European Organisation for Astronomical Research in the Southern Hemisphere

Organisation Européenne pour des Recherches Astronomiques dans l´Hémisphère Austral

Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

E-ELT PROGRAMME

TOP LEVEL REQUIREMENTS FOR ELT-CAM

E-SPE-ESO-257-1270 Issue 1

ESO-193104

25/01/2013

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Change record

Issue	Date	Section / Paragraph affected	Reason / Initiation Documents / Remarks
1	25/01/2013	All	First Issue

Contents

Abbreviations

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

1 Scope

The scope of this document is to define the Top Level Requirements for the E-ELT instrument: diffraction limited, near-infrared imager (ELT-CAM).

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 [RD3].

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.

2 Related documents

2.1 Applicable documents

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.

AD1 Common definitions and acronyms;
E-ESO-SPE-313-0066 Issue 4

2.2 Reference documents

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.

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

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

RD3 MICADO Scientific Analysis Report;
E-TRE-MCD-561-0007 Issue 2

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

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

3 Science Case for ELT-CAM

The unique spatial resolution of the E-ELT is one of its key defining characteristics. The scientific advances to be expected from the ability to operate a 40-m-class telescope at its diffraction limit form the core of the Science Case for the E-ELT [RD1], and the need for diffraction limited performance was hence a strong driver for the design of the telescope. Thus, the E-ELT clearly requires instruments that can exploit this capability.

The need for such instruments was recognized and strongly emphasized by the E-ELT Science Working Group (SWG) in its recommendation regarding the E-ELT's first-light instruments [RD2]. Having assessed all proposed first-light instruments, the SWG came to the conclusion that a diffraction limited imager and integral field spectrograph represented a particularly powerful combination of instruments, which covered a broad range of science cases for the E-ELT [RD1] and featured compelling discovery potential. Additional assessment criteria included immediate scientific impact, complementarity with other facilities, scientific flexibility, secure scientific return, and the capability of doing science in a broad range of atmospheric conditions.

In this document we derive the Top Level Requirements for ELT-CAM, a diffraction limited near-infrared imager 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-CAM. Although not a complete list, this set is nevertheless representative of the science to be enabled by ELT-CAM. We provide brief descriptions of these cases, as well as the instrument requirements derived from them.

3.1 The Galactic Centre

3.1.1 Outline of the science case

The centre of the Milky Way is a unique laboratory for exploring strong gravity around the closest massive black hole (MBH), and for studying fundamental and broadly relevant processes happening in a very dense star cluster surrounding this MBH, at a level of detail and quality that will not ever be possible in external galaxies. The Galactic Centre also serves as a crucial guide for theoretical studies of accretion onto MBHs and the important issue of co-evolution of MBH activity and nuclear star formation.

Arguably the most fundamental goal of Galactic Centre research in the next decades will be dynamical measurements of the gravitational potential ever closer to the event horizon, with the ultimate goal of testing General Relativity (GR) in the strong field limit. GR is very well tested in the weak field regime, through table-top, solar system and binary pulsar measurements. However, there are two strong-field predictions of GR that have no weak-field fingerprint: (i) The presence of a horizon around collapsed objects and (ii) the lack of stable circular orbits in the neighbourhood of black hole or neutron stars.

Strong-field tests of gravity are therefore of ground-breaking importance, and the Galactic Centre provides us with an ideal environment in which to do it. Such tests will not only allow us to test GR and other metric theories of gravity but may ultimately result in new insights on the nature of spacetime itself: since GR is a classical theory, one might expect it to eventually break down in the strong field limit.

According to GR the size of post-Newtonian effects depends exclusively on the distance from the central object, while in alternative theories other factors (such as the compactness of the central object) also play a role. Therefore the closer one can get to the black hole horizon the stronger will be the constraints on GR and alternative theories and the higher the chances of identifying new physics.

As a benchmark, the horizon size of a Schwarzschild (non-rotating) four million solar mass black hole at the Galactic centre is about 10 μas.

If there are stars in highly eccentric orbits around the black hole with periods of a few months to a year, the precessions of their orbital planes can be as high as 10 μas/year, assuming a black hole rotation rate of at least half the maximum allowed value. Astrometric observations of two or more such stars will yield simultaneous measurements of the angular momentum and quadrupole moment of the black hole, thereby allowing a test of the so-called 'no-hair theorem'. Such a test could be the definitive proof of the presence of a GR black hole at the Galactic Centre.

The currently available observations with the VLT and Keck of the orbits of ~30 bright 'S-stars' in the stellar cusp around the MBH coincident with the compact radio source SgrA* provide the best tool available in astrophysics today for clean dynamical measurements of the gravitational potential to a scale of $\geq 10^3$ times the radius of the event horizon, R_s. However, the VLT/Keck observations are strongly limited by confusion. Fainter stars than presently observable are very likely present, as expected from extrapolating the observed K-band luminosity function. In addition, the volume density of the S-stars increases inwards, such that there is a very good chance that higher resolution measurements will find fainter stars at $10^2 – 10^3$ R_s. At that radius, orbital velocities approach 0.1c and orbital periods may be as short as a few years, allowing the detection of the effects of Special Relativity (SR) and GR on these orbits. Such measurements will test SR and GR in a hitherto completely unexplored regime of spacetime curvature and mass scale. Still further in, at a radius of a few R_s, variable infrared emission from transiently accelerated electrons ('flares') probe the innermost accretion zone around the MBH. Detection of orbital motions of this hot gas requires an astrometric precision of about 10 μas on time scales of a few hours.

Because of the effects of confusion mentioned above, the current precision of astrometric measurements is significantly worse than the fundamental measurement limit. Higher spatial resolution observations (with higher precision and lower confusion) are required for detecting the Newtonian precession of these orbits due to any extended mass outside of the central MBH. Such a distributed mass distribution consists of the observed stars themselves ($< 10^2$ $M_\odot$ in the central 0.1 arcsec) and in addition, stellar remnants (stellar BHs and neutron stars: estimated to be $\leq 10^4$ $M_\odot$) and perhaps dark matter. Detection of these components is obviously of great interest, especially also for determining the expected rates of extreme mass ratio in-spiral events leading to gravitational waves.

Another important issue is whether gas falling into the nuclear region forms stars near the MBH, or whether it is accreted directly into the hole, and whether nuclear star formation and MBH activity are related. Current observations of the Galactic Centre have yielded the remarkable result that episodic star formation deep in the sphere of influence of the MBH appears to be efficient, and apparently has a top-heavy mass function. A better quantitative determination of the processes involved in stellar formation in this extreme environment, a precise determination of the resulting stellar mass function and the exploration of the connection between the rates of star formation and black hole accretion are critical for understanding the cosmological co-evolution of galaxies and MBHs.

3.1.2 Requirements derived from the science case

It is obvious from the discussion above that the most important instrument requirement for Galactic Centre research is high quality (50 μas, goal: 10 μas), stable (time scale of years) astrometry and a stable, diffraction limited (Strehl ratio >30%) PSF. A detailed astrometric study (Trippe et al., 2010, MNRAS, 402, 1126) has shown that achieving the astrometric goals in the highly crowded central stellar cusp around SgrA* requires substantial oversampling of the PSF, with a desired pixel scale of 1–2 mas. The required photometric accuracy is ~0.05 to 0.07 mag. Other important requirements include a high throughput, near-diffraction limited spectroscopic capability for measuring radial velocities from faint star spectra, and a moderately large field (10 – 20 arcsec). The Galactic Centre studies rely mostly on H and K band observations, perhaps with an option to extend to J band.

Astrometric accuracy	50 µas (goal: 10 µas)
Adaptive optics	High-Strehl, diffraction limited core; NIR NGS available
Pixel scale	2 mas (goal: 1 mas)
Field of view	10 arcsec (goal: 20 arcsec)
Wavelength range	HK (goal: JHK)
Other	High throughput, diffraction limited spectroscopy

Table 1: Summary of requirements of science case 1.

3.2 Solar system science

3.2.1 Outline of the science case

The advent of a sensitive and high resolution imaging camera on the E-ELT will benefit solar system science in multiple areas: planetary imaging; cometary imaging; determining physical properties of small bodies (asteroids, outer satellites, distant comets, trans-neptunian objects [TNOs]); search for multiplicity (asteroids and TNOs).

For planetary imaging, the choice of appropriate filters allows one to build 3D maps of planetary atmospheres, with penetration levels ranging from a few bar up to levels of < 1 millibar. An adequate list of filters has to be selected, including the deep continuum (1.58 µm, deep troposphere), the CH_4 filter (1.690 µm, upper troposphere) and the polar haze (2.14 µm, stratosphere). Monitoring planetary disks in these filters will enable climatology studies of planetary atmospheres at unprecedented spatial resolution.

For small bodies the scientific objectives are the monitoring of jets and the evolution of the inner coma in bright and large comets, the search for binary systems, density determination on multiple systems, search for activity in distant comets, and surface characterization of small bodies (outer satellites, asteroids, TNOs). This requires a specific set of filters to identify the CH_4 and H_2O ice bands on TNOs, and the CN fluorescence in comets.

3.2.2 Requirements derived from the science case

As pointed above this science case requires a comprehensive set of narrow-band filters. Details are given in the Appendix.

Searching for multiplicity and studying gravitational/non-gravitational effects and physical properties (spin, size, shape) of small bodies requires very high Strehl ratio. For the brightest small bodies (V < 15 – 16) the AO loop can be closed on the science target itself. For fainter objects the observations can be timed such that the target lies within a few arcsec of a bright NGS.

Adaptive optics	Very high-Strehl, diffraction limited core on-axis or over a few arcsec FoV using NGS; ability to use NGS moving at non-sidereal rate
Other	Comprehensive set of narrow-band filters

Table 2: Summary of requirements of science case 2.

3.3 Direct imaging of exoplanets

3.3.1 Outline of the science case

Detection and characterisation of exoplanets is one of the key science cases for the E-ELT. Pending the installation of a dedicated facility to search for and characterise mature/cold exoplanets, ELT-CAM will provide a unique scientific opportunity, primarily owing to the increase of angular resolution by a factor of ~5 with respect to the VLT. ELT-CAM should arrive when planet finders on 8-m class telescopes (SPHERE/VLT, GPI/Gemini) will have completed their main results (large discovery surveys) and soon after the start of JWST operations. The exoplanets science case described here fits in this general context.

Radial velocity (RV) and transit searches are pushing towards the discovery of lighter planets (Super-Earths) ideally in the so-called habitable zone of stars. Direct imaging so far has only revealed a handful of planetary mass objects due to the high contrast required at small separations (less than 1 arcsec). Nevertheless, a few exemplary objects have been discovered and studied, such as ß Pic b (Lagrange et al., 2010, Science, 329, 57), the four planets around HR 8799 (Marois et al., 2008, Science, 322, 1348; Marois et al., 2010, Nature, 468, 1080) and the intriguing object in the Fomalhaut system (Kalas et al., 2008, Science, 322, 1345).

So far, direct imaging has focussed on young stars because of the reduced star-to-planet contrast (the decay of a planet's luminosity is age-dependent). However, it is also clear that only young systems will bring information about the planetary formation process. Old systems have certainly lost their memory of initial conditions due to migration and/or planet scattering, as demonstrated by the diversity of planets in the Solar System and among the known exoplanets. Imaging of young planetary systems captures them soon after they have formed and while they are still evolving in dusty disks, providing information about system architecture. For instance, the discovery of a planet around ß Pic, a ~10 Myr old system, is a direct measurement of the formation timescale. Similarly, a potential planet in formation detected in the 2 Myr old LkCa 15 system (Kraus et al., 2012, ApJ, 745, 12) shows that some giant planets can form very fast.

The role for ELT-CAM with respect to near-term instruments (SPHERE, GPI, JWST) is the improvement of the angular resolution with moderate contrasts. For the exoplanet science case, ELT-CAM may play a similar role for the E-ELT as NACO did for the VLT, i.e. a general-purpose imager with adaptive optics offering the highest possible Strehl ratio and contrast on-axis. After a learning phase, NACO now delivers very high quality data and is able to detect and study young giant exoplanets as well as circumstellar disks. The same kind of instrument on a ~40-m telescope will improve the angular resolution by a factor of 4 to 5. Assuming the same level of contrast is achievable, a ß Pic b-like object is detectable at ~2 AU instead of 8 – 10 AU. ELT-CAM will have the ability to reach closer physical separations than NACO and even SPHERE on nearby targets (< 50 pc). This range overlaps with that probed by RV, which is now becoming applicable on young early type stars, even though they are active. Therefore, it will be possible to infer the true mass of a planet from the minimal mass measured by RV and the inclination measured from imaging (several epochs needed). A more precise calibration of evolutionary models will become feasible, with the advantage to perform better spectral characterisation. In addition, ELT-CAM will be able to search for young giant and massive planets (10 M_J) on wide orbits (> 20 – 30 AU) around young star associations that are more distant than those observed with SPHERE (100 – 150 pc rather than 30 – 90 pc). Therefore, the number of potential targets is larger. Moreover, these observations performed in several bands (JHK) will allow us to derive near-IR colours and to constrain some atmospheric properties like temperature and surface gravity.

With respect to spectral characterisation, the improvement of angular resolution will be a major benefit to long-slit spectroscopy for some planets that are sufficiently separated, with the ability to achieve a spectral resolution of several thousand while SPHERE will provide only a few hundred. In addition to better detecting some broad spectral lines (CH_4, NH_3, H_2O, CO_2, etc.) this higher spectral resolution is of particular interest to bring more constraints on the atmospheric properties (metallicity, clouds and dust). This high level of characterisation will be devoted to bright exoplanets.

To summarise, building on the current capabilities of NACO, ELT-CAM will have the ability to complement SPHERE, in particular by extending the search area for very young giant and massive planets to shorter orbital separations (a few AU) for nearby stars (20 – 50 pc), as well as around more distant star associations (100 – 150 pc). This is essentially a search program with a small level of characterization (near-IR colours with medium resolution spectroscopy for the brightest planets).

3.3.2 Requirements derived from the science case

Direct imaging of exoplanets requires the ability to achieve high contrasts, implying a high on-axis Strehl ratio (~70%) as well as a coronagraph. The requirement is for ELT-CAM to be able to image the same exoplanets as SPHERE.

Contrast (5σ)	5×10^{-5} at 100 mas (goal: 20 mas) 5×10^{-6} at 500 mas (goal: 100 mas)
Adaptive optics	Very high-Strehl, diffraction limited core on-axis using NGS
Other	Coronagraph, diffraction limited spectroscopy

Table 3: Summary of requirements of science case 3.

3.4 Discovering exoplanets using astrometry

3.4.1 Outline of the science case

The search for planetary systems orbiting other stars has demonstrated that planets are extremely common objects in the Universe. Fundamentally, we also have learned that planetary systems are much more diverse than originally predicted. This has highlighted the danger of generalising from a single system and the absolute necessity of combining the knowledge acquired by exploring the solar system with that derived from studying exoplanets.

In particular, little is known about the formation of planets around low mass stars, the most common stars in galaxies. From an empirical point of view, considering that disks are observed around low mass stars and even brown dwarfs, the formation of planets around low mass stars should be possible. In addition, low mass stars provide us with targets where the contrast would be optimal for direct imaging of planets. Usually cool dwarfs are too faint (as well as intrinsically active) to efficiently benefit from radial velocity method's full capability. Astrometry is a good alternative to detect planets around these targets. Moreover, astrometry will probe a range of separations, so that planets discovered by astrometry may later be directly imaged, eventually leading to a full characterisation (including atmospheric features) of small planets orbiting these stars.

The potential of large telescopes to conduct accurate astrometric programmes on low mass stars has been demonstrated on the VLT. Assuming that this potential would be even higher for the E-ELT, with a (differential) astrometric accuracy of ~10 µas, the detection of a 1 M_{Earth} planet on a 1000 day orbit around a low mass star at a distance of 10 pc would be possible. Taking advantage of the sensitivity of a ~40-m telescope and the IR capability of ELT-CAM, one could imagine extending the planet search to ultra-cool dwarfs in the T and Y spectral classes. Many of these objects are currently being discovered. These targets are lighter, i.e. the detection limits in terms of companion mass goes down, and they are redder and fainter, i.e. there may be more usable reference stars.

3.4.2 Requirements derived from the science case

As a benchmark, the astrometric motion of a 0.06 M_{Sun} star at a distance of 10 pc orbited by a 3 M_{Earth} planet in 1000 days is 11.5 µas. This is clearly challenging and so a relative astrometric accuracy of 10 µas is only set as a goal. To be able to achieve this accuracy it is of critical importance that a sufficiently large number of reference stars is available. This in turn requires a large field of view. An analysis of the fields of known potential target stars resulted in a hard requirement of 50 arcsec for the size of the field of view.

Astrometric accuracy	50 µas (goal: 10 µas)
Field of view	50 arcsec (goal: 60 arcsec)

Table 4: Summary of requirements of science case 4.

3.5 Astrometry of globular clusters and dwarf spheroidal galaxies

3.5.1 Outline of the science case

Globular clusters are the oldest known components of the Milky Way, and tracing their formation may reveal important aspects of the early formation of the Galaxy itself. Measuring parallax distances, along with their proper motions will allow us to construct the 3D kinematics of a major fraction of the globular cluster system, and their orbits within the Galactic potential. This should allow us to address questions such as whether kinematic families exist among globular clusters, suggesting that they may have formed within precursor galaxies that merged, contributing to the buildup of the Galactic spheroid. Measuring accurate density distributions and proper motions of faint stars near the centre of individual globular clusters should reveal whether intermediate mass black holes exist in (some of) these stellar systems, hence enriching the problematic of globular cluster dynamical evolution and black hole formation.

Measuring the dark matter content of dwarf spheroidal galaxies is an interesting test of structure formation models. The internal motions of dwarf spheroidal galaxies can reveal the gravitational fields in these systems. Cold Dark Matter (CDM) simulations of gravitational collapse show that dark halos should be very clumpy, a consequence of the hierarchical merging that characterizes CDM cosmology. On the assumption that these clumps (sub-halos) host the dwarf spheroidal satellites, the mass function of the satellites should be similar to the high end of the theoretical mass function of clumps seen in the simulations. It will be important to attempt to establish this relation observationally: if it does not hold, it would point to a significant modification of the CDM structure formation mechanism, e.g., to the disruption of these halos by early star formation and mass loss. Intense radial velocity campaigns of dwarf spheroidals have been carried out in order to measure their dynamical masses. Typically, velocity dispersions stay flat out to large radii, suggesting indeed that rather massive halos surround the satellites. However, radial velocity measurements are subject to the orbit anisotropy degeneracy: a deeper potential can be mimicked by a tangentially biased orbit distribution. Proper motions are the way to break this degeneracy by directly measuring the shape of the velocity ellipsoid (ratio of the radial and tangential velocity dispersions) of the stars. A recent compilation of results for 23 dwarf spheroidal galaxies (Strigari et al., 2008, Nature, 454, 1096) concludes that over 4 orders of magnitude in luminosity the total halo masses of dwarf spheroidals are rather uniform. This remarkable result is affected by the unknown orbit distribution, and the observations envisaged here are precisely the measurements that will settle the issue.

3.5.2 Requirements derived from the science case

Demanding a 10% error in the parallax distance of a stellar cluster at the distance of the LMC (~50 kpc), and assuming that hundreds of stars can be used for the parallax measurement, results in a requirement for the astrometric precision for a single, well exposed, unresolved source of ~50 µas.

At a distance of 50 kpc a proper motion of 10 km/s corresponds to 40 µas/yr. Obtaining a 1% error in the measurement of this motion, again assuming that hundreds of stars are available and further assuming a 5 year measurement baseline, also results in a requirement of 50 µas for the astrometric precision.

With typical internal velocity dispersions of order 5 km/s, the above astrometric accuracy would ensure that the internal velocity fields of GCs can be mapped out with a precision of just a few per cent. Similarly, for dwarf spheroidals typical internal velocity dispersions are of order 10 km/s, and so 10% precision measurements of their internal proper motion field should be possible for most of the Local Group in ~10 years.

Since nearby dwarf spheroidal galaxies extend over several arcmin, and since the measurement of proper motions needs several reference objects (background AGN and compact galaxies), this science case requires a field of view of no less than 50 arcsec.

The astrometric accuracy required for this science case can only be achieved if the PSF has a well-developed diffraction limited core.

Astrometric accuracy	50 µas
Adaptive optics	Well-developed diffraction limited core over full FoV; LGS
Field of view	50 arcsec

Table 5: Summary of requirements of science case 5.

3.6 Resolved stellar populations up to Virgo

3.6.1 Outline of the science case

One of the key issues in modern astronomy concerns the star formation history (SFH) in the Universe. Indeed, while the development of structures is well understood in terms of hierarchical growth in the framework of the CDM model, it is still not clear how to couple the baryonic component to the CDM. Direct observations of galaxies up to high redshift can be used to map the SFH, but since the integrated galaxy light is dominated by the most recent stellar generations, the information on the underlying older stellar population is severely limited. A similar problem affects the analysis of the spectral energy distribution of galaxies, from which only luminosity averaged ages and metallicities can be derived.

Alternatively, we can make use of the fact that all galaxies are the integrated products of all the star formation during their entire lifetimes, and the chemical elements in the stellar populations of different ages provide the most detailed evidence for this past star formation. Because low mass stars can have lifetimes comparable to the age of the Universe, the low mass tail of the ancient star formation that occurred at the formation epoch of a galaxy remains visible today and provides unique clues to the earliest physical process in the Universe. Stars of all ages provide an accurate and detailed probe of changing galaxy properties. By observing large numbers of individual stars we can measure how the rate of star formation and chemical composition of a galaxy has varied from its formation to the present and thus how galaxies were built up over time. To unravel this formative epoch detailed spatial, kinematic and chemical surveys of resolved stellar populations are required; providing a unified picture between local near-field cosmology, predictions from high redshift surveys and theoretical simulations of galaxy formation and evolution.

Until now the sensitivity and resolution limitations have meant that detailed studies have only been possible within the Local Group (LG) and specifically around our own Galaxy. This means that only small dwarf type galaxies have had their ancient stellar populations accurately probed; massive galaxies still await this careful scrutiny. The LG contains only two massive galaxies (spiral systems M31 and the Milky Way) and around 60 smaller, mostly dwarf, galaxies. This is hardly representative of the range of galaxy types, and our LG is not necessarily representative of the high-density regions of the Universe where most galaxies live. Careful studies of dwarf galaxies have already shown inconsistencies between observations and the standard CDM picture, and these need to be extended to larger galaxies to make an accurate comparison with the properties of small galaxies. To make significant progress we need to study large numbers of resolved stars in a range of galaxy types and this requires us to look beyond the halo of the Milky Way.

The ultimate goal is to study the resolved stellar populations in giant elliptical galaxies, of which there is no example in the LG, and we have to look at Cen A to find the closest example of a peculiar elliptical. However, the best place to look at the properties of a range of elliptical galaxy types is the Virgo cluster which contains thousands of large galaxies and tens of giant ellipticals of a range of size and position in the cluster. Of particular interest are the crowded central regions of galaxies where most of the stellar mass lies.

Obtaining accurate photometry in order to construct and interpret the colour-magnitude diagram (CMD) of resolved stellar populations is the first step in this programme. Key issues include: what is the SFH and metallicity distribution of galaxies as derived from the CMDs of their resolved stellar populations? How do these properties compare to the corresponding quantities as derived from integrated-light studies? Are the derived SFHs consistent with the evidence from observations of their likely precursors at high redshifts? What are the SFH and metallicity gradients within galaxies? What are the evolutionary properties of super-metal-rich stellar populations?

With its superior sensitivity and resolution ELT-CAM will allow us, for the first time, to study the resolved stellar populations of galaxies out to the distance of the Virgo cluster, including their high surface brightness inner regions.

3.6.2 Requirements derived from the science case

In order to be able to derive an accurate SFH from a CMD we require a photometric accuracy of a few × 0.01 mag. The key issue for this science case is the extent to which the accuracy of the photometry of individual stars is affected by stellar crowding in the dense inner regions of a galaxy. This accuracy is entirely driven by resolution. High-quality AO correction is therefore essential for this science case. However, we note that the photometric accuracy is independent of the PSF's Strehl ratio as long as the AO correction is good enough to provide a well-developed diffraction limited core in the PSF.

The need for the highest possible resolution argues for the shortest possible wavelengths. On the other hand, the quality of the AO correction increases with wavelength. In addition, one would like to use as widely separated bands as possible, because the longer the wavelength base the more widely the different stellar populations are spread across the CMD, thus improving the diagnostic power for a given photometric error. The detailed study of these issues in [RD4] concluded that the best combination of bands for the construction of CMDs is (Johnson) I and H, straddling the wavelength where the E-ELT will achieve its highest resolution (i.e. in the J-band). The I band is also important for the derivation of metallicities and for determining distances using the tip of the Red Giant Branch.

Given the importance of resolution to this science case the pixel scale should be chosen so as to at least Nyquist sample the diffraction limited core of the PSF at the shortest wavelength considered. This leads to a requirement for the pixel scale of 2 mas.

To derive a requirement on the size of the field of view we note that a CMD must be populated with many hundreds of stars in order to obtain reliable results. Considering that a single pointing may require up to several tens of hours of integration time [RD4], and that at least tens of galaxies need to be probed at several galactocentric distances in at least two bands, the field of view should be large enough so as to include several hundred stars in most circumstances. For M87 in the Virgo cluster the stellar density at 5 effective radii and at K = 27.5 mag (= limiting magnitude for a photometric error of 0.05 mag in a 10 hour integration, see [RD4]) is ~1 star/arcsec^2/(0.1 mag). Hence we require a field of view of ~30 arcsec.

However, the requirements for the pixel scale and the size of the field of view do not need to be satisfied simultaneously. In the crowded central regions of galaxies, where the highest resolution is required, a smaller field of view of ~10 arcsec size is sufficient. Similarly, in the outskirts of galaxies, where the large field of view is required, a larger pixel size of 3 mas is sufficient.

Photometric accuracy	A few × 0.01 mag
Adaptive optics	Well-developed diffraction limited core over full FoV; LGS
Pixel scale / field of view	2 mas over 10 arcsec and 3 mas over 30 arcsec
Wavelength range	IJHK

Table 6: Summary of requirements of science case 6.

3.7 Metallicity gradients in the nearby Universe

3.7.1 Outline of the science case

Metallicity gradients are a fundamental diagnostic for constraining the chemical enrichment and star formation histories of giant galaxies. Moreover, they also play a crucial role in constraining the metallicity dependence of the most popular distance indicators such as Cepheids, the tip of the Red Giant Branch and type Ia supernovae (Bono et al., 2008, ApJ, 684, 102; Bresolin et al., 2009, ApJ, 700, 309). Measurements of metallicity gradients are based either on metal absorption lines of young stellar tracers such as blue and red supergiants (Kudritzki et al., 2012, ApJ, 747, 15) and Cepheids, or on emission lines of HII regions. The former approach has been applied only to a very limited number of nearby galaxies, while the latter one uses the O/H abundance ratio as a proxy of the metal content of the host galaxies. However, nebular abundances based on emission lines of HII regions can be affected by systematic differences on the order of 0.5 dex when compared with stellar abundances (Kewley & Ellison, 2008, ApJ, 681, 1183; Bresolin et al. 2009).

Note that chemical evolution studies of star-forming galaxies and the so-called galaxy mass-metallicity relation rely on these emission-line diagnostics. To overcome the systematic uncertainties affecting these diagnostics, it has been suggested to estimate the metallicity of HII regions using the *direct* method, i.e. using faint auroral lines which provide a measurement of the gas electron temperature (Bresolin, 2011, ApJ, 730, 129). Current findings indicate that this approach gives metallicity gradients that agree quite well with those based on blue and red supergiants, at least up to solar metallicity. At the very least auroral lines provide us with reliable *differential* metallicity measurements, and thus provide us with a reliable way of measuring metallicity gradients within galaxies and differences between galaxies. Using this method the E-ELT will allow us to obtain a detailed census of metallicity gradients in giant and dwarf galaxies in nearby galaxy clusters such as Centaurus, Fornax, Eridanus, Sculptor, and in particular in Virgo.

3.7.2 Requirements derived from the science case

The goal is to obtain near-IR long-slit spectroscopy of extended HII regions in nearby galaxies. The diagnostics to be used include He recombination lines as well as forbidden Fe, O, N and S lines (Lumsden & Puxley, 1996, MNRAS, 281, 493; Lumsden et al., 2003, MNRAS, 340, 799). Accomplishing this goal requires a spectral resolution of 1000 – 3000, a wavelength range of 0.9 – 2.5 μm, a slit length of ~30 arcsec, and a slit width of 2 − 3 times the diffraction limit. Nodding along the slit at the same position on the chip as the object gives the opportunity to remove residual sky features.

Spectroscopy	Long-slit spectroscopy with R ~ 1000 – 3000; wavelength range 0.9 – 2.5 μm; slit length ~ 15 − 20 arcsec; slit width ~ 2 − 3 × diffraction limit

Table 7: Summary of requirements of science case 7.

3.8 Studies of extragalactic transients

3.8.1 Outline of the science case

Supernovae and gamma-ray bursts constitute some of the most energetic explosions in the Universe. They play a major role in driving the physical and chemical make-up of galaxies and in shaping the dynamics of the interstellar medium. Although they are routinely used as probes of conditions in the distant Universe, and as a means with which to constrain quantities such as the stellar initial mass function, many questions relating to their origin, nature, and evolution remain unanswered. The current generation of wide-field synoptic surveys are already discovering several hundred spectroscopically-typed supernovae per year, with a factor of at least five times more candidate objects that are often too faint to be confirmed spectroscopically with currently available facilities.

For all transients, key questions include the nature of the progenitor system, the physics of the explosion, the rate of each sub-type, the dependence on environmental factors such as metallicity, and how each of these evolve – if at all – as a function of redshift. The results of each of these questions impact on several other areas of astrophysics.

Furthermore, explosions resulting from the first generations of stars pinpoint faint, high-redshift, star forming galaxies that might otherwise remain undetected. Their redshift distribution is an important ingredient in models of structure formation.

3.8.2 Requirements derived from the science case

Low resolution (R ~ few hundred) long-slit spectroscopy between 0.8 – 2.5 μm is ideally suited to classification and potential follow-up of transients as the majority of sources will have broad lines due to fast-moving ejecta (several thousand km/s). However, the impact of OH sky lines in the near-IR region on the target spectrum needs to be mitigated. Moderate dispersion spectra (R ~ 4000) could be used to mask out the OH lines, following which the spectra can be rebinned to the desired resolution.

All transients are point sources, and so diffraction limited spectroscopy is necessary to maximise the signal, in particular for high-redshift sources which are likely to be blended with their host galaxies, as well as for targets occurring in crowded regions, e.g. spiral arms or clusters.

Spectral lines that are the signatures of various sub-types will be redshifted into the red part of the visible and into the near-IR region for z >~ 0.5. Examples include the Balmer lines, indicative of type II supernovae, the SiII doublet (near 0.63 μm) and the W-shaped feature due to SII (near 0.545 μm), characteristic of type Ia supernovae. Firm typing of supernovae is critical for a variety of studies, and simultaneous access to important diagnostic lines is not only essential for classifying objects, but also for determining redshifts. The redshift in turn provides the absolute peak brightness – an important discriminator of the mechanism by which the supernova is powered. The availability of host redshifts also lends itself to ancillary science. Finally, rapid and simultaneous access to as large a wavelength region as possible would be desirable for transients that evolve on short timescales (minutes).

The likely provenance of targets is expected to be from space-based facilities, e.g. JWST, Euclid. These events would necessitate spectroscopic classification on relatively short timescales (days) to inform subsequent observational strategies.

Spectroscopy	Diffraction limited spectroscopy with simultaneous coverage of the range 0.8 – 2.5 μm at R ~ 4000 – 8000

Table 8: Summary of requirements of science case 8.

3.9 Resolved structure and physical properties of high-redshift galaxies

3.9.1 Outline of the science case

The physical processes driving galaxy formation and evolution are still an enigma. Given the most recent results from high resolution studies (imaging and integral field spectroscopy, from the ground and from space) it is now becoming clear that galaxies at redshift z ~ 1 – 4, when they were undergoing their most rapid phase of stellar mass assembly, were very different from local galaxies. High redshift galaxies have higher rates of gas accretion and star formation, and more intense radiative and mechanical feedback from star formation and AGN. Most z > 1 star-forming galaxies look irregular and very often clumpy in current imaging. Kinematic mapping indicates they are far more gas-rich and turbulent than z ~ 0 galaxies, implying that they are unstable and should fragment into self-gravitating units. Despite these new insights, the detailed workings remain elusive. Theoretical models and numerical simulations still do not reproduce satisfactorily the observed characteristics of individual galaxies and of galaxy populations, at high redshift and consistently across cosmic epochs to the present day. This is largely attributed to simplified and often inadequate recipes for the complex phenomena that govern the evolution of galaxies such as feedback, merger and mass accretion history, redistribution of mass and angular momentum, chemical enrichment, heating/cooling processes, etc. The main limitation is spatial resolution: at best, resolutions of ~50 – 100 mas can be achieved with current telescopes, even with AO. This corresponds to ~400 – 800 pc at z ~ 1 – 4, and provides a limited number of resolution elements across typical high redshift galaxies. This is clearly insufficient to resolve substructure on scales of individual giant star-forming complexes and clusters, which is necessary to pin down the physical and dynamical processes involved.

High resolution imaging of z > 1 galaxies will thus be crucial for a proper understanding. Their typical sizes are ~0.2 – 0.3 arcsec at z ~ 2 – 4, decreasing at higher redshift roughly as 1/(1+z) at fixed rest-frame luminosity (e.g., Bouwens et al., 2004, ApJ, 611, L1), and decreasing with lower luminosity (roughly as $L^{0.5}$). Moreover, it has also become clear that quiescent galaxies at high redshift tend to be very small and dense – they are still unresolved with HST (e.g., Toft et al., 2007, ApJ, 671, 285). The presence of substructure on <~ 100 pc scales in high redshift galaxies is not a trivial issue, but some studies suggest it is very likely: near-IR integral field spectroscopy of a few strongly lensed z ~ 1 – 3 galaxies shows clumps on physical scales of ~100 pc (Swinbank et al., 2006, MNRAS, 368, 1631); local analogs of z ~ 3 Lyman-break galaxies contain super star clusters (Overzier et al., 2008, ApJ, 677, 370); and numerical simulations of turbulent gas-rich disks show that the Jeans-scale kpc-sized clumps may further break up into smaller-scale structure.

Observations at the diffraction limit of the E-ELT will correspond to approximately 60 pc in physical length (for z > 1), and will be of comparable quality to 1 arcsec imaging of Virgo galaxies. This will allow us to isolate and even resolve regions with sizes comparable to individual star-forming complexes such as 30 Dor in the LMC, N66 in the SMC, or super-star clusters seen in nearby starburst galaxies. Furthermore, this resolution will typically provide >100 resolution elements across the galaxies, and deliver detailed information about the morphology, dynamical state, and variations in stellar/physical parameters across the galaxy.

At very high redshifts (z ~ 7 and beyond) galaxies may be discovered and studied via their Lyman-α emission by imaging in narrow wavelength windows in the near-IR. Such observations constrain the galaxy luminosity function at very high redshift, which in turn constrains the possible sources of reionisation in the early Universe.

3.9.2 Requirements derived from the science case

Overall, a key objective is to study at least ~1000 galaxies to cover the known diversity of morphologies at high z, and allow investigations as a function of redshift and mass. This requirement is more important than the actual pixel scale as long as the diffraction limited core of the PSF is Nyquist sampled. With a typical density of 5 sources per $arcmin^2$ at $K_{Vega} < 21$ mag, this implies that an area of 200 $arcmin^2$ must be covered, comparable to 1 GOODS-sized field. With a field of view of 1 $arcmin^2$ and fiducial 10 hour integrations, this will take 2000 hours. It is therefore clear that a large field of view is essential, to allow building up a sufficiently large sample.

For emission line mapping with narrow-band filters of "redshift spikes", the field size needs to be sufficiently large to encompass proto-clusters. The earliest and most massive protoclusters found to date (around radio galaxies) at z ~ 2 – 5 are ~1.5 – 2 Mpc across, translating into 3 – 4 arcmin (e.g., Venemans et al., 2007, A&A, 461, 823). Less massive structures may be smaller. Hence, the (large) field size requirement is important for this aspect of the present science case as well.

The PSF needs to be well described over the full field, so that consistent and accurate photometry can be done over all galaxies observed. Good characterization of the PSF is essential to derive accurate structural parameters and colours (and line ratios, line-to-continuum ratios). Experience indicates that for these purposes, PSF characterization to better than 10% accuracy is needed (encircled energy and FWHM being the critical parameters here). Acceptable variations across the field of view are of < 5%. A further consideration motivating these requirements is that typical observing strategies for deep imaging of high redshift galaxies involve many exposures dithered within boxes ~10 arcsec on a side, meaning the effective PSF at any location is complex and an average over all co-added frames, so too large variations over this scale of ~10 arcsec will result in significant loss of effective resolution.

For sufficient diagnostic power to reliably distinguish age, extinction, and metallicity, one needs a sufficiently long wavelength baseline. Ideally, one would like to bracket the age-sensitive 4000Å/Balmer break. For z ≥ 2, this is achieved with λ = 0.9 – 2.2 μm (rest-frame range ≥ 3000 – 7300 Å).

Extremely valuable information about galaxies can be gained from line emission, which map out HII regions, shock-excited interstellar medium, and outflows from star formation and/or AGN. For z ~ 1 – 4, lines of Hα, Hβ, [NII], [OIII], [OII], [NeIII] become accessible in the near-IR, which provide diagnostics of the star formation rate, extinction, excitation sources, gas-phase abundances, densities, and ionization parameter. Ideally, the aim is to obtain spatially resolved mapping in this entire set of lines using narrow-band filters. There exist about 5 redshift slices (in the range 2.2 to 2.4) that allow one to obtain all of those lines simultaneously within telluric windows and between the night sky lines. Covering just two of these requires 12 filters of width 50 – 200 Å. Considering that the most massive protoclusters known at z ~ 2 – 5 have typical velocity dispersions of ~500 – 1000 km/s (Venemans et al. 2007) these filter widths would ensure mapping of protocluster members across the full field of view.

For studies of galaxies at z > 7 there are broadly two types of narrow-band Ly-α searches described in the literature. The first uses narrow-band filters (R ~ 100, i.e. 50 – 300 Å width) in spectral windows of high transmission and compares observations to broad-band observations of the field (see e.g. the studies using SuprimeCam on Subaru). For this a set of at least 3 (goal of 8) narrow filters are needed, but there will be overlap with other requirements. For example, it is likely that many of the 12 filters described above for observing other lines at z = 2 – 5 would be suitable for observing Ly-α at very high redshift.

The second type of observation uses custom-made ultra-narrow band filters (R ~ 300 – 1000, i.e. 30 Å width) in spectral regions that are both high-transmission and clear of OH emission lines (see e.g. the DAzLE instrument on VLT). In this case observations through adjacent ultra-narrow filters are compared. A set of at least two narrow-band filter pairs that lie within clean regions of the sky spectrum, between OH lines is required. A good starting point would be the highest redshift dark windows in J, i.e. the 1.19 μm window which corresponds to z = 8.8 and the 1.32 μm window which corresponds to z = 9.8 (see table in Horton et al. 2004). Note that the effective wavelength of ultra-narrow band filters may shift across the field depending on instrument design. The filters must be chosen carefully such that the band-passes remain 'clean' of OH lines after allowing for these shifts. Definition of these filters therefore requires detailed modelling of the OH lines and atmospheric transmission spectrum, and knowledge of the optical design of the instrument. The feasibility of such filters and their detailed specifications should be studied by the instrument team in the next phase. The requirement here is to ensure sufficient filter slots are available in order to include such filters in future. The goal is to actually provide the filters.

Clearly for studying faint distant galaxies, throughput should be maximized.

Adaptive optics	Diffraction limited core over full FoV, with < 5% PSF variation over at least 10 arcsec; LGS
Field of view	60 arcsec
Wavelength range	IJHK
Throughput	Maximum
Other	12 narrow-band filters of width 50 – 300 Å; slots for two pairs of ultra narrow-band filters of width 30 Å; providing these filters is a goal

Table 9: Summary of requirements of science case 9.

4 Derived science requirements

4.1 Compilation of requirements from the science cases

	Field of view	Pixel scale	Adaptive optics	Wavelength range	Other
Galactic Centre	10 (20) arcsec	2 (1) mas	High-Strehl, diffraction limited core; NIR NGS available	(J)HK	Astrometric accuracy = 50 µas (goal: 10 µas) High throughput, diffraction limited spectroscopy
Solar System			Very high-Strehl, diffraction limited core on-axis or over a few arcsec FoV using NGS; ability to use NGS moving at non-sidereal rate		Comprehensive set of narrow-band filters
Direct imaging of exoplanets			Very high-Strehl, diffraction limited core on-axis using NGS		Contrast (5σ) = 5×10^{-5} at 100 mas (goal: 20 mas) 5×10^{-6} at 500 mas (goal: 100 mas) Coronagraph Diffraction limited spectroscopy
Exoplanets from astrometry	50 (60) arcsec				Astrometric accuracy = 50 µas (goal: 10 µas)
GCs and Dwarf Spheroidals	50 arcsec		Well-developed diffraction limited core over full FoV; LGS		Astrometric accuracy = 50 µas
Resolved stellar populations in Virgo	10 / 30 arcsec	2 / 3 mas	Well-developed diffraction limited core over full FoV; LGS	IJHK	Photometric accuracy = a few × 0.01 mag
Metallicity gradients	30 arcsec			0.9 – 2.5 µm	Spectroscopy with R ~ 1000 – 3000; slit length ~ 15 – 20 arcsec; slit width ~ 2 − 3 × diffraction limit

Extragalactic transients				0.8 – 2.5 µm	Diffraction limited spectroscopy with simultaneous coverage of the range 0.8 – 2.5 µm at R ~ 4000 – 8000
High-z galaxies	60 arcsec		Diffraction limited core over full FoV, with < 5% PSF variation over at least 10 arcsec; LGS	IJHK	12 narrow-band filters of width 30 – 200 Å

Table 10: Summary of requirements from all science cases.

4.2 Science requirements for ELT-CAM

Astrometric accuracy	The relative position on the sky of an unresolved, unconfused source of optimal brightness with respect to an optimal set of reference sources must be reproducible to within 50 µas (goal: 10 µas) over a central, circular field of 20 arcsec diameter (goal: across the entire field of view) and over all timescales in the range of 1 hour to 5 years.
Photometric accuracy	The relative flux of an unresolved, unconfused source of optimal brightness with respect to an optimal set of reference sources must be reproducible to within 0.02 mag (goal: 0.01 mag) across the entire field of view.
Contrast	Direct imaging of exoplanets requires the following contrasts (5σ): 5×10^{-5} at a separation of 100 mas (goal: 20 mas) 5×10^{-6} at a separation of 500 mas (goal: 100 mas)
Pixel scale and field of view	Two combinations of pixel scale and field of view must be provided: 1. The most stringent requirement for the pixel scale derives from the need of the Galactic Centre case to substantially over-sample the diffraction-limited core of the PSF in the H band, and from the need of the resolved stellar populations case to at least Nyquist sample the diffraction limited core of the PSF at the instrument's shortest wavelength (I band). This results in a requirement for the pixel scale of 2 mas (goal: 1 mas). However, these cases only require a field of view of 10 arcsec (goal: 20 arcsec). 2. The need of the exoplanets and GCs and Dwarf Spheroidals cases for a sufficient number of reference sources in any given image leads to a requirement on the size of the field of view of 50 arcsec. The need of the high-redshift galaxies case to be able to build up a sizeable sample argues for a larger field of view size of 60 arcsec. However, since in this case field of view size can be traded against observing time to keep survey speed constant, a 60 arcsec field of view is only set as a goal. Furthermore, since these cases are not concerned with extremely crowded fields the requirement on the pixel scale can be relaxed to 3 mas.
Adaptive optics	Several cases require the PSF to have a well-developed diffraction limited core over the full field of view at wavelenghts > 1 µm. Spatial PSF homogeneity is required to allow for the combination of dithered exposures without loss of resolution. Hence PSF variations must be < 5% on scales < 10 arcsec. LGS are required.

	The exoplanet imaging and solar system cases require very high on-axis Strehl ratios, with the science targets serving as NGS. The study of circumstellar disks is another science case requiring these capabilities. For the solar system case this implies the ability to use NGS moving at non-sidereal rates.
Wavelength range	Combining the requirement for ELT-CAM to operate at the diffraction limit with the expected performance of AO systems as a function of wavelength naturally leads to the NIR wavelength range. The resolved stellar populations case requires the wavelength range to extend slightly below the wavelength at which ELT-CAM will achieve the best spatial resolution, i.e. down to ~0.8 μm (I band). In addition, the I band is needed for the derivation of metallicities and the interpretation of horizontal branch populations. Covering the age-sensitive Balmer break in z > 2 galaxies also requires the I band. At the red end the K band is required by all cases. Thus the requirement on the wavelength range is 0.8 – 2.5 μm.
Filter set	Broad-band filters: I, z, Y, J, H, K_s Studies of (exo)planets and minor bodies in the solar system require at least the following narrow-band filters (wavelengths in μm): 1.58 (planetary tropospheres); 1.69, 1.75, 2.30 (CH_4); 2.14 (planetary polar haze); 1.495, 2.06 (H_2O). Providing the additional, lower priority filters listed in Table 12 and Table 13 below is set as a goal. Classical indices adopted to investigate stellar populations (late spectral types) in the MW and in nearby stellar systems include the following gravity sensitive spectral features (wavelengths in μm): 0.8183, 0.8195 (NaI doublet); 0.991 (Wing-Ford band); 0.843, 0.888 (TiO); 2.29 (CO). Additional narrow-band filters required for stellar population studies include (wavelengths in μm): 2.17 (Br γ); 2.12, 2.24 (H_2); 1.64, 1.67 (FeII); 1.53 (NH_3); 1.58, 2.10, 2.50 (CH_4); 2.06 (HeI); 1.28 (Pa ß); 1.88 (Pa α). Classification of late-type brown dwarfs requires the following narrow-band filters (wavelengths in μm): 1.495, 1.595, 1.75 (H_2O); 1.66 (CH_4); 1.55 (NH_3). Emission line mapping of z ~ 2.3 galaxies and searches for very high-redshift Lyman-α emitters require a set of ~15 narrow-band filters of widths 30 – 300 Å in regions of high atmospheric transmission and free of sky emission lines. It shall be possible to accommodate the majority of these filters within the cryostat simultaneously.
Spectroscopy	Measuring radial velocities and determining the stellar types of Galactic Centre stars and studies of extragalactic transients require high throughput, long-slit, R ~ 4000 – 8000 spectroscopy over the wavelength range 0.8 – 2.5 μm with a slit width matched to the size of the diffraction limited core of the PSF. Spectroscopy of extended HII regions in nearby galaxies also requires a wider slit by a factor of 2 (goal: 3) and a correspondingly lower resolution, as well as a minimum slit length of 15 arcsec (goal: 20 arcsec).
Other	High-contrast imaging requires a coronagraph.

Table 11: Final top level requirements for ELT-CAM.

5 Appendix: Additional information on narrow-band filters

5.1 Solar system science

Priority	Filter	Central wavelength (μm)	Bandwidth (μm)	Pressure level probed	Reference
1	Deep Continuum	1.580	0.023	10 bar	Sromovsky et al. (2009), Irwin et al. (2009)
1	CH_4	1.690	0.113	1 bar	«
4	High continuum	2.20	0.05	0.1 bar	«
3	Polar haze	2.14	0.05	0.1 bar	Kim et al. (1990)
5	H_3+	2.093	0.01	< 1 mbar	Drossart et al. (1989)

Table 12: Useful narrow-band filters for planetary science.

Priority	Filter	Central wavelength (μm)	Bandwidth (μm)	Type of object	Reference
5	CN fluorescence	1.095	0.10	Bright and large comet	Maillard et al. (1987), Johnson et al. (1983)
6	H_2O-excited fluorescence	2.45	0.08	«	«
6	H_2O- continuum	2.37	0.08	«	«
1	H_2O	2.06	0.06	Distant comets & TNOs	Merlin (2012), NACO filter
1	CH_4	2.30	0.06	«	«
3	H_2O	1.50	0.10	«	«
3	CH_4	1.75	0.10	«	«

Table 13: Useful narrow-band filters studying small bodies.