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Affected Section(s)	Changes / Reason / Remarks
Mostly Sect. 4, with minor changes over the whole document	Second Version takes into account conclusions of Feb. 9 – 11 2015 PST meeting

Contents

3 **Abbreviations**

See applicable document AD1 (see section 2.1 herein for references of applicable documents).

1. Scope

5 The scope of this document is to define the Top Level Requirements for the E-ELT instrument: mid-infrared imager and spectrograph (ELT-MIDIR).

6 The Top Level Requirements are derived from the Science Case of the E-ELT. For particular instruments, they were developed during the concept phase for the instruments (between 2007 and 2010), as well as in the process of defining the Design Reference Mission and Design Reference Science Plan for the E-ELT. The present document draws heavily on METIS science analysis report.

7 The Top Level Requirements are developed by the E-ELT project with the help of its Project Science Team. They can be refined by the Consortium contracted to deliver the instrument, and are the basis for setting up the Technical Specifications for the instruments.

8 In general, no priority of one science case over another is made nor do the TLRs aim to be complete. However, in the case of the MIDIR instrument, the limitations of ground based observations and the competition from the JWST do place priorities and these are identified in the introduction.

2. Related documents

2.1 Applicable documents

11 The following applicable documents form a part of the present document to the extent specified herein. In the event of conflict between applicable documents and the content of the present document, the content of the present document shall be taken as superseding.

12 AD1 Common definitions and acronyms;

ESO-193178 Version 6

https://kronosrv.hq.eso.org/kronodoc/HQ/ESO-193178/6

2.2 Reference documents

14 The following Reference Documents provide background information as to the present document. Under no circumstance shall the content of Reference Documents be construed as applicable to the present one, in part or in full.

15 RD1 E-ELT Science Case;
E-TRE-ESO-080-0806 Issue 1

16 RD2 Science Working Group input to the E-ELT Instrument Plan;
E-PLA-ESO-080-0770 Issue 1

17 RD3 METIS Science Analysis report
E-TRE-MET-503-0004 Issue 2

18 RD4 The E-ELT Design Reference Mission;
E-TRE-ESO-080-0717 Issue 2

19 RD5 The E-ELT Design Reference Plan;
E-TRE-ESO-080-0840 Issue 2

3. Science Case for ELT-MIDIR

21 The unique photon collecting area of the E-ELT is one of its key defining characteristics. The scientific advances to be expected from the angular resolution of a 40-m telescope forms an important part of the Science Case for the E-ELT [RD1]. High resolution spectroscopy is also a key area where the instrument sensitivity can be competitive.

22 The need for such an instrument was already recognized and emphasized by the E-ELT Science Working Group (SWG) in its recommendation regarding the capabilities of the E-ELT's first generation of instruments [RD2].

23 In this document we derive the Top Level Requirements for ELT-MIDIR, a mid-IR imager and spectrograph for the E-ELT. As has been well established, many of the sciences cases for the E-ELT [RD1] require such an instrument. In this section we assemble that sub-set of science cases that drive the requirements for ELT-MIDIR. Although not a complete list, this set is nevertheless representative of the science to be enabled by ELT-MIDIR. We provide brief descriptions of these cases, as well as the instrument requirements derived from them.

24 It is critical that the reader appreciates the context in which the science case for the MIDIR instrument is established. The sensitivity of any thermal infrared instrument at a ground based observatory is strongly constrained by the enormous background generated by the telescope itself, the instrument, and in some cases the sky. The variability of this background is the source of many complex instrumental effects and a challenge not only in observations but also in calibration of data. The most recent sensitivity figures in imaging place an optimized thermal infrared instrument at a significant competitive disadvantage to space missions that have already flown and others that are likely to fly before the E-ELT. All of this has been taken into account at the time the choice was made to have a mid-infrared capability for the E-ELT.

25 **Therefore, the science case for the MIDIR instrument has some very strong prime movers where the E-ELT has a competitive advantage. The high angular resolution of the E-ELT to image exoplanets must be exploited by MIDIR at L & M bands. The high spectral resolution in the L & M bands is also critical for the transmission spectroscopy case. Furthermore, as the JWST lifetime is limited, the capabilities of MIDIR in low resolution spectroscopy of Solar System objects across the broad wavelength band (out to 19 µm if possible*) are considered unique.**

***** In this document the term Q band is meant to cover the 17 – 19 µm range.

3.1 Proto-planetary disks and the formation of planets

3.1.1 Outline of the science case

28 MIDIR on EELT will provide unique diagnostic capabilities to help us understand the chemistry, distribution, and interplay of the various constituents of circumstellar disks, and how these factors lead to the formation of planets. Gas and dust are the key players in these phenomena, and their interactions are central to disk evolution and planetesimal growth. For example, young circumstellar disks should have a flaring geometry, due to the heating and resulting “puffing up” of the H_2 gas.

This heating depends on efficient capture of starlight by dust particles and molecules near the surface of the disk, a process which can be traced via line emission of polycyclic aromatic hydrocarbons (PAHs) on the skin of the disk. As the disk evolves, the dust condensates into larger particles, which settle to the midplane, thereby reducing the heating and flaring of the disk. The gas component eventually dissipates or forms planets, and the dust forms the cores of both rocky and gas giant planets. During this process, the gas controls the dynamics of the dust particles and moderates inward and outward migration of the forming planets. The sensitivity and spatial resolution of MIDIR on EELT will allow us to study this full suite of processes in unprecedented spatial and spectral detail.

29 Specific breakthrough science will be enabled by ELT-MIDIR's ability to:

30 1) *Reveal the spatial distribution of gas and dust on ca. 1 AU scales* in the nearest star forming regions. During the earlier phases of disk and planet evolution, this will allow an assessment of the geometry and flaring of circumstellar disks and how disks change with age and spectral type. In older disk systems, exquisite imagery may reveal the presence of planets via gaps, wakes, and shock structures in the disk. These studies are highly complementary to investigations of circumstellar disks through infrared interferometry at finer angular scales and with ALMA's focus on the outer, cooler portions of the disk (diagnostics: thermal emission, PAH, possibly H_2).

31 2) *Allow kinematic and spatial studies of disk dynamics* using sensitive, high spectral resolution (R~100,000) analysis of CO fundamental emission at 4.65 µm. Variations in spectral signature with wavelength (spectro-astrometry) should reveal sub-AU scale processes. Such studies should allow an assessment of the 3-dimensional structure of disks across all spectral types and allow us to identify Keplerian motion, outflows, and turbulence, which can be a diagnostic of viscosity (diagnostics: v=1-0 CO).

32 3) *Permit spatio-chemical analysis of gas and dust-phase disk constituents*. This includes the dominant component, molecular hydrogen, as well other critical species, such as water vapour and organics, which form the basis of life. MIDIR, through its increased sensitivity, spatial resolution, and dynamic range, will also allow new insights into the processing and transport of circumstellar dust grains, and how, in particular, silicate grains get annealed to crystalline form far out in the disk. Isotopic studies can provide similar clues to long-standing mysteries of fractionation seen in meteorites (diagnostics: H_2 at 12, 17 µm; H_2O, CH_4, C_2H_2, HCN, C=H stretch in L, L' bands; 10 µm Si, ^{13}CO, $C^{18}O$, $C^{17}O$, $H_2{}^{18}O$, HDO – isotopic studies)

3.1.2 Requirements derived from the science case

34

Spectral range	L, M & N (goal Q)
Resolving power	spectral resolution to 100,000 & IFU
AO	Diffraction limited performance
Photometric stability	Spectro-astrometry
Coronagraph	Yes

Table 1: Summary of requirements of science case 1.

3.2 Characterization of exoplanets

3.2.1 Outline of the science case

37 Exoplanetary atmosphere studies were initiated more than a decade ago with the atmospheric characterization of hot and strongly irradiated Jupiters like HD209458 (Charbonneau et al. 2002) using transit observations. Such observations have been reported for over 30 exoplanets to date (Seager & Deming 2010), including hot Jupiters, hot Neptunes (e.g. Stevenson et al. 2010), and even super-Earths (Demory et al. 2012). Nowadays, three main observing techniques are currently used to study the atmosphere of exoplanets: low/medium resolution spectroscopy in transmission during transit or using secondary eclipse, high-dispersed spectroscopy and high contrast low-resolution spectroscopy in direct imaging. The two last techniques are particularly well suited for MIDIR at EELT.

38 1. VLT observations with CRIRES at high-spectral resolution recently showed that spectral features from the planet atmosphere can be disentangled from telluric and stellar lines making use of the radial velocity variations of the exoplanet (Snellen et al. 2010; Brogi et al. 2012, 2013). This high-dispersion spectroscopy technique is particularly promising to derive stellar and planetary masses in case of transiting systems and the planet's inclination and true mass in case of non-transiting ones. This technique also revealed the existence of CO or H_2O in the atmosphere of HD209458b and 51 Peg b. With MIDIR, a whole range of molecular gases will be detectable in the thermal infrared, like CO, CH_4, NH_3, PH_3 to characterize exoplanetary atmosphere composition and photochemical processes. The phase function of the brightest targets can be studied, which is directly linked to their global atmospheric circulation, revealing changes between a planet's morning and evening spectrum. The increased capabilities of the E-ELT will offer the opportunity to perform new measurements: line by line study of planet's spectrum to probe the atmospheric temperature-pressure profiles, atmosphere dynamics and longitudinal spectral variation.

The combination of the E-ELT and MIDIR will typically be an order of magnitude more powerful than the instruments currently used. This means that the studies performed today on a handful of planets will be extended to a few hundreds of hot Jupiters and to temperate and smaller planets.

39 2. For non-strongly irradiated planets at relatively wide orbits, advancements have come in the form of direct imaging, spatially resolving the planet from its parent star - which enables high-resolution spectroscopy of self-luminous planets in Jovian-like orbits (Janson et al. 2011; Konopacky et al. 2013). A plethora of new discoveries should come with the upcoming high contrast instruments within the next few years, e.g., SPHERE at the VLT (Beuzit et al. 2006, The Messenger, 125, 29), and GPI at Gemini (Soummer et al. 2009, SPIE, 7440, 1). Using high-contrast spectroscopy at low-resolution, the physics of the planetary atmosphere can be here directly probed to study the composition, the formation and sedimentation of clouds or the effect of non-equilibrium chemistry. The access to thermal wavelengths is very favourable in terms of contrast. In addition, the combination of the high angular resolution of the E-ELT, the optimal wavelength coverage at thermal wavelengths where exoplanets emit the most and the high contrast devices offered by MIDIR will open a new observing discovery window for the detection of close-in exoplanets around young, nearby systems targeted by SPHERE and GPI, but also for the direct imaging of low-mass planets detected in radial velocity or in astrometry with Gaia. This will offer for instance a unique opportunity to combine these different techniques to properly constrain the physics of exoplanets (mass – luminosity relation), their formation processes and physical evolution. Accessing very close inner working angle is crucial to fully exploit the E-ELT angular resolution with respect to JWST.

3.2.2 Requirements derived from the science case

41 (1) For high-dispersed spectroscopy, spectral resolution higher than 100,000 is mandatory to disentangle the planetary spectral lines from telluric and stellar lines making use of the radial velocity variations of the exoplanet. The spectral lines of CO, CH_4, H_2O, NH_3 will be optimally probed between 2.9 and 5.4 μm to derive the planet radial velocity and study the atmosphere composition.

42

Spectral range	L & M
Resolving power	R = 100 000 (Transit)
Simultaneous spectral coverage	Goal: yes

Table 2: Summary of requirements of science case 2 (transit).

43 (2) In high-contrast imaging and spectroscopy, high angular resolution is required which implies the use of an AO system to correct on-axis with Strehl ratios higher than ~80% for NGS brighter than 12th magnitude in I-band. Coronagraphy is mandatory, as well as the capability to conduct angular differential imaging for speckles subtraction, in order to access significant contrast at close angular separation of a few lambda/D. Low spectral resolution will be sufficient to probe the broad molecular band of CO, CH_4, NH_3, PH_3, H_20, C_2H_4. The possibility to use the combination of coronagraphy and spectroscopy must be considered.

44

Spectral range	L, M and N
Resolving power	R ~ 100 – 4000 (long-slit)
AO	Diffraction limited Strehl > 80% for stars brighter than 12^{th} magnitude in I-band; Nyquist sampled; On axis NGS
Coronagraphy	Coronagraphy at L, M and N-bands to access small inner working angles Angular differential imaging capability for speckles suppression will be necessary.
Contrast	5σ contrast of 3.10^{-5} (goal 10^{-6}) at 5λ/D (goal 2λ/D) at L and M-bands for 1hr of observation.

Table 3: Summary of requirements of science case 2 (imaging).

3.3 Physical characterization of the transition from brown dwarfs (L,T, Y-type) to giant planets

3.3.1 Outline of the science case

47 At the far end of the optical regime (SDSS) and in the near-infrared (DENIS, 2MASS) surveys have disclosed two new spectral classes: L and T-type high-mass brown dwarfs with effective temperatures around 2,000 and 1,000 K. More recently thanks to new NIR (UKIDSS) and MIR (WISE) surveys the existence of a new spectral type Y-type with effective temperatures around 600 K has also been suggested. This means that in the transition between late M-type to late Y-type we are crossing the limit between stars and brown dwarfs (M~0.08 Msolar, hydrogen burning limit) and the limit between brown dwarfs and planets (13.5 $M_{Jupiter}$). To overcome the problems connected with the knowledge of mass this group of objects are called Ultra-Cool-Dwarfs (UCDs).

48 The UCDs are very interesting structures and the reasons are manifold. Soon after a transient deuterium burning they lack an energy source and, therefore, their destiny is to cool down for their entire life (evolving along a pseudo MS). This means that they show on their surface planetary-like chemical compositions, together with iron and silicate clouds. The UCDs are the crossroad of several radiative transfer, molecular chemistry, dynamical and meteorological problems. Moreover, they are the bottom-end of stellar structures and the very top of giant planets. Solid constraints on their initial mass function, and in particular, the dependence of the quoted transitions on gravity and metallicity will improve our knowledge in one of the last "terra incognita".

49 In the transition from late M- to early L spectral types the chemical composition of the atmosphere changes from metal oxides to metal hydrides. However, the occurrence of H_2O and CH_4 absorption features are considered typical for both L and T-type UCDs. They are also affected by the strong opacity source given by the collisional induced absorption of H_2 (see Fig. 1 in Marley & Leggett 2008). The late T-type and the early Y-type appear to be dominated by NH_3 absorption bands. However, the current theoretical and empirical scenario is quite complex, since the line list for NH_3 is not complete in the NIR regime. Moreover, current atmosphere models (Saumon et al. 2006) indicate that N_2 can be dragged into the atmosphere due to vertical mixing. If confirmed by observations this would imply that the presence of NH_3 is not a good diagnostic to identify Y-type dwarfs. Age and therefore gravity could also significantly influence the physics of young UCDs and therefore their photometric and spectroscopic properties to understand the bottom of the substellar initial mass function (IMF_ in young star-forming regions (SFRs).

50 This science case has a fundamental issue to be solved: the identification of the targets. This is a very interesting science case for JWST, and probably EUCLID, since the sensitivity of their NIR and MIR images will allow them to identify a significant fraction of nearby brown dwarfs. The same applies for some of the nearby open clusters (Pleiades, Iades, Young nearby associations). The latter opportunity becomes even more compelling for E-ELT, and in particular, for ELT-CAM. Current theoretical predictions indicate that the above instrument will be able to detect giant planets (~10 $M_{Jupiter}$ in nearby stellar systems (d<1 kpc) and 1 $M_{Jupiter}$ planets in nearby SFRs (d~150 pc). This would imply a complete census of cluster brown dwarfs in relatively young star systems (Burrows et al. 2003; Casewell et al. 2007) that later could be characterized by E-MIDIR.

3.3.2 Requirements derived from the science case

52 AO to improve spatial resolution for cluster candidate and the S/N ratio of the spectra of faint objects. IR wavefront sensing would be well suited for these faint targets.

53

Field of view	Few arcseconds
Spectral range	M, N and Q
Resolving power	R ~ 1000

Table 4: Summary of requirements of science case 3.

54 Spectral coverage from 5 to 19 µm, since it includes water, methane and ammonia. Moreover, the SiO vibrational band can be detected in small silicate grains. The detection opens the path to a more quantitative analysis of grain silicate opacities. This means the opportunity to discriminate between different silicate species (forestite, enstatite, quartz; Marley & Leggett 2008). In this context the MIR spectral resolution will play a crucial role, since JWST/MIRI in spectral mode at R~1000 would be two order of magnitude less sensitive than in imaging mode (Burrows et al. 2003).

3.4 The formation history of the solar system

3.4.1 Outline of the science case

57 The formation history of the solar system is partially reflected in the physico-chemical properties of its most primordial bodies, in particular comets and trans-neptunian objects, but also giant planets and outer satellites. The study of terrestrial planets can also bring insight about their origin, as illustrated by the history of water on Venus, the Earth and Mars. The mid infrared range is especially suited for investigating the properties of solar system bodies whose thermal radiation typically peaks between a few microns and a few tens of microns. High-resolution spectroscopy is essential for probing the atmospheres of planets, satellites and comets, as demonstrated by previous observations on existing mid and large telescopes, in particular CRIRES and VISIR at the VLT (Brandl et al., METIS Science Analysis Report, 2009). ELT-MIDIR will thus be an ideal tool for this research.

58 More specifically, the following measurements should be performed:

59 (1) Elemental and isotopic abundances in cometary volatiles, with in particular the measurement of D/H and C and N isotopes in different types of comets, the organic composition of comets, their possible influence in the origin of the terrestrial water, and the measurement of the comets' formation temperature through the H_2O and NH_3 ortho-para ratios (Mumma et al. Science 310, 5746, 2005). These measurements will help establishing the composition and temperature profile in the protosolar disk. The advantage of the ELT is its increased sensitivity, giving access to a larger number of samples. The Kuiper-belt comet population is presently very poorly studied. About 3 to 5 Oort-cloud comets and 3-5 Kuiper-belt comets per year are expected to be observable with the ELT in this program.

60 (2) Elemental abundances in giant planets, as a clue of their formation scenarios. In particular, searching for PH_3 and CO in Uranus and Neptunes' tropospheres will give information on the structure and elemental composition of their interiors (Lellouch et al. A&A 430, L37, 2005). As was

first realized thanks to the Galileo probe measurements on Jupiter (Owen et al. Nature 402, 269, 1999), the internal elemental composition of the giant planets can constrain the temperature of the planetesimals that formed their building blocks. The advantage of the ELT-MIDIR versus CRIRES at the VLT lies in its increased sensitivity.

61 (3) Mapping of minor species in the atmospheres of Mars (CO, HDO, search for CH_4; Villanueva et al. Icarus 223, 11, 2013) and Venus (CO, HDO), including seasonal variations on Mars and monitoring of atmospheric dynamics on Venus; interpretation in terms of climate models and comparative planetology. The advantage of the ELT-MIDIR versus CRIRES at the VLT lies in the higher spatial resolution, especially important for the search for minor species.

62 (4) Mapping of atmospheric species on small bodies. In the case of Pluto and Triton, it will be possible to map CH_4 at 3.3 µm, CO at 4.7 µm and CH_3D at 4.6 µm. As these bands are much stronger than at shorter wavelengths, these measurements will give access to D/H and to C and O isotopic ratios. In the case of Io, the mapping of SO_2 at 4.0 µm (Lellouch et al. EPSC, 495, 2009) will make possible the monitoring of volcanic sources.

63 (5) Composition of refractory dust in comets. Crystalline silicates have been found in comets, which suggests a formation in a hot environment before incorporation in the cometary nucleus at large heliocentric distances (Wooden EMP 89, 247, 2003; Hanner and Zolensky, Lect. Notes in Phys. 815, 203, 2010). As in the case of (1), the advantage of the ELT is its sensitivity, hence the access to a larger number of comets, in particular the Kuiper belt comets. The number of observable comets in the N band is expected to be similar to (1), i.e. 6-10 per year.

64 (6) Composition of ices and organics in small bodies (comets, asteroids, TNOs). These objects may have fed the Earth in water and organics. In particular, water ice has been identified in some main-belt asteroids, in particular Themis (Campins et al. Nature 464, 1320, 2010) and Cybele (Landsman et al. BAAS 42, 1035, 2010); this suggests that these objects may have been a reservoir for terrestrial water. In the case of TNOs, only a few objects have been characterized so far and show some diversity in composition, with possible identification of nitriles or deuterated methane (Protopapa et al. A&A 490, 365, 2008). ELT-MIDIR will allow the confirmation of these observations and extend them to a larger number of objects, thus addressing the question of possible prebiotic compounds in TNOs, and/or possibly enabling the measurement of D/H at far heliocentric distances. The E-ELT sensitivity will give access to an increased number of Kuiper belts objects, possibly several tens assuming an observing time of 1-2 ELT nights per object.

65 (7) Thermal inertia of minor bodies (asteroids and large TNOs) in order to get insight on their internal structure and to constrain their formation models (rock, dust, rubble pile). Such information can be derived from rotation light curves in the thermal regime (Müller et al. A&A 443, 347, 2005). Assuming typical rotation periods of 6-12 hours, and one observing night per object, several tens of objects could be sampled within this program.

3.4.2 Requirements derived from the science case

67 (1) As demonstrated by observations of comets by CRIRES, this program requires a resolving power of 100,000 in the L and M bands. In addition, because of possible temporal variations in the comets' activity, simultaneous wavelength coverage of L and M is needed for comparing the relative intensities of the fluorescence lines.

68 (2) The study of CO and PH_3 in the troposphere of Uranus and Neptune requires R = 100,000 in the M band. There is no special need for simultaneous wavelength coverage.

69 (3) The study of CO and HDO, as well as the search for CH_4 on Mars require R= 100,000 in L and M. Simultaneous spectral coverage within each band is needed to account for possible temporal variations.

70 (4) This program requires a high resolving power (100,000) in the L and M bands. Simultaneous coverage of L+M is needed for the determination of D/H.

71 (5) The N band is needed, a moderate resolution (R = 1,000) is sufficient. The Q band will give access to the 18 µm band of silicates and provide a higher S/N for the cold objects. Simultaneous spectral coverage in N+Q is needed to account for possible temporal variations.

72 (6) This program requires the L and M bands with a resolving power of 1,000. Simultaneous coverage of L+M is needed to account for possible temporal variations.

73 (7) This program requires photometry in the N band and also in the Q band, to better refine the temperature model and to have access to colder TNOs.

74

Spectral range	L, M (cases 1, 3, 4, 6) M (case 2) N + Q as a goal (cases 5 and 7)
Resolving power	100,000 in L and M (case 1 and 3) 100,000 in M (case 2) 100,000 in L and M (case 4) 1,000 in N + Q as a goal (case 5) 1,000 in L and M (case 6)
Simultaneous spectral coverage	Needed in L + M (cases 1, 3, 4 and 6) Needed in N + Q (case 5)
AO	Differential tracking needed

Table 5: Summary of requirements of science case 4.

3.5 Dust formation in the transition from thermal pulsing AGB to OH-IR to PNs (LMC, SMC)

3.5.1 Outline of the science case

77 Asymptotic giant branch (AGB) and red supergiants (RSG) are stars in advanced evolutionary phases evolving either into planetary nebulae (AGB stars) or into Wolf-Rayet and core-collapse supernovae (RSG stars). AGB stars are low- to intermediate-mass stars with masses between 0.8 and 8 solar masses. The RSGs have masses ranging from 10 to 25 solar masses. Both AGBs and RSGs are the major contributors to the total luminosity of stellar systems. The former have luminosities of 10^3 to 10^4 times solar, while RSGs have even higher luminosities ranging from log(L/L¤)=4.5-5.5. One of the major problems in dealing with advanced evolutionary phases are the strong stellar winds. The RSGs have mass loss rates ranging for 10^{-7} to 10^{-4} M¤/yr, while the AGBs display mass loss rates of the order of 10^{-5} - 10^{-4} M¤/yr. Plain physical arguments indicate that more than 2/3 of all the material injected into the ISM comes from AGB stars (Sedlmayr 1994). This means that AGBs play a key role both in the cosmic chemical enrichment as well as in planetary system formation.

78 In particular, AGB stars are responsible for the production of carbon, nitrogen and oxygen. Since carbon and oxygen form very stable CO molecules, the more abundant of the two elements dominates the chemistry in the stellar atmosphere (and in the circumstellar environment). If C/O<1, all the carbon is locked in CO, and the atmosphere is dominated by oxygen molecules: the star is of M-type. If C/O > 1 the atmosphere will be enriched in carbonaceous material: the star is of C-type. When C/O~1 the star is called an S-type star, with the spectrum characterized by ZrO bands. For O-rich stars the most important molecules are H_2O, CO, TiO, and SiO (Tsuji et al. 1997; Ohnaka 2004), and the dust consists of Al_2O_3 and silicates. For carbon-rich stars the molecules are CO, CN, and the dust consists mainly of amorphous carbon and SiC.

79 AGB stars are characterized by large radial oscillations (semi-regular, Mira) that, during the pulsation cycle, form shock waves propagating outwards, significantly affecting their atmospheric structure. The shock propagation and the low effective temperature of AGB stars lead to the formation of dust in the outskirts of their atmospheres. The newly formed dust grains are then accelerated by radiation pressure and are expelled from the star. Due to drag coupling, nearby gas is accelerated along with the grains, forming a stellar wind. This description is valid for carbon stars (Hofner & Dorfi 1997), while for oxygen rich stars it still remains unclear if the dust is sufficiently opaque to drive the winds.

80 The physical mechanisms driving the mass-loss in AGB stars are still poorly understood. During the last few years AGBs have been the subject of a paramount theoretical (radiative transfer, hydrodynamics, molecular opacities; dust-driven winds Wachter et al. 2008; Hoeffner 2009; Mattsson et al. 2010) and observational (NIR and MIR spectroscopy, interferometry; Wittoski et al. 2004; Paladini et al. 2011) effort to constrain the dependence of mass-loss rates on stellar parameters (binarity, mass, temperature, dust, metallicity). In this context, AGB stars in the Magellanic Clouds play a crucial role since they cover a broad range in metallicity and are located at a known distance.

81 Finally, several recent investigations focussed on the geometry and the nature of the dust in the circumstellar environment (CSE) of Galactic AGB stars using both coronagraphy and polarimetry (Maercker et al. 2010, A&A, 511, A37; Olofsson et al. 2010, A&A, 515, A27; Ramstedt et al. 2011 A&A, 531, A148, Jeffers et al. 2012, A&A 539, A56). This approach appears more promising for Galactic than for AGB stars in the Magellanic Clouds (MCs). The reason is because the angular size of the CSE in MC AGB stars ranges from subarcsec to a few arcsecs (linear size from $5*10^{16}$ to $\sim10^{18}$ cm, Maercker et al. 2010). Moreover, the MC AGB stars are fainter.

3.5.2 Requirements derived from the science case

83 To characterize the chemical composition, the geometry of the inner environment, the transition between the CSE and the ISM, and the geometry of the inner dust shells, high spatial and spectral resolution is required. Recent investigations indicate that a significant fraction of dust shells surrounding AGB stars have signs of asymmetric dust distributions (Ragland at al. 2008, ApJ, 679, 746; Paladini et al., 2012). The processes leading to the amorphous, asymmetric structures observed in planetary nebulae (PNe) are still poorly understood. Moreover, we still lack a detailed knowledge of physical mechanism(s) driving the formation of the different dust species (carbonaceous, silicates). In particular, we still lack a detailed knowledge of the strong emission bands (3.3, 6.2, 7.7, 11.3 μm) dominating the mid-IR spectra of many extra-galactic sources. They are typically associated with the IR fluorescence of UV-pumped PAHs. The PAH bands display a broad range of shapes and strengths between different sources (ISM, CSE). The largest spectral variability is seen in the CSE of post-AGB stars and proto-planetary nebulae (PPNe). The working hypothesis to explain the observed spectral variability and the chemical differences is the role played by aliphatic versus aromatic structures (C-atoms connected in open chains versus arranged in a honeycombed lattice structure; Boersma et al. 2010). Validation of this leading hypothesis requires high-spatial resolution and high-spectral resolution to detect PAH emission (aromatic and aliphatic bands) in the innermost regions of their circumstellar environment.

84 A field of view of 10 – 15 arcsecs is required for imaging to see the transition from the CSE to the ISM and a few arcsecs for the high-resolution IFU spectroscopy of the regions where the dust is formed and accelerated. The density of AGB stars across the bar of the LMC is on average of the order of one per pointing (Nikolaev & Weinberg 2000, ApJ, 542, 804). As AGB stars can be extremely bright in the mid-infrared, high Strehl ratio (~ 80%) and corogronaphy are required to have a good contrast in the CSE. High-spectral resolution ≥ 70,000 in the L, M bands and ≥40,000 in the N band is required.

85

Field of view	10 – 15 arcsecs for imaging, 1 – 2 arcsecs for IFU spectroscopy
Spectral range	L, M & N
Resolving power	R ~ 70,000 (L & M) R ~ 40,000 (N)
AO	80% Strehl ratio
Coronagraphy	Yes

Table 6: Summary of requirements of science case 5.

3.6 Extragalactic transients

3.6.1 Outline of science cases

88 Supernovae and gamma-ray bursts constitute important astronomical sources over all wavelength ranges. Key unresolved issues include the nature of the progenitor system and the evolutionary path leading to explosion, the physics of the explosion itself, relative rates of the various subtypes, and the ramifications in terms of elemental yields and potential dust production that will impact on many adjacent areas.

89 Currently, ground-based mid-infrared studies of the vast majority of supernovae are extremely challenging – if not impossible, even from the highest-altitude facilities. This is due to a combination of conspiring factors: strong terrestrial atmospheric absorption and generally high background in mid-infrared regimes. Added to this, by the time the supernova has evolved sufficiently for mid-infrared diagnostics to become useful, the current generation of 8-10-m facilities would barely be able to detect nearby objects at distances of ~10-20 Mpc. A key exception was SN 1987A (d~50 kpc); however, events as close as SN 1987A are expected to only occur every few hundred years. Although the situation changed dramatically with the advent of the Spitzer Space Telescope, the bulk mid-infrared properties for significant samples of supernovae of all types has remained elusive, and the poorer spatial resolution of Spitzer compared to either ground-based AO at 8-10m-class facilities, or HST, has hampered studies of nearby supernovae in crowded fields, as well as objects in more distant galaxies. This has biased mid-infrared studies towards the most nearby, and therefore the most commonly occurring supernova type. Consequently, supernova behaviour longward of about 2.5 µm is largely uncharted territory.

3.6.1.1 Mid-infrared diagnostics

91 For both thermonuclear and core-collapse supernovae, spectral line diagnostics from the mid-infrared region can provide key tests of explosion physics. At epochs of a few hundred days post-explosion, the ejecta become transparent to the optical/IR emission. The study of this phase is crucial since all the ejecta can now be seen; homologous expansion means that the Doppler-

broadened line profiles (FWHM ~ few thousand km/s) map out the relative kinematic distribution of the nucleosynthesised materials.

92 The large number of lines in the optical/UV regions, coupled with the strong Doppler-broadening can make line profiles difficult to measure. Strong extinction effects often introduce additional error. In contrast, the infrared region has fewer lines and reduced sensitivity to extinction uncertainty, allowing for firm line identification and accurate measurement of line strength and evolution. Several lines of iron-group elements exist in the 5-30 μm region.

93 Measurement of the [FeII] 17.99 μm line has previously only been possible for the nearby SN 1987A. For supernovae at more typical distance of say 10 Mpc, we would expect a flux density for the above-mentioned spectral line of ~1.1 x 10^{-14} erg cm^{-2} s^{-1} μm^{-1} at an epoch of ~400 days. Similarly, the [ArII] 6.98 μm line would have an expected intensity of 6.7 x 10^{-15} erg cm^{-2} s^{-1} μm^{-1} at ~400 days again for an assumed distance of 10 Mpc.

94 Additionally, as warm dust radiates most strongly in the mid-IR, this region is ideal for following the potential condensation of dust grains in supernova ejecta and/or shocked circumstellar material. As has been demonstrated by several studies, monitoring the development of infrared light echoes resulting from pre-existing circumstellar or interstellar dust is key to understanding the mid-IR evolution. Molecular emission (e.g. CO and SiO) observed in core-collapse supernovae yield clues to the grain composition, as well as the extent of microscopic mixing in the expanding ejecta.

3.6.1.2 Supernova rates

96 It has long been recognized that searches for transients will be biased against those occurring in regions that are heavily obscured by dust e.g. nuclear regions or (U/Hy/LIRGs). The use of extragalactic transients to probe the cosmic star formation history should therefore be corrected for the potentially large number of objects that are missed. Currently, this factor is highly uncertain.

3.6.2 Requirements derived from the science case

98 Requirements from the above cases: low-resolution diffraction limited spectroscopy. L & M-band coverage would ensure that the CO fundamental is accessible for low redshift objects. Broad wavelength coverage (i.e., including the Q-band) is necessary to ensure that lines of different species can be measured, as well as providing access to later epochs as the ejecta cools.

99 The key requirement is spatial resolution and stability of PSFs to allow image subtraction to be successfully performed. Image alignment to reference images from archival sources can require up to tens of isolated point sources, thereby imposing a constraint on the field-of-view.

100

Resolving power	Few 1000
Wavelength coverage	L-Q
AO	Better than 0”.1
Field-of-view	10 – 15 arcsecs

Table 7: Summary of requirements of science case 6.

3.7 Active Galactic Nuclei and the Growth of Supermassive Black Holes

3.7.1 Science case outline

103 The growth and evolution of galaxies is thought to be profoundly influenced by the feedback from their central supermassive black holes. However, theoretical models, trying to reproduce the relations between the mass of the black hole and the properties of the stellar spheroid around it, have to make broad assumptions about the physical processes involved. One of the key issues is the rate and efficiency with which gas flows inwards and accretes onto the black hole. At redshifts greater than 1 where co-evolution largely occurs, small scales cannot be resolved and studies have focused instead on the questions of where the gas originates and on the integrated properties of the galaxies. In contrast, detailed studies of nearby active galaxies – especially those for which the luminosity overlaps that of AGN at higher redshifts – provide a unique opportunity to reveal the mechanisms that help or hinder gas inflow and outflow. By guiding and critically testing the prescriptions used in models of galaxy and black hole co-evolution, spectra in the wavelength range 3-12 µm that are spatially resolved at the diffraction limit of the E-ELT have the potential to lead to profound and unique insights into the physical mechanisms that drive the properties of structures on 1-100 pc scales around AGN. In particular, the 'torus' is the centerpiece of the unification scheme and fundamental to our current understanding of active galaxies. Yet many questions about it remain unanswered by contemporary observational facilities. Is it one single structure or does it comprise several distinct sub-structures that encompass the scales from 0.1pc to >10pc on which the torus is thought to exist? Is it discrete or continuous with its surroundings? What level of time variability does it exhibit? To what extent are its properties driven by small scales (e.g. AGN luminosity) or large scales (e.g. gas inflow)? What role does star formation play?

104 In their analysis of VLTI observations of the 10 µm continuum emission from nearby AGN with MIDI, Burtscher et al. (2013) discussed the wide variety of sizes (half-light radii) they found, a result that is remarkable because it is unexpected. Modelling of the data has suggested that the sizes of the extended component are, in the majority of cases, in the range 25-300-mas, equivalent to a few parsecs. Between 3 and 12 µm – wavelengths long enough that the stellar contribution to the continuum is negligible – these tori can be spatially resolved by the E-ELT (the contemporary facility JWST will not have sufficient spatial resolution for these observations). Achieving a direct view of the distribution of hot dust around AGN in this way will immediately show whether the torus itself or a dusty wind (e.g. Hoenig et al. 2013) is responsible for the bulk of the mid-infrared continuum, which, together with the size and spectral shape, will provide a critical constraint for torus models.

105 This science case requires high spatial resolution, and observations of a statistically meaningful sample of AGN in order to assess the range of properties of tori. It is not necessarily photon limited. For example, the mid-IR brightest 20 AGN all have point source (at VLTI scales) fluxes >100mJy, and similarly fluxes, over ~200mas scales, >100mJy. One would also want to observe fainter AGN. Asmus et al. (2011, 2014) show that approximately $L_{2\text{-}10keV} \sim L_{12\mu m}$ in the central arcsec. In order to probe a large and complete sample of AGN down to the luminosity at (below) which the torus is predicted to disappear (Elitzur & Shlosman 2006, Hoenig & Beckert 2007), one would observe AGN with $L_{2\text{-}10keV} \sim 10^{41}$erg/s ($10^{40}$erg/s), to 100 (30) Mpc. This corresponds to a flux of ~0.3mJy.One of the most compelling observations of AGN at mid infrared wavelengths would be to spatially resolve the kinematics of molecular hydrogen lines, such as S(4) at 8.0 µm S(3) at 9.7 µm and S(2) at 12.3 µm. In contrast to the near-infrared H_2 lines such as 1-0 S(1) which trace gas at 1000-3000K, the mid-infrared lines are rotationally excited and trace gas at temperatures up to 500K. Crucially, recent analysis of millimeter molecular lines (e.g. CO, HCN, etc) is now beginning to indicate that the bulk of the gas around AGN is at such temperatures (e.g. Krips et al. 2008). Thus the S(2) to S(4) lines will also trace the bulk gas but, in contrast to ALMA observations at comparable resolution,

interpretation will be without the complications introduced by the modified molecular abundances in X-ray irradiated gas. Quantitative comparison of the fluxes and kinematics of these lines, to the millimeter lines and rotational-vibrational H_2 lines, as well as to the mid-IR continuum, will lead to key insights into the physical properties of the clouds, the stratification of the gas, the mechanisms that drive gas inwards, and the impact on the local interstellar medium of outflows.

106 Based on the large aperture Spitzer spectra of nearby AGN, and assuming that a significant fraction of the total flux is concentrated into knots (associated with shocks, star formation, the AGN, etc, as occurs for the H_2 lines), observations of nearby AGN will not be photon limited for moderate exposure times.

3.7.2 Requirements derived from the science case

108 These science goals rely on the availability of integral field data, given the need to study the 2D distribution of continuum and line emission, at wavelengths 3 to 13 μm, with moderate spectral resolution and diffraction limited spatial resolution.

109

Spectral bands	L, M, N
Simultaneous coverage	at least 1 full band
Spectral resolution	3000-5000
AO performance	Diffraction limited; PSF knowledge available
Field of view	≥0.5”
IFU	yes

Table 8: Summary of requirements of science case 7.

4. Derived science requirements

111 The requirements derived from the science cases discussed above are summarized here.

4.1 Compilation of requirements from the science cases

113

	Field of view	**Spectral coverage**	**Spectral resolution**	**IFU**	**AO**	**coronagraphy**	**Other**
Proto-planetary disks		L, M & N (goal Q)	100,000	yes	Diffr lim	yes	

114

Exoplanets (high-dispersed spectroscopy)		L & M	100,000				simultaneous spectral

								coverage (goal)
115	**Exoplanets (high-contrast imaging and spectroscopy)**		L, M & N	100 – 4,000		Diffr lim	yes/ADI	5σ contrast of 3.10^{-5} (goal 10^{-6}) at 5λ/D (goal 2λ/D) at L and M-bands for 1hr of observation
116	**Transitions from BD to planets**	Few arcsecs	M, N & Q	1,000				
117	**Formation of solar system**		L, M & N (goal Q)	1,000 (L+M,N+Q) 100,000 (L+M,M)		differential tracking		simultaneous spectral coverage (L+M,N+Q)
118	**AGB**	10 – 15 arcsecs (imaging), 1 – 2 arcsecs (IFU)	L, M & N	70,000 L & M 40,000 N	yes	80% Strehl ratio	yes	
119	**Transients**	10 – 15 arcsecs	L, M, N & Q	Few 1,000		< 0.1”		
120	**SMBH**	≥ 0.5”	L, M & N	3,000 – 5,000	yes	Diffr limit		simultaneous spectral coverage of at least one full band

4.2 Science requirements for instrument ELT-MIDIR

122	**Field of view**	The FoV needs to cover at least 10 – 15 arcsecs (with a goal of 20 arcsecs for the N band). The smallest value comes from the supermassive black hole case while the largest value is needed by the AGB and transients cases. Half the cases have no FoV requirement.
123	**Spectral coverage**	The spectral coverage has to extend over the L, M, N, and Q bands (~ 3.5 – 19 μm). The Q band is required by two cases (brown dwarfs to planets and transients) and is a goal for two more (proto-planetary disks and solar system). All cases apart from one (brown dwarfs to planets) need the L band. Q-

		band low-resolution spectroscopy should be considered as a goal.
124	**IFU**	Integral Field Unit spectroscopy is required by three cases: proto-planetary disks, AGB stars, and supermassive black holes.
125	**Spectral resolution**	The required resolving power has a bimodal distribution: four cases (proto-planetary disks, exoplanets, solar system, and AGB stars) require very high (≥ 40,000, up to 100,000) spectral resolutions, while the remaining ones need only values in the 100 – 5,000 range.
126	**AO**	Three science cases require a diffraction limited core (proto-planetary disks, exoplanets, and supermassive black holes), one needs a high Strehl ratio (80%; AGB), and another one demands a spatial resolution < 100 mas. The solar system case requires differential tracking.
127	**coronagraphy**	A coronagraph is needed by three cases (proto-planetary disks, exoplanets, AGB stars).
128	**Others**	Additional requirements include simultaneous spectral coverage (solar system [L+M,N+Q], goal for exoplanets [L+M], one full band for the supermassive black hole case) and 5σ contrast of 3 x 10^{-5} (goal 10^{-6}) at 5λ/D (goal 2λ/D) at L and M-bands for 1hr of observation (exoplanets).

4.3 Priorities

130 In general, all of the requirements described in the previous section are of similar scientific priority. However, the core of the instrument is considered to be:

- L, M, N band imaging;
- L, M, N band low-resolution spectroscopy;
- L, M band high-resolution IFU spectroscopy.

131 Therefore, the following are of lower priority:

- N-band IFU. This was considered to be of slightly lower priority than the other instrument capabilities, since the science cases for it are less compelling than for the core capabilities.
- Q-band (i.e. 17 < λ < 19 μm) imaging. This was considered to be of slightly lower priority than the other instrument capabilities, since the science cases for it are less compelling than for the core capabilities. Q-band low-resolution spectroscopy should be considered as a goal.

5. Appendix A: Filters proposed for ELT-MIDIR

Filter	Central wavelength	Bandwidth
L	3.78	0.58
M	4.66	0.1
PAH1	3.21	0.05
PAH	3.28	0.05
PAH2	3.35	0.05
Bralpha1	4.0	0.06
NB4.07	4.07	0.06
Bralpha2	4.17	0.06
N1	8.6	1.4
N2 (Silicate)	9.7	0.8
N2	10.7	1.4
N3	12	1.4
PAH1_1	8.38	0.4
PAH1	8.59	0.4
PAH1/SIV_1	9.10	0.4
SIV	10.49	0.16
SIV_2/PAH2_1	10.70	0.19
PAH2	11.26	0.59
PAH2_2/NeI_1	11.88	0.37
NeII	12.8	0.21
NeII_2	13.03	0.22

Table 9: Summary of filters proposed.

6. Appendix B Additional justifications for modes of ELT-MIDIR

135 **This section is maintained in the appendix. It does not form part of the TLRs but contains valuable information with respect to the needs for particular modes.**

6.1 A/ IFU-N band

137 **A.1 Accessing the [Ne II] (12.81 µm) excitation line.** The [Ne II] fine-structure line at 12.81 µm offers the best opportunity to confirm or deny the existence of a slow (~10-km/s) ionized wind from a T Tauri disc. The high ionization potential of neon (21.56-eV) means that Ne^+ only exists close to T Tauri stars in photoionized gas, so forbidden emission lines from neon ions are unlikely to arise elsewhere.

138 **A.2 Accessing the H2 (12.2 µm) rotational line.** This measurement is important as it has the potential of giving a direct measurement of the bulk of optically thin gas in the disk, without the recourse to conversion factors that are dependent on assumptions on the gas chemistry. In transition disks, it offers the potential of measuring the gas mass inside the cavity observed in the sub-mm. The challenge is that H_2 mid-IR emission is faint. According to some calculations assuming LTE emission (Carmona 2008) to detect those lines in a large fraction of objects, we should be able to go down to a sensitivity of 1e-16 erg/s/cm2 (1e-19-W/m^2) a factor 100 better than current observations. Models of typical Herbig Ae disks that calculate the gas heating and cooling (Tilling 2012) suggest fluxes of the order 1e-15 erg/s/cm^2. For the HD135344B transition disk, fluxes of 2e-16 erg/s/cm2 are predicted for the 12.2 µm line from the gas inside the cavity. Taking all together, if we reach a sensitivity of 1e-16 erg/s/cm2 we will be able to detect H_2 emission for a large sample of disks, transition disks, T Tauri stars and Herbig Ae stars. With a lower, 1e-15 erg/s/cm^2 sensitivity, we will be able to detect H2 in objects that have hot disk atmospheres such as Herbig Ae stars with flaring disks. There are a couple objects (AB Aur, HD 97048) on which pure-rotational lines have been observed at sensitivity 1e-14 erg/s/cm^2, so this number should get higher.

139 **A.3 Sample.** The sensitivity of VISIR 1.0 (before the upgrade) was typically a line flux of 1e-14 erg/s/cm^2 in one hour on-source. In some targets we manage to get down to 5e-15 erg/s/cm^2 (it depends on the continuum). The sensitivity of Spitzer was 2e-14 erg/s/cm^2. If we aim to a 3-sigma sensitivity to 5e-16 erg/s/cm with an IFU we can observe

1) 35 sources with [NeII] detections with Spitzer not followed up from the ground due to sensitivity (total Spitzer detections ~72);

2) 14 sources with [NeII] detections with Spitzer but not detected from the ground;

3) 16 sources with Spitzer water detections and fluxes lower than 1e-14 erg/s/cm^2;

4) 12 Herbig Ae/Be stars with tentative water detections with Spitzer.

That makes 77 sources. If we add the 21 sources which we have detected [Ne II] from the ground, but we will benefit enormously from the improvement of the ELT, one can observe a total of ~100 sources.

6.2 B/ Q-band Imaging and long-slit spectroscopy

141 **B.1 Resolving inner edge of pre-transition disks (100-200-K).** Q-band is more advantageous to study the inner edge of outer component of pre-transition disks (i.e. HD142527) as the contrast is more favourable for the detection of cool dust at 100-200-K (see Maaskant et al., 2013; Honda et al., 2012 and Verhoeff et al., 2011). N-band is too sensitive to the contributions of the inner regions. The angular resolution of the EELT will be unique to access typical physical separations of 20-50 AU to characterize the inner disks geometry and physics around Herbig stars and even T Tauri stars (not observable with VISIR).

142 **B.2 Dust size.** Q-band will offer a rich diagnostics to constrain the particles size of more than hundred of circumstellar disks (see Telesco et al., 2005) by taking advantage of the high angular resolution provided by MIDIR at E-ELT.