The observation and characterization of the exoplanets and planetary architectures are crucial to broaden and complete our vision of the formation and evolution of planetary systems but also of the physics of the atmospheres of the exoplanets. In this context, MICADO, the European Extremely Large Telescope first-light imager will be equipped with an imaging mode dedicated to exoplanets and a long slit spectroscopy mode (R = 20 000) with an unbeaten sensitivity. The 5-fold increase in the angular resolution between the current instruments like SPHERE or GPI and MICADO will allow a quantitative and qualitative jump on the study of these planetary systems. Among the promising scientific cases: the characterization of exoplanets in synergy with GAIA and radial velocity surveys (eg SPIRou), the study of disk-planet interactions, the high-resolution study of exoplanetary atmospheres.

Keywords: exoplanet, high contrast imaging, coronagraph, MICADO

1 Introduction

Instruments based on extreme adaptive optics like SPHERE on the VLT (Beuzit et al. 2019) or GPI on GEMINI (Macintosh et al. 2015) improved our understanding of the formation and evolution of planetary systems. However, questions are still pending on formation scenarii, the physics of planet atmospheres, the frequency of giant planets in long orbits (> 5-10 AU), etc. While space instruments aboard JWST (2020) will bring new insights to exoplanet science, they will be limited in contrast and angular resolution compared to an instrument that would take place on the ELT. Such an instrument that would be dedicated to direct imaging and spectroscopy of exoplanets on the ELT will only come after the first light instruments. Taking advantage of the 5-fold increase in the angular resolution between the ELT and the current ground-based telescope (or the planned space-based telescope), there is an opportunity for exoplanet science before this dedicated ELT planet finder comes online in 2030s.

2 MICADO

MICADO is the European Extremely Large Telescope first-light imager. The instrument will work in the near-infrared, from 0.8 to 2.4 microns, with a field of view of about one arcmin, delivering images at the telescope diffraction limit thanks to adaptive optics correction (Clenet 2019). MICADO will offer to the astronomers four observing modes:

1. Classical imaging with a field of view (FOV) up to 50"x50" and more than 30 broad and narrow filters.
2. Astrometric imaging with a precision of 10 to 50 μas relative to a set of reference sources in the field.
3. Long-slit spectroscopy covering simultaneously several spectral bandwith (IJ or HK) with a spectral resolution up to 20 000 for point sources that can be used to study exoplanet atmospheres.
4. High contrast imaging with a FOV of 6"x6" that can use either focal plane coronagraphic masks (classical Lyot or more complex phase mask) or pupil plane coronagraphic masks. This mode is design for the observations of exoplanetary systems.

The project kick-off took place in October 2015. The preliminary design took place in 2018 and first light is expected in 2025-2026.

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3 MICADO high contrast mode

Unlike SPHERE, MICADO is not fully dedicated to exoplanet science. The optical design of MICADO is thus the results of a trade-off between all the modes of the instrument. The main components of the high contrast mode of MICADO are described below:

1. **Three Focal plane coronagraphs**

   (a) **Classical Lyot Coronagraph with the radius of 25.34 mas**
   Because of its large central obscuration and its segmented pupil, the ELT pupil is not optimized for coronagraphy. Indeed, the large central obscuration and the presence of gaps increase the number of edges in the pupil, thus the amount of stellar light diffracted by these edges. One solution to overcome this problem is to couple the focal plane mask with an apodization mask at the entrance pupil of the instrument to compensate the effect of the diffraction by the central obscuration. This solution is used on SPHERE and GPI but the final design of MICADO does not permit it. Thus, simple Classical Lyot Coronagraphs (CLC), without apodization are selected as a baseline. A CLC is an occulting mask in the focal plane and must be coupled with a Lyot stop located in a pupil plane downstream of the focal plane mask. To take full advantage of the high angular resolution of the ELT, we decided to select one CLC that allows the detection of planet at short distance from the star (coronagraph with a small Inner Working Angle, IWA).

   (b) **Classical Lyot Coronagraph with the radius of 50.68 mas**
   Correction of atmospheric dispersion can only be apply downstream of the focal plane coronagraph. This will limit the spectral bandwidth for a small inner working angle coronagraph. A second CLC is optimized with a medium IWA (4-5 λ/D) to take care of the PSF atmospheric dispersion with broadband filter and to ensure a good sensitivity of the coronagraphic mode. The selection of the size of the 2 focal plane masks is linked to the selection of the dimension of the Lyot stop. The sizes of the 3 elements are optimized at the same time and the final radius of the CLC are 25.34 mas and 50.68 mas. For more information on this optimization, see Perrot et al. (2018).

   (c) **One focal plane slot for a more complex phase mask coronagraph**
   One of the drawbacks of the CLC is the limited attenuation of the coronagraph when decreasing the size of the occulting mask. Thus, the detection of a planet located at shorter angular separation to its star is limited. To improve the sensitivity to planet close to the star, one can use a phase mask with a smaller IWA to allow detection of planets at small angular separation of the star (1-1.5 λ/D in K band : 10-15 mas). We define a slot for such a coronagraph but the exact type of coronagraph planned for this slot is still under study.

2. **Three Lyot stops** coupled with these focal plane coronagraphs. These Lyot stop are located downstream of the focal plane coronagraph and will block the stellar light diffracted by the mask. These Lyot stop have an identical shape but 3 different transmissions (60%, 6%, 0.06%) to allow calibration of the star flux even for bright stars (K=3).

3. **One or two pupil plane coronagraphs based on phase apodization**
   These coronagraphs use interferences to attenuate the diffraction wings in a limited area of the field of view (FOV) without decreasing the total transmission of the instrument. This apodization decreases the Strehl ratio though and an optimization needs to be done to maximize the Strehl ratio and the useful FOV while minimizing the diffracted light at the shortest angular separation. In MICADO, we plan to use the implementation of vector Apodizing Phase Plate (vAPP, Snik et al. 2012). The vAPP can be designed for any pupil geometry even though complex pupil structure might decrease the Strehl ratio when trying to reach short angular separation.

4. MICADO will also include **one or two Sparse Aperture Masks (SAM)**. The principle of SAM is to insert in the pupil an opaque mask with a number of holes spatially distributed so that each pair of holes will contribute to a unique spatial frequency. Thus SAM imaging mode avoids the combinations of multiple spatial frequencies which – adding incoherently – may degrade the transfer function. With a well known transfer function of the instrument, one can partly distinguish the effect of optical aberrations from astronomical information and retrieve more precisely the environment of the star at very short angular separation (Lacour et al. 2011).

5. A **series of filters** partly optimized for high contrast imaging are located inside the MICADO cryostat.

6. The field of view will be rotating during observations to allow the stabilization of the pupil on the instrument (**pupil tracking mode**). This solution already used on all the high contrast imaging techniques helps improving the stability of the data and use optimized post-processing techniques for exoplanet study, such as Angular Differential Imaging or its derivatives (Galicher et al. 2018).

7. **A fine pointing control of the PSF** will be ensured by a dedicated coronagraphic image analysis to avoid potential drift between the coronagraph and the PSF position define by the adaptive optics (AO).

4 Performance of the MICADO high contrast mode

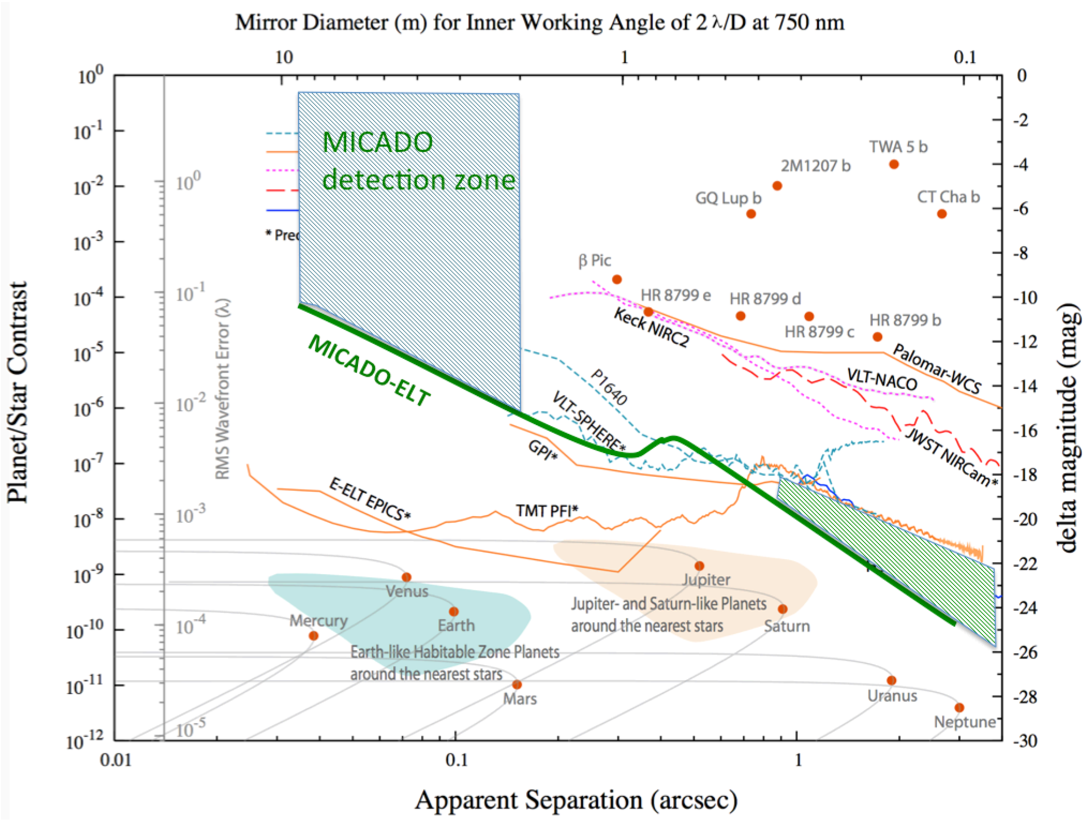

Fig. 1. Current and projected high contrast imaging capabilities in space and from the ground (adapted from Mawet et al. 2012). The left axis shows the planet/star contrast ratio. The x axis shows the angular separation in arcsec. All detectivity curves are 5σ for bright stars and scaled for a 1-hour observing time. MICADO expected performance is added to the figure. Shaded areas correspond to discovery space unreachable by actual instruments like SPHERE or GPI.

We developed a dedicated simulation tool that uses the output of MICADO single conjugated AO simulation (Vidal et al. 2018) to estimate the performance of MICADO in the context of exoplanet detection. The main inputs of this simulator are recalled below:

1. **Adaptive Optics residuals**
The residual dynamical phase aberrations are calculated using a dedicated COMPASS simulation for a conservative seeing (0.79") assuming telescope wind shake compensated by guide probe. The AO system simulated is a pyramid with a frequency of 500Hz (Vidal et al. 2018).

2. **Optical elements**
The simulation takes into account missing segments on the primary mirror, aberrations at different po-

sitions in the optical train (segments, upstream and downstream of the coronagraph). These aberrations can be either static or varying. The simulator tool includes the different CLC and vAPP coronagraphs

3. **Configurations**
Other inputs of the simulator are the declination of the star (to calculate parallactic rotation and atmospheric refraction), the total observation time (typically 1hr centered around the transit of the star), star magnitude, planet spectrum. The simulation also takes into account photon noise for a given magnitude, detector readout noise and atmospheric emission. Different astrophysical scenes can be simulated: planets, disks.

4. **Post-processing** is included in the performance analysis using classical Angular Differential Imaging.

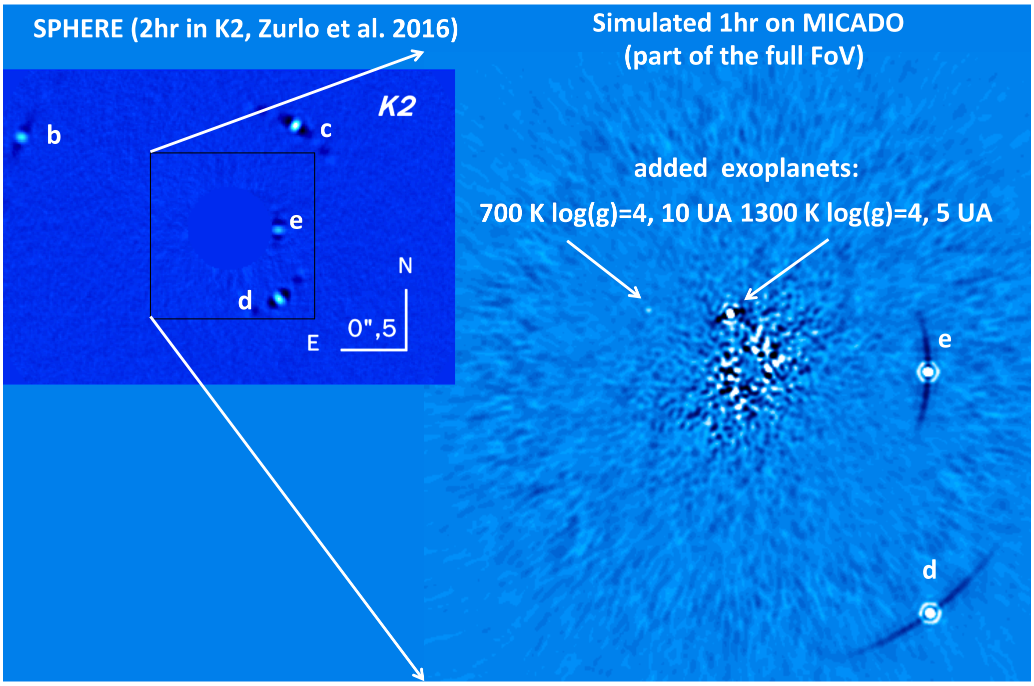

Fig. 2. Example of post ADI image showing: *on the left:* actual detection of 4 planets around HR 8799 by SPHERE (Zurlo et al. 2016) in K2 band ($\lambda = 2.255\mu m$), *on the right:* detection of simulated planets around HR 8799 using the actual measured flux for the closest planet *d* and *e* and using synthetic planet spectrum from EXOREM (Charnay et al. 2018) assuming 1 hour observation on MICADO at the same wavelength.

Simulation of MICADO performance for bright stars showed that the high contrast mode can improve the planet detection in two ways. On one hand, the ability to reach angular resolution below 200 mas is unprecedented and, on the other hand, a deep sensitivity at distance larger than one arcsecond is expected (Fig. 1).

Thus, MICADO should allow the search of new planets in already known planetary systems. These planets could be closer to their star or less massive than the one already detected. An example of such detection is shown in Fig. 2 where we simulated the observation of two additional inner planets in the HR8799 planetary systems, one of which with a temperature of only 700K. Note that the planets simulated are located at an angular distance where SPHERE is virtually blind as show on the left part of Fig. 2 where the central area is set numerically to zero.

The improvement in angular resolution will also enlarge the samples of ages of planetary systems by observing in more distant young associations (100-150 pc) and at close distance to these young stars (10 AU). Morphological and dynamical studies of planet-disk interactions will also be improved with the increase in both angular resolution and sensitivity. Finally, the simultaneous coverage of H+K of the long-slit spectroscopy at a resolution of 20 000 is also well suited to better define the composition of exoplanet atmospheres by removing systematics in the spectrum.

5 Conclusions

The high contrast imaging mode of MICADO includes focal plane and pupil plan coronagraphs, a series of Lyot stops and spectral filters, as well as a dedicated observation mode. A detailed simulation has started during the preliminary design phase and the estimated performance is very exciting by extending the search area of SPHERE for very young giant and massive planets at shorter orbital separations (a few AU) of nearby stars and around more distant star associations (100-150 pc). Gain in angular resolution and sensitivity should also allow MICADO to characterize more distant debris disks than SPHERE and gives a more detailed images of the closest ones. Performance will be refine during the final design phase with a better knowledge of detection signal to noise allowing to estimate the spectral and/or physical information we should be able to derive from the measurements.

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