Scientific Requirements for Extremely Large Telescopes
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The science case for exoplanets and star formation using mid-IR instrumentation at the OWL telescope

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Abstract. A Mid-IR instrumentation study for OWL has been performed by the Max-Planck-Institut für Astronomie in Heidelberg (Germany), and a Dutch consortium led by the Leiden Observatory (The Netherlands). MIR imaging and spectroscopic observational capabilities are compared to contemporary IR to sub-millimeter facilities, especially concentrating on the MIR-capabilities of JWST(MIRI). Our best effort calculation of the sensitivity for both MIR imager and spectrograph indicate a huge discovery potential in numerous areas from our planetary system to the high redshift Universe. Here we focus on the field of exo-planets and nearby star formation. Starting with the science cases, top level requirements are deduced and summarized including MIR instrumental constrains for the telescope itself.

1. Introduction

ESO has initiated an instrumental pre-phase A study for OWL to answer the questions if an ELT like OWL should be equipped with a thermal and Mid-Infrared (MIR) ($3.5 - 27\,\mu$m) instrument and if so, which are the required observational capabilities, is it technically feasible and how does such an instrument compare to future projects like JWST and ALMA. This study has been performed by a small consortium of the MPIA, Observatory of Leiden and Astron (Dwingeloo) with contributions from MPS (Lindau) and ESO. In a first step we have compiled a list of most interesting science cases that require higher sensitivity and/or resolution than is provided by current 8m-class telescopes and instrumentation or even by planned instrumentation of missions that might be contemporaries of an OWL telescope around 2020. Based on these science cases we have proposed a concept for such a thermal to mid infrared instrument. Observational requirements are deduced, technical solutions are offered and some specific problems are addressed.

Especially for the field of exo-planets and star formation such an instrument would provide an extraordinary powerful tool: we will briefly touch the item of our solar system, where we can learn a lot concerning the development of a planetary disk by observing trans-neptunian bodies. The field of protoplanetary disks is discussed as well as MIR observations of protostars. OWL equipped with a MIR instrumentation will certainly deliver breakthrough science for a number of additional fields especially for numerous extragalactic studies, but are not considered here.

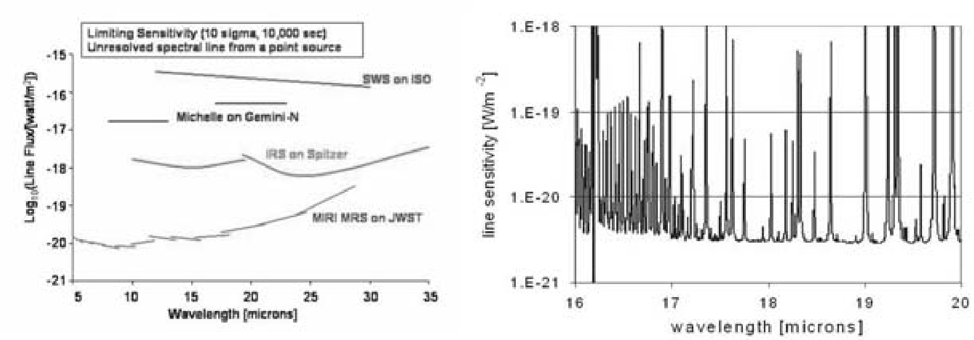

Figure 1. High spectral resolution (R=50 000) sensitivity of a 100m-ELT for unresolved sources within the Q-band.

2. Sensitivity

Ground-based MIR observations are limited by transmission and absorption of our atmosphere. Thus, in a first step we have studied the dependence on wavelength, site elevation and weather conditions for standard mid-latitude atmospheric parameters, using the HITRAN code distributed by the Harvard-Smithsonian center of Astrophysics. Especially for the wavelength region beyond 20 μm, high elevation, e.g. as offered by the altiplano region near ALMA, is essential. With additional assumptions for the telescope and instrument transmission and thermal emission as well as detector efficiency, we can derive spectral sensitivity curves for given wavelength regions and spatial and spectral resolutions. To be competitive with space telescopes, an ELT at MIR wavelengths should focus on diffraction limited spatial resolution (Fig. 1). In this case, a 100m-ELT can provide similar broad band imaging sensitivities as the next generation space telescope, with more than a magnitude better spatial resolutions (see Fig. 2). In this sense, within those MIR bands which are accessible from the ground, high resolution spectroscopy is well comparable to space projects.

3. Science case

3.1. *Solar system*

A 100m telescope with thermal and mid-infrared observational capabilities is especially interesting for monitoring solar system body surfaces like Geyser activity on Triton for example or volcanic activities on Io. Table 1 summarizes the diffraction limited surface resolution and number of resolution elements per disk for typical solar system observations. Even the currently most distant trans-neptunian object Sedna can be resolved at 3.5 μm. Spectroscopy of Oort cloud objects could provide exciting input to the theory of planetary disk evolution. Such an instrument available for the deep impact experiment, would have been capable to resolve the nucleus and the dust ejecta as observed by the fly-by spacecraft 15min after closest approach.

3.2. *Detection of exo-planets*

A very important field of application of such MIR instrument at an 100m ELT is the observation of exo-planets, in direct imaging and spectroscopy. The contrast between the

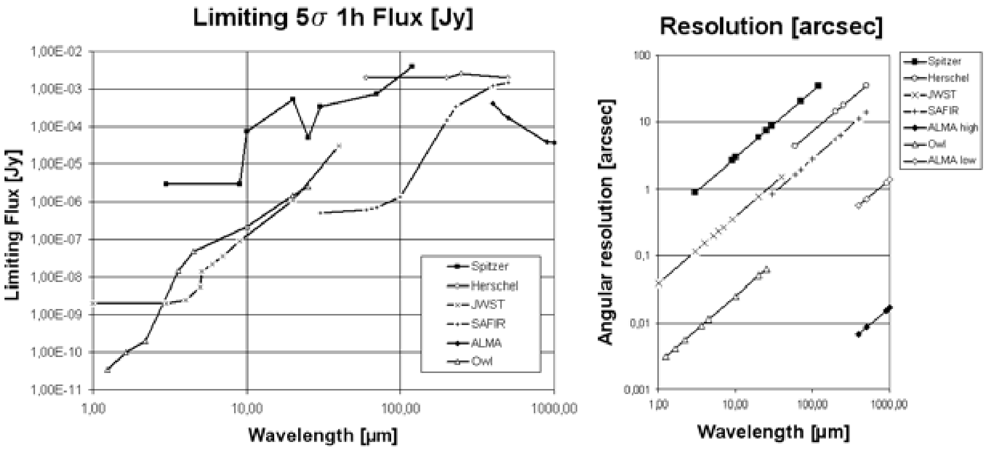

Figure 2. OWL MIR point source sensitivity and spatial resolution compared to contemporaries and competitors. The point-source sensitivity of a 100m telescope for thermal and MIR wavelengths is well comparable to the expected sensitivity of MIRI(JWST), while the diffraction limited resolution is 15 times better.

Table 1. Diffraction limited surface resolution of a 100m ELT and number of resolution elements per typical disk

Object	Surface resolution	Resolution elements per typical disk	Note
Moon	10m	3×10^5	
Mars	≈700m	1000	
Asteroids	10 - 20km	≈70	Ceres, Vesta
Jupiter	24km	170	Galilean Moons
Saturn	45km	100	Titan
Uranus	90km	10	Ariel
Neptune	130km	30	Triton
Pluto	180km	30	
Sedna	400km	4	most dist. TNO

central star and a planet at 10 μm is about a factor 100 more relaxed than at visual or near infrared wavelengths. As shown in Fig. 2, OWL will be of similar sensitivity as MIRI(JWST) for point sources, thus, because of the higher spatial resolution (compared to the “poor quality” 6.5m PSF), it might be especially apt for direct observations of earth-like exo-planets at 10 μm.

Ground based search for exo-planets using adaptive optics systems up to now is limited by the residual speckle noise, a problem which, again, is much more relaxed at 10 μm compared to the 1 μm regime. First estimates indicate that Jupiter like planets at a distance of 3 parsec are easily detectable on a 5σ level within 10 min at 10 μm, even earth like planets are detectable within an hour. However, this science case will significantly suffer from downscaling the ELT from 100m to 40m, e.g. required integration times will increase over-proportionally, reaching soon unreasonable values.

3.3. *Circumstellar disks*

An inner dust disk radius of ≈4AU has been measured in the 10Myr old proto-planetary disk around TW Hydrae (Calvet *et al.* (2002)). Other examples are the object Coku Tau/4 with an evacuated inner zone of radius ≈10AU (Quillen *et al.* (2004)) and GM Aur with a significant decrease of the dust re-emission inside ≈4AU around the central star (Rice *et al.* (2003)). This gap is characterized by a depletion of at least the population of small dust grains, which are responsible for the near-to-mid-infrared flux. The confirmation of these indirectly (via SED modelling) determined gaps, as well as examining other disks for the existence/non-existence of similar gaps will provide valuable constraints on the evolution of the planet-forming region and thus on the process of planet formation itself. Once (proto-)planets have been formed, they may significantly alter the surface density profile of the disk and thus create signatures in the disk that are much easier to find than the planets themselves. This gap, which is located along the orbit of the planet, may extend to several astronomical units in width, depending on the mass of the planet and the hydrodynamical properties of the disk.

The dominant observable quantity originating from the inner disk region ($r \leqslant$ 10-20AU) is the emission of MIR continuum radiation by hot dust. Given the typical distance of nearby star-forming regions of ≈140-200 pc and the spatial resolution achievable with a ≈100m telescope in the mid-infrared wavelength range (up to ≈10mas), a 100m MIR telescope will facilitate studies of the planet-forming region in circumstellar disks.

In the N-band we can see characteristic emission from warm silicate dust grains. Possible science targets include pre-main sequence stars with circumstellar disks or solar-system comets. By modeling the entire N-band spectrum we can conclude on the level of dust evolution (grain growth and crystallization), which is of particular interest in young circumstellar disks within the framework of planet formation. In this case, the spectral N-band coverage per single setting is of higher interest than spectral resolution. Currently resolved imaging spectroscopy can only be done for a very small number of nearby disks. Nevertheless, the spatially resolved spectroscopy of silicate and PAH has opened the completely new field of mineralogy inside circumstellar disks (van Boekel *et al.* (2004a), van Boekel *et al.* (2004b), Okamoto *et al.* (2004)). Spatially resolved spectroscopy in molecular lines will facilitate the study of the evolving disk chemistry.

3.4. *Protostars*

Deeply embedded young stellar objects with hundreds of magnitudes of visual extinction are prime targets for high-resolution mid-infrared spectroscopy. Traditionally, efforts have focused on high-mass proto-stars with luminosities of $10^4 - 10^5$ $L_\odot$. The high luminosity sets up a temperature gradient in the gas and dust through the envelope, with temperatures up to a few hundred K in the inner part, decreasing to 10-20K in the outer part. This temperature range is well probed by the CO fundamental rotational-vibrational bands at 4.7 μm, and indeed, a forest of strong lines of ^{12}CO and ^{13}CO is routinely detected (e.g. Mitchell *et al.* (1990)). Rotational diagrams provide a direct measure of this temperature gradient. High spectral resolution is essential to resolve the lines, since many of them are highly saturated. Intrinsic line widths are typically a few km s^{-1}, with outflow components of up to 100 km s^{-1}. Many other molecules can be identified in these spectra. Detections include gaseous CH_4, C_2H_2, HCN, NH_3, HNCO and CH_3 at 7-14 μm, indicative of a rich chemistry in the hot cores near the proto-stars. These mid-infrared lines are highly complementary to the sub-millimeter lines of massive YSOs, which are biased toward the cooler outer layers. The infrared spectra of the coldest proto-stars are also full of ices, which can be probed at $R \approx 3000$. The previous data were limited to the brightest, most massive proto-stars ($\leqslant$100Jy at mid-IR); a 100m ELT would allow solar-mass proto-stars with luminosities comparable to those of our proto-Sun (10-100mJy) to be probed. An exciting prospect is that the line of sight may pass through the flaring layers of the forming circumstellar disk (Boogert *et al.* (2002)).

3.5. *Starbursts*

Spectroscopy in the MIR region is of fundamental importance to starburst research. The thermal and MIR spectral range contains a large variety of unique diagnostic tools, from polycyclic aromatic hydrocarbons (PAHs), molecular hydrogen, and forbidden transitions of fine-structure lines, to silicate features. Altogether, these diagnostics provide excellent measures of the local kinetic temperatures and gas densities, and the properties of the exciting radiation field. The combination of several spectral features provides an excellent basis for starburst modeling. However, since the spatial extent and distribution of higher excitation regions with respect to lower excitation regions varies on parsec scales, spectroscopy at highest angular resolution is crucial. A medium resolution IFU/MIR spectrograph at a 100m telescope will provide 500 times narrower slits making it possible to model the properties of physical regions rather than spatially averaged systems. For instance, the spatial resolution of the 100m ELT with an IFU at $10\,\mu$m corresponds to only 0.4pc at the distance of NGC 5253.

Deriving the total masses, densities, and IMFs of super star clusters would be of greatest interest regarding their future evolution towards globular cluster systems, the origin of the galactic field star population, and the time scales and sub structures of luminous starbursts. At $3.5\,\mu$m, the 100m ELT could provide seven times higher spatial resolution than HST/WFPC-2 for the study of heavily embedded super star clusters while the negative impact of extinction is minimized. A MIR ELT will provide a breakthrough in this field.

4. Conclusion

MIR imaging and spectroscopic capabilities with an ELT will provide a powerful tool to study protoplanetary disks, exo-planets and star formation in up to now unrivaled details. The imaging and spectroscopic device should concentrate on highest spatial resolution. In addition, high spectral resolution beyond R = 3000 (offered by JWST(MIRI), combined with an IFU, is essential. For the majority of science cases studied within the MIR OWL Study, a 60m telescope will provide already an enormous progress of observational capabilities of MIR astronomy. For some single projects as direct detection of earth-like planets or resolving the broadline region of AGNs larger ELTs are required.

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