Conditions and Impact of Star Formation
R. Simon, R. Schaaf and J. Stutzki (eds)
*EAS Publications Series, **75-76** (2015) 405–410*

E-ELT/METIS

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Abstract. The Mid-infrared E-ELT Imager and Spectrograph (METIS) will be one of the first three scientific instruments on the European Extremely Large Telescope (E-ELT). It will be the only instrument to cover the thermal/mid-infrared wavelength range from 3–19 μm. METIS offers a number of scientifically important observing modes, including diffraction-limited imaging, low resolution slit spectroscopy, coronagraphy, and high resolution ($R \sim 100{,}000$) integral field spectroscopy at very high sensitivity.

This paper gives a brief summary of METIS and focuses on its unique discovery space in the area of protoplanetary disks, where METIS is quite complementary to ALMA and JWST.

1 Introduction to METIS

METIS is the name of the Mid-infrared ELT Imager and Spectrograph, the only E-ELT instrument to cover the scientifically important thermal/mid-infrared wavelength range from 3–19 μm. METIS will be one of the the first three science instruments on the E-ELT, anticipating first light in 2025.

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DOI: 10.1051/eas/1575082

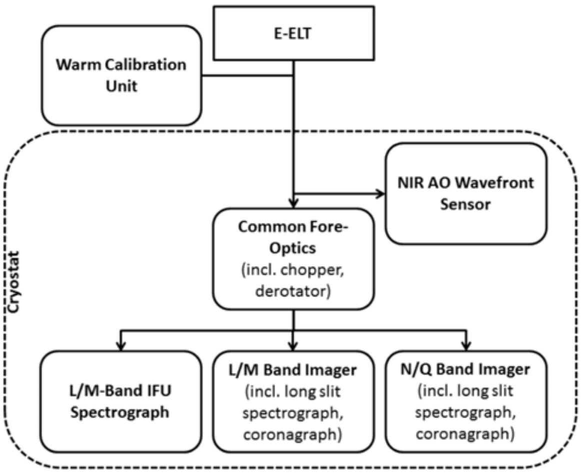

Fig. 1. METIS block diagram. A common re-imaging fore-optics provides the necessary processing like calibration, chopping, thermal background and stray light reduction (cold stop), image de-rotation etc. before the light enters into the science modules. The focal plane of the EELT lies outside the cryostat, as well as the warm calibration unit.

METIS will provide diffraction-limited performance in a variety of observing modes:

- Imaging at L/M band and N/Q band. Focusing mostly on known, compact targets, METIS requires only a moderate imaging field of view size (approximately $10'' \times 10''$).
- Low/medium resolution ($R \sim$ few hundred–thousand) slit spectroscopy.
- Several coronagraphic concepts for high contrast imaging.
- High resolution ($R \sim$ 100,000) IFU spectroscopy at L/M band, including a mode with extended instantaneous wavelength coverage.

Figure 1 shows the conceptual design of METIS. For more information we refer the reader to (Brandl *et al.* 2014). All observing modes work at the diffraction limit. The atmospheric turbulence will be corrected by a single conjugate (SC) or a laser tomography (LT) adaptive optics (AO) system. With this baseline, METIS incorporates important capabilities of several successful VLT instruments, most notably NACO, CRIRES and VISIR.

The METIS simulator (Schmalzl *et al.* 2012) has been used to derive the end-to-end instrument sensitivities, which are presented in Table 1. Although the imaging sensitivity of ground based thermal IR instruments is inferior to cooled space telescopes, the huge gain in angular resolution on a 39 meter telescope makes up for this. Due to the large dispersion, the spectroscopic sensitivity of METIS is even comparable with JWST-NIRSPEC for unresolved spectral lines, which often applies to Galactic targets.

Table 1. METIS sensitivity on spatially unresolved ("point") sources and spectrally unresolved lines. The sensitivities are for 10σ detections within one hour in either broad-band imaging or $R \sim 100,000$ integral field spectroscopy.

Band	λ_{center}	$F_{imaging}$	$F_{imaging}$	$F_{spectroscopy}$
L	$3.6\,\mu$m	21.3 mag	$0.9\,\mu$Jy	$2 \times 10^{-21}\,\mathrm{W\,m^{-2}}$
M	$4.8\,\mu$m	18.1 mag	$9.6\,\mu$Jy	$4 \times 10^{-21}\,\mathrm{W\,m^{-2}}$
N	$10.6\,\mu$m	15.1 mag	$34.1\,\mu$Jy	

The METIS consortium consists of seven institutions: NOVA/Leiden University (the Netherlands, PI: B. Brandl), MPIA (Germany, co-I: M. Feldt), CEA-Saclay (France, co-I: E. Pantin), UK-ATC (United Kingdom, co-I: A. Glasse), KU Leuven (Belgium, co-I: Ch. Waelkens), ETH Zrich (Switzerland, co-I: M. Meyer), and the A* Consortium [Universities of Wien, Linz, Graz, and Innsbruck] (Austria, co-I: M. Guedel).

2 Scientific perspectives of METIS

METIS unique contributions to astrophysics in the 2020s will likely be in science areas where high spatial or high spectral resolution or a combination of both is crucial. The METIS science case covers a broad range of science topics, including: Solar System bodies, exoplanets, proto-planetary disks, the Galactic Center, brown dwarfs, massive stars and stellar clusters, evolved stars, active galactic nuclei (AGN), local starbursts, transient events, and peculiar sources at intermediate redshifts. However, METIS will have a specific focus on research related to circumstellar disks and extrasolar planets. *In the context of this conference paper, we will elaborate on the discovery potential for circumstellar disks, and – due to limited space – focus on two subtopics.*

A key science case for METIS is to leverage the high spatial resolution of the E-ELT to observe, and image, the process of planet formation, in the primary planet-forming regions from 1–10 AU, at all evolutionary stages, from protoplanetary disks through debris disks. To achieve these objectives, METIS' unique combination of high spatial and spectral resolution will be crucial: a slice width of 18.3 milli-arcsec at $4.7\,\mu$m corresponds to radii of around 1–2 AU in protoplanetary disks in the nearest star-forming regions (*e.g.*, Ophiuchus, Chamaeleon or Lupus). The highest spectral resolution offered by METIS ($R \sim 100,000$) in the L and M bands) matches the Keplerian velocity in a disk around a $0.3\,M_\odot$ star at 10 AU. The high spectral resolution is therefore needed to obtain kinematic information at the angular scales spatially resolved by the ELT 39 m aperture.

2.1 Structure and evolution of PP disks

It is well-known that CO rovibrational line emission from most disks around Herbig Ae and solar mass stars exhibit extended and complex structure on 1–10 AU scales,

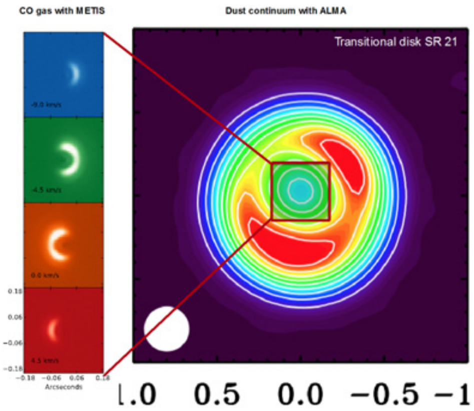

Fig. 2. Model of a METIS observation of CO rovibrational emission at 4 μm in the transitional disk around SR 21 in Ophiuchus (*left panels*), compared to the ALMA dust continuum (0.88 mm) image (*right*, (Pinilla *et al.* 2015)). Note that it is already known from CRIRES spectroastrometry observations (Pontoppidan *et al.* 2008) that the CO gas traces an inner ring at ∼7 AU (corresponding to the orbits of Jupiter and Saturn in the Solar system), separated from the outer dust ring at ∼35 AU as seen with ALMA. METIS can directly image this ring and provide further constraints on any embedded planets sheparding the rings.

but progress is limited by a lack of spatial resolution. The METIS integral field unit (IFU) will directly image the kinematics of protoplanetary disks with a spatial resolution 5–10 times better than that offered by current 8 m telescopes or line imaging with ALMA (van der Marel *et al.* 2015). The 4–5 times higher spatial resolution with the E-ELT will, in combination with higher surface brightness sensitivity, lead to spectrally resolved CO line cubes over as many as 82 spaxels or more (Fig. 2). METIS will resolve moving gas structures as small as 2 AU in size at typical distances of 120 pc and as little as 1 AU for the closest disks. Furthermore, the high sensitivity of METIS will ensure that the entire variety of disks will be available to such studies, including faint disks around brown dwarfs and those in transition to the debris disk phase. Optically thin ^{13}CO and C^{18}O isotopologs can be imaged as well, probing deeper into the disk. A large sample of at least a hundred protoplanetary disks across the stellar mass range, from brown dwarf disks to disks around young A-stars, can potentially be targeted.

2.2 *Signatures of protoplanets*

The unique combination of high spectral and spatial resolution offered by METIS allows spectro-imaging of the spatial distribution of disk material and kinematics of warm protoplanetary gas on AU scales. One of the most exciting prospects, given this capability, is the detection, imaging and kinematic characterization of dust and gas directly sculpted by the presence of still-forming Jupiter-mass planets. This may be accomplished in at least four different ways:

1. Thermal continuum emission from warm protoplanets and their circumplanetary disks may be detected using high contrast imaging.
2. Unseen planets may be detected using spatio-kinematic departures from Keplerian motion, including infall of gas toward the planet from the protoplanetary disk.
3. Detected accreting giant planets may be confirmed and characterized by measuring the Keplerian motion in the circumplanetary disk using CO rovibrational lines.
4. Dust imaging, in combination with ALMA, as a function of dust grain size to search for indirect evidence of dynamical sculpting by newly formed planets and dust gaps.

The kinematic action of an embedded giant planet will not only clear gaps in the protoplanetary disk, but will also perturb the Keplerian motion of disk gas by inducing eccentric gas orbits (Regaly *et al.* 2010), as well as local pertubations near the planet, by as much as 1–2 km/s across a few AU region (Perez *et al.* 2015). The detection of such kinematic signatures may not only confirm the presence of a compact object in a hot spot detected by METIS in the 10 μm continuum emission, but will also measure its mass. Detecting and measuring the masses of protoplanets while they are forming will provide a transformative comparison to mature exoplanetary systems. Furthermore, the orbital parameter space covered by METIS will match that relevant for giant planets in solar system analogs.

METIS may also be able to detect warm CO gas in local Keplerian motion in a circumplanetary disk. Such a scenario is modeled in Figure 3. A key property of the gas signature from a circumplanetary disk is that it will be offset from the local disk velocity by up to 5–10 km/s due to the planets own motion around the star, thus avoiding interference from ambient disk gas. Such kinematic signatures, in particular in combination with continuum detections, will constitute an unambiguous detection of the planet itself, and will allow an estimate of its mass. Detections of circumplanetary disks in near-Keplerian rotation may also provide the first evidence for prograde moon systems, such as that of the Jovian system. As the physics of circumplanetary disk accretion may be crucial in limiting planet masses (Morbidelli *et al.* 2014) these studies are of fundamental importance for constraining models of planet formation.

2.3 *ALMA and JWST*

ALMA is mainly sensitive to the cold and large dust particles of the disk midplane. The spatial resolution, even for the brightest CO lines, cannot match the high resolution of broad-band continuum imaging, and will be limited to 5–10 AU from the central star. Moreover, ALMA cannot observe symmetric molecules without

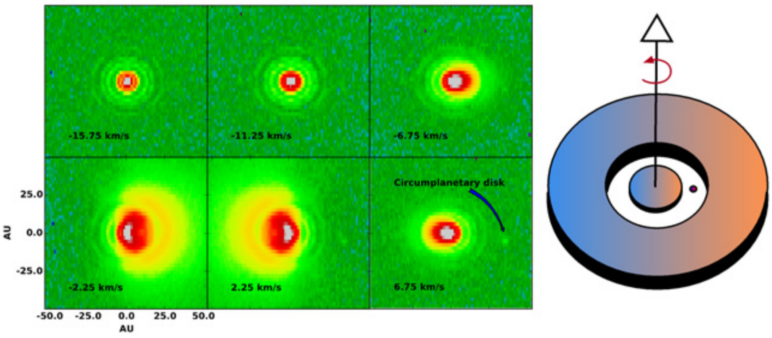

Fig. 3. Simulation of a 1 hour METIS-IFU observation of a 0.01 M_{Jup} protoplanetary disk with an embedded protoplanet. The spectral setting is centered on the 4.7 m CO ro-vibrational band. Shown is a stack of 5 CO lines from a gas-rich disk around a solar-mass young star. The strength of the CO lines is matched to existing observations with, *e.g.*, VLT-CRIRES of similar disks. Offset by 30 AU from the central star, and indicated by the arrow, is a 10 M_{Jup} protoplanet surrounded by a circumplaneary disk. The warm circumplanetary disk is clearly separated from the cooler disk material in several planes of the cube (Pontoppidan *et al.* 2009).

a dipole moment, such as CH_4 and C_2H_2. JWST-MIRI and NIRSPEC cover the METIS wavelength range at comparable or better sensitivity, but with a factor of 6.5 poorer spatial resolution, and with a spectral resolving power of at most 3000, insufficient to probe kinematics. In summary, METIS will be the perfect compliment to JWST and ALMA.

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