3. Science case

3.1 Introduction

When the development of the OWL concept started in 1997, its size was set to the rather overwhelming 100-m diameter in order to be able to reach three main science goals: the spectroscopy of faint (though not the faintest) galaxies to be discovered by the then 8-m diameter NGST; the observation of solar type stars in the Virgo cluster of galaxies; and the detection of earth-like planets around other stars. These science cases were supported by qualitative and quantitative arguments and by simulations [117], and provided a first set of requirements on which the concept design work could be based. Although sufficient as a starting point, these preliminary science cases were however developed in a crude, even naïve, way. In particular, they accounted only approximately for instrumental effects.

In March 2000 the OPTICON network was formed under the aegis of the European Commission Framework Program FP5, and is now continuing into FP6. One of its core activities is to produce a science case for a European ELT of diameter from 50 to 100m. The OWL efforts in this direction merged in a natural way in the new activity (in fact, ESO was leading the science case working group during FP5). Since then and with large participation of the astronomical community (more than 100 astronomers are involved) a series of science cases have been developed to an ever-increasing level of detail and depth. These results have just been published by OPTICON (see RD526), which represents the basic reference for this chapter. For simplicity we will refer to it as the "*Science Book*". It is part of the documentation sent to reviewers.

In this chapter, after a brief overview of the capabilities of OWL, we summarize the results of the science book and derive from them a set of scientific requirements for the telescope and instruments that in turn will form the basis of the top-level requirements for OWL. It should however be stressed that the science case and the conceptual design have been developed in parallel so that not only some cross talk has taken place but also the process of setting the design requirements has not followed the straightforward path described here.

Readers interested in a more in depth discussion of the science case are referred to the *Science Book*. Science cases that are the drivers for the instrument conceptual studies are described in chapter 12. They expand and complement the science cases developed in the *Science Book*.

3.2 Science with OWL

The science case for Extremely Large Telescopes (ELTs) covers a vast range of topics from our own solar system to the furthest observable objects at the edge of the visible Universe. Table 4.1 gives an overview of the main science cases presented in the *Science Book*. They include the quest for terrestrial planets (including possibly the detection of exo-biospheres) in extra-solar systems; the study of stellar populations in a large sample of the Universe (including in elliptical galaxies, missing today – sometimes referred to as the “Virgo or bust!” science case); the still mysterious relation between matter, dark matter and dark energy (with their link to particle physics); the star formation history of the Universe and the evolution of the Cosmos from big bang to today; the first objects and the epoch of re-ionization (including primordial stars and their role); the *direct* measurement of the expansion rate of the Universe (with no assumptions, no extrapolations, no models).

Are there terrestrial planets orbiting other stars?	Direct detection of earth-like planets in nearby extra-solar systems and a first search for bio-markers (e.g. water and oxygen) may become feasible.
How typical is our Solar System? What are the planetary environments around other stars?	Direct detection of proto-planetary disks will become possible around many nearby very young stars. In mature planetary systems, detailed spectroscopic analysis of Jupiter-like planets, determining their composition and atmospheres, will be feasible. Study of the planets and small bodies in our Solar System will complement space missions.
When did galaxies form their stars?	When and where did the stars now in galaxies form? Precision studies of individual stars determine ages and the distribution of the chemical elements, keys to understanding galaxy assembly and evolution. Extension of such analyses to a representative section of the Universe is the next challenge in understanding the visible Universe.
How many super-massive black holes exist?	Do all galaxies host central monsters? When and how did super-massive black holes form and evolve in the nuclei of galaxies? Extreme resolution and sensitivity is needed to extend these studies to normal and low-mass galaxies in order to address these key puzzles.
When and where did the stars and the chemical elements form?	Can we meet the grand challenge to trace star formation back to the very first star ever formed? By finding and analyzing distant galaxies, gas clouds, and supernovae, the history of star formation and of the creation of the chemical elements can be fully quantified.
What were the first objects?	Were stars the first objects to form? Were these first stars the source of the ultraviolet photons which re-ionized the Universe some 200 million years after the Big Bang, and made it transparent? These objects may be visible through their supernovae/hypernovae or their surrounding ionization zones.
How many types of matter exist? What is dark matter? Where is it?	Most matter does not emit any electromagnetic radiation and can be identifed only through its gravitational pull on surrounding visible objects. By mapping the detailed growth and kinematics of galaxies out to high redshifts, we can observe dark-matter structures in the process of formation.
What is dark energy? Does it evolve? How many types are there?	Direct mapping of space-time topology, using the most distant possible tracers, is the key to defining the dominant form of energy in the Universe. This is arguably the biggest single question facing not only astrophysics but also fundamental physics as a whole.
Extending the age of discovery	In the last decades astronomy has revolutionized our knowledge of the Universe and established it as the ultimate physics laboratory. The next big steps are likely to be discoveries of unimagined new physical processes.

Table 3-1. Primary science cases

Three cases have been identified in the *Science Book* as highlight science cases both because they have generated high levels of enthusiasm and discussion, and since they are seen as some of the most exciting prospects for ELTs since they push the limits of what can be achieved (and will provide some of the more challenging technical specifications for the telescope). These are i) terrestrial exoplanets, ii) resolved stellar populations in a representative section of the Universe, and iii) first lights and the re-ionization history of the Universe. These set the collecting power requirement at a minimum of 60m for iii)[34], and to 100m for i) and ii). The *Science Book* analyzes to what extent different telescope sizes affect specific science cases. More discussion on tradeoffs between scientific capabilities and telescope size can be found in 2.13.1.

3.2.1 OWL performance

Before summarizing the highlight science cases that determine the requirements of the telescope and instruments there are some general aspects of the scientific performance of OWL that deserve some comments.

3.2.1.1 Confusion about confusion

There is some concern that ELTs may hit the confusion limit, thereby voiding their very *raison d'être.* Much of this concern comes from past observations at poor angular resolution (e.g. X-ray data or deep optical images taken with 2" seeing in the '80s). Recent results with much better spatial resolution lead to resolving the "confusion" into individual objects (e.g. the X-ray background, now mostly if not completely resolved, or the HDF images showing 20 times more empty space than astronomical objects). Ultimately, some confusion level may be reached (e.g. using imagers not working at the full diffraction limit) but the 3-dimensional nature of astronomical objects (position and velocity) virtually ensures it will not be a limiting factor with OWL. In fact, a lack of confusion may offer information on the covering factor of galaxies, and seems tantalizingly connected to Olbers' paradox.

3.2.1.2 Étendue, or the AΩ product

The AΩ product is often used to compare the capabilities of telescopes of different sizes. This is very dangerous, as it may lead to surprising (and wrong) conclusions. For example, nobody would claim from $A\Omega_{\text{human eye}} \approx A\Omega_{\text{FORS@VLT}} \approx A\Omega_{\text{30''@OWL}}$ that these three "telescopes" are interchangeable in performance. Instead, it would be perfectly correct to deduce from $A\Omega_{\text{LSST}} \approx 120\ A\Omega_{\text{VIMOS@VLT}}$ that the 8-m LSST will offer a much better wide field capability than the VLT. The point is that when comparing telescopes of different sizes one cannot leave sensitivity out, and therefore AΩ-based comparisons make sense only for telescopes of similar size. A much better estimator of relative performance is the time needed to achieve a given scientific goal.

3.2.1.3 Signal-to-noise vs diameter D

A too common misapprehension regards the dependence on D of signal *S* and signal-to-noise

$$S/N = S \,/\, \sqrt{(S + Bgd \times n_{\text{pix}}\,\Omega_{\text{pix}} + n_{\text{pix}} \times RN^2)} \qquad \textit{Eq. 3-1,}$$

where *Bgd* is the background flux per unit surface, Ω_{pix} is the pixel angular area, n_{pix} the number of pixels involved, and RN the readout noise. Too often one finds an $S \propto D^4$ assumption when the telescope works at the diffraction limit which is (alas!) not true: while the *peak* of the PSF indeed scales as D^4, its *integral* within a typical λ/D pixel increases as D^2 only. This means that the S/N is proportional to D^2 in the background-limited regime ($S \propto D^2$, $Bgd \propto D^2$, $\Omega_{\text{pix}} \propto D^{-2}$, $S/N \propto D^2/\sqrt{\text{const}}$), and to D in the shot noise regime ($S/N \propto D^2/\sqrt{D^2}$).

The time to achieve the same S/N for telescopes of different size is proportional to $(S/N)^2$ and is a better estimator of the relative performance of different telescope diameters (see Figure 3-1; this of course makes sense only when comparing a given science case). The relative merits of

[34] possibly also i) if terrestrial exoplanets are very common

different telescopes are therefore a function not only of diameter but also of particular science cases.

For example, in the exo-earths science case (see below), which is in the background-limited regime for any realistic scenario (unless AO delivers almost exactly 100% Strehl, the 10^{10} contrast between star and planet makes any residual from the AO correction much brighter than the planet), a 30m telescope would need ~ 120 times longer exposures than a 100m to observe star/planet systems that both can resolve.

3.2.1.4 The power of a 100m telescope

Current Adaptive Optics systems on 8-m class telescopes have recently demonstrated performance close to the theoretical diffraction limit. Figure 3-2 shows the diffraction limits for 8m, 30m and 100m telescopes compared to the typical sizes of astronomical objects. While 8m telescopes can resolve large regions within galaxies (between 300 and 1000pc in size) at redshifts around unity, Extremely Large telescopes can, given appropriate adaptive optics capability, resolve structures of a few tens of parsecs in size, the approximate size of a major star-forming region, at similar redshifts.

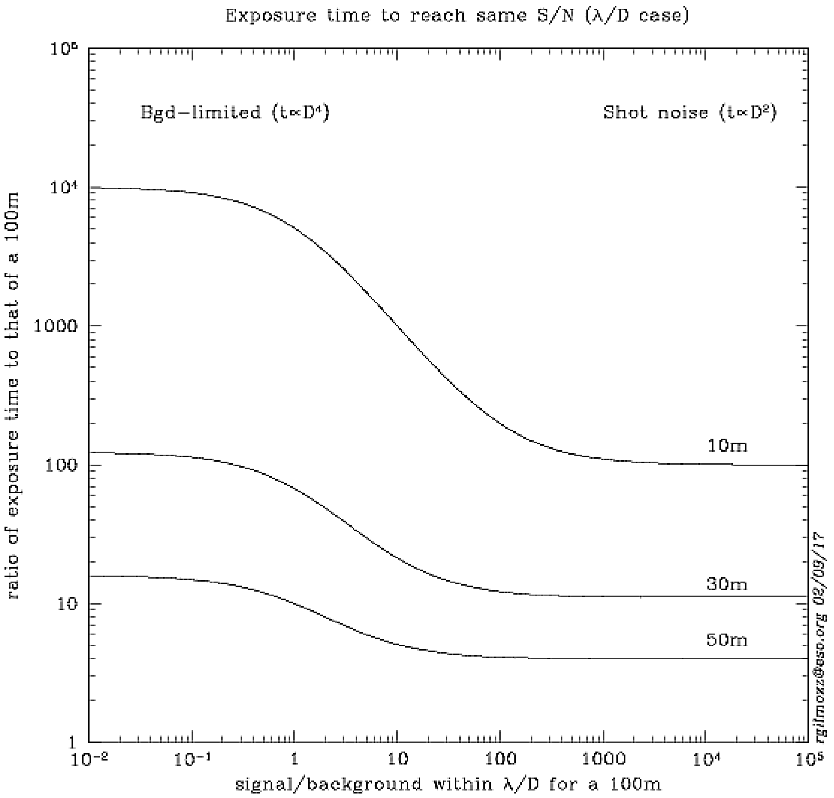

Figure 3-1. Time needed to achieve the same S/N on diffraction-limited telescopes as a ratio to the time needed on a 100m, i.e. t/t100 (note the background limited, t/t100 ∝ D4, and shot noise limited, t/t100 ∝ D2, regimes).

A smaller diffraction limit combined with increased light-collecting aperture translates into great gains in sensitivity as telescope diameter is increased, particularly for unresolved point sources. For example a 100m telescope with perfect diffraction-limited images would reach about 8 magnitudes fainter for point sources than an 8m telescope that delivers 0.5 arcsec images, for the same signal-to-noise and exposure time (in the near IR). In this simple scaling argument, we have assumed perfect diffraction-limited images (Strehl = 1). Even with a moderate Adaptive Optics (AO) correction that results in the majority of the light falling inside a 0.1 arcsec aperture, a 100m telescope would give a gain of 4.5 magnitudes for point sources compared to an 8m telescope producing 0.5 arcsec images, a factor of 60 in intensity (Table 3-2).

8m	30m	100m	Comments
0.0	1.4	2.7	Seeing limited
1.0	2.4	3.7	e.g. Ground-layer AO
1.7	3.2	4.5	
0.6	3.5	6.1	e.g. Multi-conjugate AO
2.4	5.2	7.8	Theoretical limit

Table 3-2. (From Science Book) Gains in magnitude for the same signal-to-noise and exposure time when observing unresolved sources in the background-limited regime. The gains are shown relative to an 8m telescope delivering 0.5" images.

Table 3-3 shows the comparison between ELTs of various sizes and JWST, showing that in the near infrared ground based astronomy is very competitive, and highlighting the potential for synergy between space and ground (very similar to today's complementarity between HST and the 8-10m class telescopes). In the case of extended objects the comparison is more difficult to quantify as it depends on the science case and on several parameters like the field of view and frequency on sky of the objects of interest (e.g. for z ~ 7 galaxies OWL would have a sensitivity advantage of a factor ~ 40 which would be partly offset by JWST's larger field of view of 10 x 10 arcmin; a large multiplex would strengthen OWL's advantage).

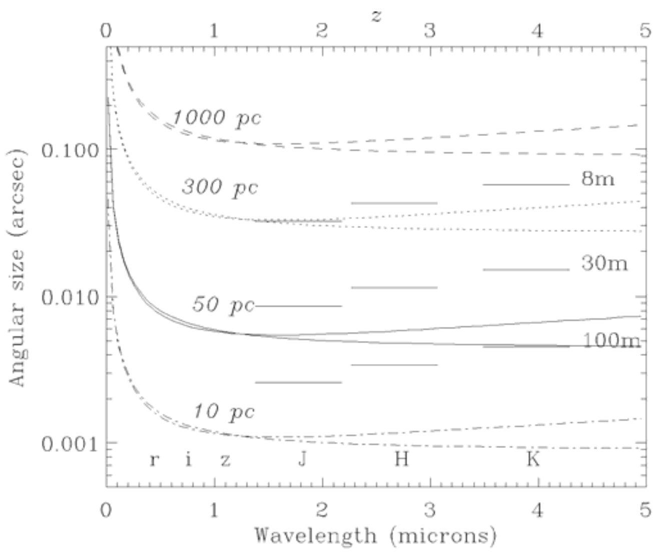

Figure 3-2. (From Science Book) The theoretical diffraction limits (λ/D) for 8m, 30m and 100m telescopes are plotted at three wavelength values corresponding approximately to the J, H and K infrared bands (horizontal bars). Also plotted are curves of projected angular size as a function of redshift for objects of various physical sizes (10pc, 50pc, 300pc and 1kpc) for two sets of cosmological parameters: (ΩM,ΩΛ)=(0,0) and (0.3,0.7) for the lower and upper curves respectively.

Table 3-4 provides the resolution and 3-σ limiting magnitude in the optical near infrared for various telescope sizes, in the simplified assumption that the performance is the same at all wavelengths for all telescopes. Although clearly highly improbable in certain combination of size and wavelength (it is unlikely that we could achieve high Strehl ratios in the U band with a 100m OWL, for example), the table is useful as a reference as it demonstrates the relative performance of various telescope sizes.

The science cases have made use of an exposure time calculator developed by ESO[35].

[35] http://www.eso.org/observing/etc/bin/gen/form?VIEW.APPLIC.HTM=ins-elt.htm

λ (µm)	Imaging (R=5)				Spectroscopy (R=10,000)			
	20m	30m	50m	100m	20m	30m	50m	100m
1.25	2.1	3.6	10.2	34.8	5.8	9.1	15.8	30.6
1.6	1.2	2.3	6.2	22.7	5.8	9.1	15.8	30.4
2.2	0.92	2.1	4.0	6.1	4.5	7.4	13.2	25.8
3.5	**0.036**	**0.080**	**0.221**	0.86	0.50	1.1	2.9	10.9
4.9	**0.005**	**0.020**	**0.054**	**0.20**	**0.042**	**0.095**	**0.27**	1.00
12	**0.012**	**0.030**	**0.079**	**0.30**	**0.088**	**0.200**	0.54	2.15
20	**0.004**	**0.031**	**0.088**	**0.33**	**0.045**	**0.107**	**0.30**	1.15
25	**0.004**	**0.031**	**0.088**	**0.33**	**0.039**	**0.088**	**0.24**	0.92

Table 3-3. (from [118]) IR performance of several ELTs compared to that of the JWST space telescope, in terms of the point source sensitivity ratio ELT/JWST. In the near-infrared an ELT outperforms a 6.5m cold (~30K) space telescope such as JWST (bold font shows ratio > 0.5).

3.2.1.5 The wavelength range

A large fraction of the ELT science cases lies in the near infrared domain. For the cosmology case, this is obviously a consequence of the expansion of the Universe (Figure 3-2): with increasing light gathering and spatial resolution with diameter, a 30-m telescope may actually tackle best the cosmology cases in the [Z-J] region, a 50-m in [J-H] and a 100-m in [H-K_s]. For the exo-earths science case, the H-band offers a more favorable luminosity contrast between the parent star and the putative planet than shorter wavelengths; also the challenge to attain a high Strehl ratio, while already tough in H, is certainly much more accessible than in the optical domain. A strong push towards visible wavelengths (*I* and *R* bands), with at minimum moderate adaptive optics correction, comes however from exo-earths spectroscopy and from the Virgo stellar population science driver. A special case is that of the Codex experiment to measure directly the cosmic expansion rate as a function of redshift that works only in the visible and would benefit from (some level of) AO correction but would still be feasible in the seeing limited regime.

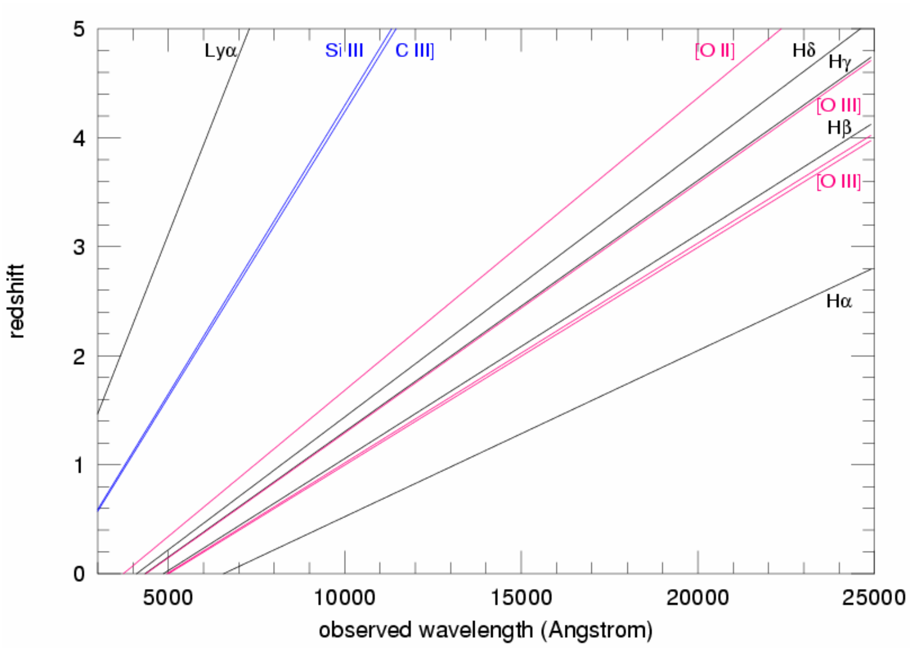

Figure 3-3. Observability of major emission lines with redshift.

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Tel	U		B		V		R		I		J		H		K	
[m]	Res	mag	Res	mag	Res	mag	Res	mag	Res	mag	Res	mag	Res	mag	Res	mag
10	9.1	32.3	11.1	33.1	13.8	32.1	17.6	31.7	22.1	30.6	31.8	28.3	41.8	26.6	54.9	25.3
20	4.5	33.8	5.5	34.6	6.9	33.6	8.8	33.2	11.1	32.1	15.9	29.8	20.9	28.1	27.4	26.8
30	3.0	34.7	3.7	35.5	4.6	34.4	5.9	34.0	7.4	33.0	10.6	30.7	13.9	29.0	18.3	27.7
40	2.3	35.3	2.8	36.1	3.5	35.1	4.4	34.7	5.5	33.6	8.0	31.3	10.4	29.6	13.7	28.3
50	1.8	35.8	2.2	36.6	2.8	35.6	3.5	35.2	4.4	34.1	6.4	31.8	8.4	30.1	11.0	28.8
60	1.5	36.2	1.8	37.0	2.3	35.9	2.9	35.6	3.7	34.5	5.3	32.2	7.0	30.5	9.1	29.2
70	1.3	36.5	1.6	37.4	2.0	36.3	2.5	35.9	3.2	34.8	4.5	32.5	6.0	30.8	7.8	29.6
80	1.1	36.8	1.4	37.7	1.7	36.6	2.2	36.2	2.8	35.1	4.0	32.8	5.2	31.1	6.9	29.9
90	1.0	37.1	1.2	37.9	1.5	36.8	2.0	36.4	2.5	35.4	3.5	33.1	4.6	31.4	6.1	30.1
100	0.9	37.3	1.1	38.1	1.4	37.1	1.8	36.7	2.2	35.6	3.2	33.3	4.2	31.6	5.5	30.3

Table 3-4. Diffraction limit (Res, in milliarcsecond) and corresponding limiting magnitudes for various telescope sizes, under identical conditions and assumptions (i.e. same Strehl ratio of 50%, efficiency 30%, sky background from Paranal, no atmospheric extinction). While the absolute values may change with assumptions, the relative ones should not.

Compelling cases have been made for the thermal infrared (see e.g. the science case of the T-OWL instrument in chapter 12), as well as for the sub-mm range where an OWL-like telescope would offer a powerful wide-field searching capability for the ALMA Observatory (Table 3-5).

	SCOWL (100m)		ALMA	
	850µm	450µm	850µm	450µm
Flux sensitivity (mJy/√sec)	0.3	0.6	1.9	11
Dust mass sensitivity (cf SCUBA-2)	70	170	11	9
Resolution (arcsec)	2.1	1.1	0.02	0.01
Confusion limit (mJy)	0.01	0.005	4e-4	2e-4
Mapping speed (time per square degree to 0.01mJy)	2 days	10 days	7yr	900yr

Table 3-5. Summary of the capabilities of a sub-mm instrument on OWL compared to those of ALMA.

3.2.2 The highlight science cases

The HST, Spitzer and other astronomical satellites, complemented and expanded by the present generation of 8- to 10-m ground based telescopes now in operation, have generated a new view of our universe. The universe is now thought to be dominated by dark matter and vacuum energy, with stars forming as early as 200 Myrs after the Big Bang at a redshift between 10 and 20. Jets, outflows and disks around stars have been shown to be a common by-product of starformation. A large fraction of all stars in today's universe is surrounded by planets, more than 100 or them have been detected.

Astronomy faces many challenges in the investigations of the coming decade: the luminosity contrast between parent star and planets (factor of billions) has so far prevented direct imaging of a planet in all but a single special case. Stellar populations can be studied in detail only in the nearby universe, devoid of the massive and important elliptical galaxies. Alternative theories of galaxy formation cannot be disentangled, as we cannot yet see the far away faint building blocks. Cosmological distances are measured using secondary indicators such as supernovae Ia. The sources of the re-ionization of the universe are too faint to be detected. The existence of super-massive black holes inside high redshift Quasi-Stellar Objects (Quasars) is a challenge to our ideas of how black holes form, and indirectly to our understanding of stellar evolution.

JWST will replace HST within the next decade. However, as it is the case in the current HST/VLT era, powerful ground-based telescopes are necessary for detailed studies of interesting objects. Only an ELT such as OWL will provide the capabilities to achieve the necessary breakthroughs. Of all the science cases listed in the "science book", three are the strongest drivers for the technical requirements of OWL. These "highlight science cases" are summarized below.

3.2.2.1 Terrestrial Planets In Extra-Solar Systems

The recent discovery that a large fraction of all solar-type stars host massive planets has opened a new domain for research. With current large telescopes, it is in principle possible to directly image massive planets in orbit around relatively faint stars. However, the more interesting less massive planets around solar-type stars, which are similar to Earth and might harbour life, are out of the reach of current telescopes. One of the most exciting prospects for OWL is the possibility of not only *directly detecting* (by imaging) earth-like planets orbiting other stars, but also *studying* large numbers of them in detail (via spectroscopy) and even find indicators of life on them.

The habitable zone around a star is the region where water on earth-like planets can exist in its three phase states. Water is a pre-requisite for life as we know it. The detection of terrestrial planets in this zone relies on them being illuminated by their parent star. The reflected light makes such planets bright enough so that OWL could easily detect them if they were well separated from any bright star (see Figure 3-4 for a simulation). The challenge of detecting Earth-like exo-planets is the fact that their projected distances from the parent stars are extremely small, and that the star is about 10 billion times brighter than the planet.

Not all stars have planets and few will have planets in the habitable zone. Therefore, a large number of possible candidate stars has to be surveyed to find a habitable planet, and the closest one is likely to be at a relatively large distance. The number of stars that can be studied is proportional to the spatial resolution to the cube (i.e. to D^3, where D is the telescope diameter). The time to achieve the same signal to noise in the background-dominated regime is proportional to D^4. A 100m telescope can in principle detect an earth-like planet around a solar-type star out to a distance of 100 light years, which means that there are about 500 stars of this type to be observed. By contrast, there are only about 100 candidate stars for a 50m telescope and less than 15 stars for a 30m telescope. Unless the population of earth-like planet is unexpectedly large, it is therefore unlikely that a 30m telescope will be able to detect such a planet. However, a 100m telescope such as OWL will have a much better chance achieving this challenging goal. A key to success is the light gathering that will allow improving the contrast between planet and star through the detection of in situ spectroscopic features.

Once exo-planets have been imaged, spectroscopy can be used to determine properties of their surfaces and atmospheres. The state of the surface (liquid or solid) and the existence of "bio-markers" such as water, oxygen, carbon dioxide and methane atmosphere has the potential to provide first indications of extraterrestrial life. An extremely large telescope is needed to collect sufficient light from a faint planet to be able to analyze it spectroscopically. This science is unique to OWL and cannot be carried out with a 30m telescope (see Figure 3-4).

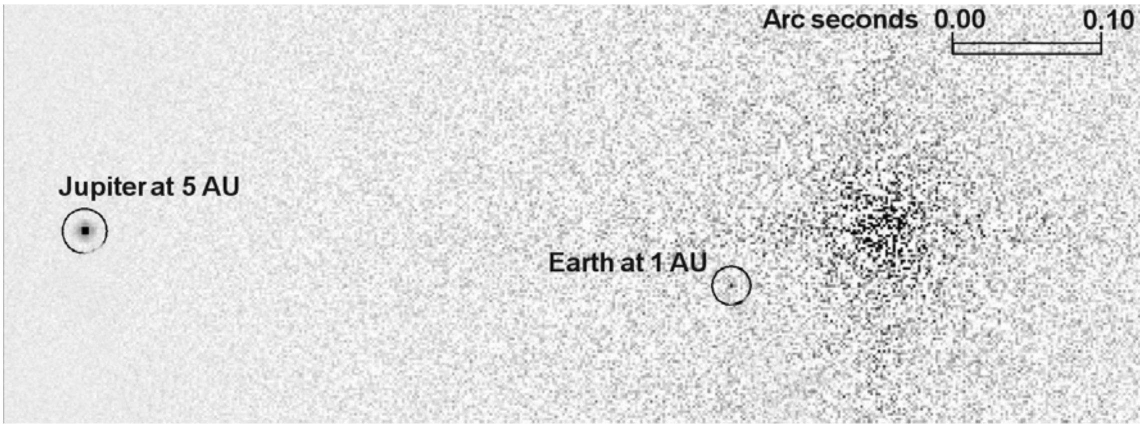

Figure 3-4 Simulated image of a solar-type system at 10 parsec (32 light-years)

While searching for terrestrial planets, OWL will also detect the larger giant gas planets (equivalents of Saturn and Jupiter) in the exo-systems. From this we can determine how common are systems with multiple planets of varying sizes (like our own solar system). We can also characterize systems in different environments, such as around metal-poor stars, white dwarfs, massive stars and brown dwarfs. Such statistics will provide the clues for the detailed understanding of the formation of stars and their planetary systems, for example which stars have planets, what is required to form planets, what is the chemical composition of the parent stars and are there planets around special stars (e.g. white dwarfs, very old halo stars or very young T Tauri stars). Only by doing this can we determine to what extent our own solar system and Earth itself is unique, and assess the probability that other planetary systems could support life.

3.2.2.2 Resolved Stellar Populations in a representative sample of the Universe

How did all the galaxies that we observe around us today come to be formed? This remains one of the most intriguing questions in modern astronomy. It is now generally believed that galaxies form out of dark matter halos at large redshifts. As the initially small density perturbations grow, baryons fall into the dark matter potential wells. Eventually, stars start to form and their light makes the baryonic component of galaxies visible. At high redshifts, global galaxy properties can be investigated to test this picture. However, individual stars at the redshifts at which galaxies from are out of reach even for a 100m telescope. Such stars can only be resolved in galaxies within the local universe. The lifetime of low mass stars is comparable to the age of the universe or even longer. Therefore, some of the stars which formed very early in the universe are still there today and are therefore observable in local galaxies. By picking out stellar populations of different ages, the star formation history of galaxies can be reconstructed. This is illustrated in Figure 3-5.

Mergers between galaxies are thought to play an important part in the build-up of the galaxies we see today. If so, we would expect to see evidence of these past mergers. Indeed, recent studies of individual stars in our own Milky Way galaxy have revealed populations of stars with distinct ages and composition. These distinct populations are thought to be remnants of previous mergers, and give clues as to when the main mergers in the Milky Way's history happened. Up until now such studies have been limited to our own Galaxy and its nearest neighbors. However it is unknown whether these are special cases and whether the merger history is similar for all galaxy types. In particular, our own galaxy is a spiral galaxy, and no examples of large elliptical galaxies are within reach of current telescopes for this type of study.

To study a representative section of the Universe requires reaching at least the nearest large galaxy clusters which contain large elliptical galaxies. This means observing galaxies in the Virgo or Fornax clusters at distances of 16 or 20 Mega-parsecs respectively. The challenge here is twofold. Firstly, individual stars at these distances appear very faint (about V=35 magnitudes). Secondly the stars must be individually resolved from each other in order to determine their ages and chemical composition. As in the case of detecting faint planets, both these challenges are addressed in parallel with an extremely large telescope - the sheer collecting area allows the colours (hence ages and chemical composition) of very faint stars to be measured (by imaging), and the diameter of the telescope allows the image of each star to be sufficiently sharp that they can be separated even in crowded regions (provided the telescope is equipped with an adaptive optics system that allows it to observe close to the diffraction limit). Again, initial feasibility studies look very promising - simulations show that a 100m class telescope could observe individual stars within galaxies in the Virgo cluster, and determine their ages (even for the oldest, hence faintest stars) and composition with sufficient accuracy that a picture of the galaxies' history could be derived.

3.2.2.3 The First Objects And Re-Ionization Structure Of The Universe

3.2.2.3.1 The highest Redshift Galaxies

Over the past decade, a broad consensus on the main ingredients and the evolution of the universe emerged. In this so-called concordance model, the universe’s main ingredients are dark energy and dark matter which contribute about 96% of the density, while observable normal matter represents only about 4% of the density. About 380000 years after the Big Bang, these baryons cooled enough for hydrogen to become neutral. It took at least another 200 Myrs before the first generation of stars formed. Within the first billion years, massive black holes also formed and started to power bright quasars. The first stars and quasars both produced UV photons, which gradually re-ionized the intergalactic matter. A simulation of the galaxy formation process is shown in Figure 3-6. Key evidence for this picture comes from observations of the Cosmic Microwave Background (CMB) with the WMAP satellite and other instruments. Current large telescopes can detect galaxies up to a redshift of about 7. At such redshifts, the age of the universe was only 800 Myrs. Spectroscopy of quasars at similar redshifts revealed that they are already evolved objects and contain metals, which must have been produced in a previous generation of stars at even earlier times. A major goal of OWL will be to detect and investigate the very first generation of galaxies which contains these stars. These galaxies at redshift 10 or above will be extremely faint and quite rare, but their angular size is expected to be large enough to be easily resolved by OWL. Detailed predictions for this population of galaxies are naturally quite uncertain, and it might be necessary to use foreground galaxy clusters as gravitational lenses in order to be able to detect them. JWST will be able to produce candidate lists for the first generation of galaxies, but only an ELT will be able to confirm them spectroscopically. Spectroscopy will also allow to determine the spectral properties of the earliest stars, possibly allowing identification of galaxies with a substantial population III component.

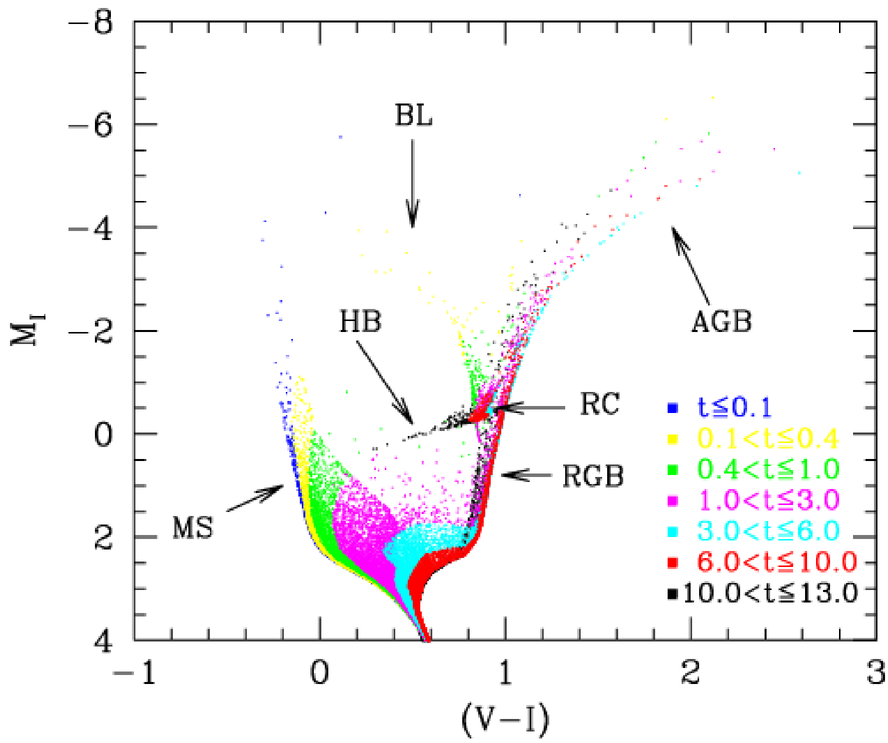

Figure 3-5 (From Science Book) Synthetic Colour-Magnitude Diagram computed using constant star formation rate from 13 Gyr ago to the present. The age of the stars are coded in different colours. Labels indicate different evolutionary phases: BL - blue loop; HB - Horizontal Branch; RC – Red Clump; RGB – red giant branch; AGB – asymptotic giant branch; MS – main sequence. From [119].

3.2.2.3.2 Galaxies at the end of Re-ionization

One of the most important questions about the evolution of the universe is: what are the sources responsible for the re-ionization of the intergalactic matter (IGM)? Stars in the first galaxies, Active Galactic Nuclei (AGNs) and the first quasars compete for the re-ionization of the IGM. Although galaxies are less luminous than quasars, they are far more numerous and might therefore be the main source of photons which re-ionize the IGM. To answer this question, galaxies and quasars in the redshift range from about 5 to redshifts only slightly lower than those of the very first galaxies have to be investigated in detail.

Candidate star-forming galaxies out to redshift about 6.5 have already been discovered and spectroscopically confirmed. These galaxies are high-redshift analogues of Lyman Break Galaxies at redshift of 3. They have typical sizes of about 0.1 to 0.2 arcsec. The objects detected thus far typically have AB magnitudes of i=25.5 and z'=25.5 at a surface density of 500 and 160 per square degree, per unit redshift at z=5.5 and z=6.0 respectively. Identical objects at z=9 and 16 would have magnitudes of J_{AB}=27 and K_{AB}=28 respectively, and apparent sizes between 0.1 and 0.4 arcsec. Such very high-redshift objects would be detectable with JWST by broadband photometric Lyman-Break techniques. However, only a 100m ELT can provide key diagnostics of both the inter-stellar medium and stellar populations in these galaxies by intermediate resolution spectroscopy in the near IR (up to redshifts 15-17).

3.2.2.3.3 Probing the universe during the re-ionization epoch

Spectroscopy of quasars at a redshift of about 6 shows that at that epoch, a significant fraction of the IGM is still neutral. On the other hand, analysis of CMB polarization measurements suggests the presence of ionized IGM at a redshift of about 17. What happened between those two epochs is completely unknown. Several scenarios for the reionization history of the universe have been proposed. One such scenario consists of two distinct re-ionization epochs, one due to the first generation of massive stars and a later one due to the first quasars and galaxies. Another scenario assumes a slower, highly inhomogeneous re-ionization period. Absorption features imprinted by the IGM on spectra of objects within the re-ionization epoch will allow distinguishing between these scenarios. The first “fairly bright” objects which are bright enough to carry out OWL spectroscopy will thus not only be markers of the beginning of the re-ionization epoch, but also be crucial for probing the inhomogeneous structure and metal enrichment of the IGM from metal absorption lines in their spectra due to intervening ionized structures of the IGM.

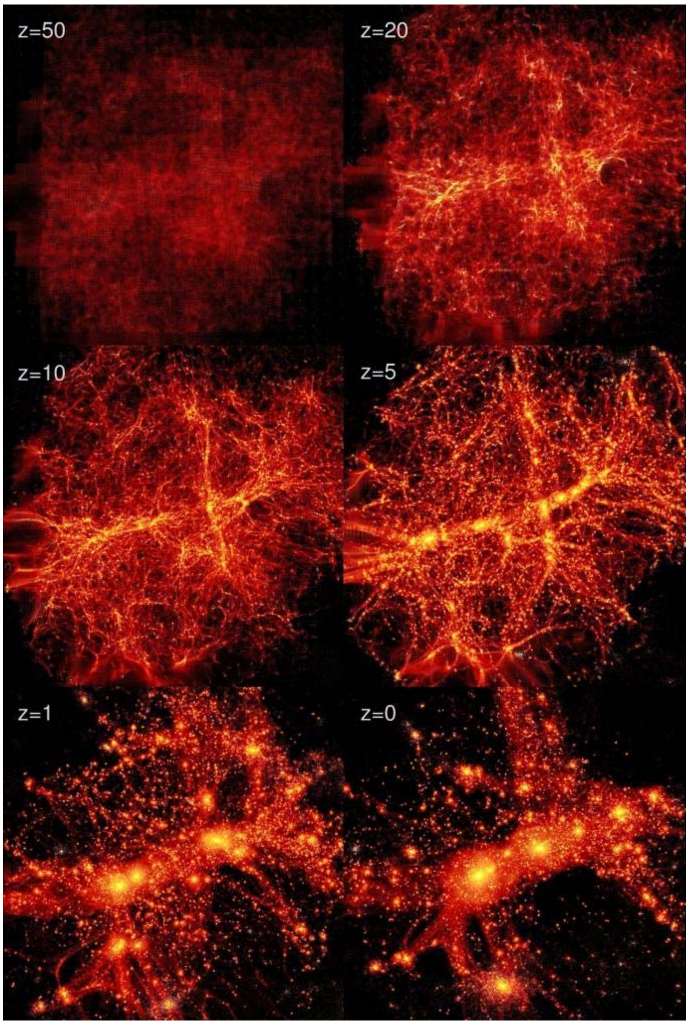

Figure 3-6 Simulation of the formation of the galaxies in the Local Group in a cold dark matter scenario, by Ben Moore, Zurich, astronomy and cosmology research group (www.nbody.net).

Short-lived gamma-ray bursts (GRBs) are an obvious population that can be detected up to z~15-20 and therefore serve as “background” sources. Explosions of population III stars (which are fainter than GRBs) can be used to probe the IGM at z~<12, although this population is rapidly disappearing with time for regions with metal enrichment higher than 1/10000 of the solar value. Although the epoch of quasar formation is a fully open question, the SLOAN quasars at redshifts around 6 which are powered by supermassive black holes suggests that a population of intermediate mass black holes might exist during the epoch of re-ionization. This population could power quasars of intermediate luminosity, which could be used to probe the

IGM up to at least redshifts of about 10. All these objects are rare. GRBs and the supernovae resulting from the explosions of population III stars will be discovered in dedicated missions/ telescopes. JWST should provide lists of quasars at the highest redshift. Probing the physics of the IGM at redshifts from 10 to 20 requires intermediate/high resolution spectroscopy in the near IR, which can only be carried out with telescopes of the 60-100m class due to the predicted low fluxes of these first "background" objects.

3.3 Requirements from the science case

The requirements derived from the science case are summarized in Table 3-7. They cover a wide section of the parameter space, and it may not be possible to meet all of them with a single technical solution.

The requirements can be distilled into a small number of broad categories, as indicated in Table 3-6, from which the top-level requirements of both OWL and its instruments have been developed. While the aim is to preserve as much as possible of the critical science, some of these requirements appear mutually incompatible, and some tradeoffs are necessary. One prime example is field of view: fully optimizing the telescope system adaptive optics capability (as required by most science cases) makes it very difficult technically to get a diffraction-limited field of view larger than a few arcminutes. Even with such relatively small fields, requirements on detectors become rapidly prohibitive: Nyquist diffraction-limited sampling (2 pixels per Airy disk) of a one arcmin field near infrared image already requires ~ 1 G pixels; in the optical, one would need to deploy ~ 7 G pixels (although it is unclear at the moment whether it is possible to correct such a “wide” field at optical wavelengths: the requirement from the science cases developed so far is around 10 arcsec). Cost is certainly an issue: for such a size to be affordable, IR chips cost per pixel should drop from the present ~ 10 cent to below 1 cent, for which according to the manufacturers there seem to be concrete possibilities (see section 12.2.7). Also, with such huge arrays, we are already looking at developing and deploying multi-ton cryogenic vessels for the near-IR and even more at optical wavelengths. In addition, the amount of information to process is huge, and methods to sample the focal plane in a targeted way (e.g. relocatable multi integral field units and multi imagers) look attractive, although they of course would not work for survey work. Handling Petabytes of data will be a challenge of its own.

Specification	**Requirement**	**Minimum**	**Goal**
Telescope size	Maximize > 60m	≥ 60m	100m
Wavelength coverage	0.5 – 25 μm	0.7 – 10 μm	0.3 – 850 μm
Field of view	Maximize	> 0.5 arcmin > 1 arcmin	Opt: 2 arcmin IR: 6 arcmin
Image quality	Diffraction limit	S >0.8 (K, SCAO) S >0.4 (V, ExAO) S >0.3 (K, MCAO, 2′×2′)	Highest contrast over FoV & spectral range
Spectral resolution	$100 – 10^5$	$100 – 10^5$	$10 – 10^6$
Throughput	Maximize	m_K > 29.5 in 1 hour	m_K > 30.5 in 1 hour
Emissivity	Minimize	< 10%	< 6%
Site	AO friendly mid and far IR	<seeing> ≤ 0.6″ τ_0 > 3 ms low PVW, > 2500m	<seeing> ≤ 0.5″ τ_0 > 5 ms low PVW, > 4000m

Table 3-6. Science requirements. S stands for Strehl ratio

Table 3-6 shows that the requirements from the science case drive towards the largest possible telescope size, with diffraction limited performance over a wide wavelength range and with a substantial field of view. Although two columns of requirements are given (minimum and goal) these should be understood as independently valid for each specification (for example the OWL top level requirement for size is according to the goal while the field of view is based on the minimum). The top-level requirements are the result of a trade-off between trying to represent as large as possible a fraction of the science cases and providing the capabilities required by the critical science highlights. Feedback from what is considered feasible (e.g. in the area of adaptive optics correction) is also folded into the tradeoffs.

	FOV	Spatial Resolution (arcsec)	Spectral (R)	Wavelength (microns)	Dynamic Range	Target density
# Planets and Stars						
Exoplanets						
HIGHLIGHT CASE: Terrestrial planets in habitable zones	~1"x1"	diff. lim. S=0.7-0.9	500-1000	0.6-1.4	10^{10} at 0.03"	~1000 in sky
Giant planets	~1"x1"	0.001-0.002	10-100	0.5-2.5	10^7-10^8	Few x 1000 in sky
Mature Gas-giant planets	few arcsec	diff. lim. high S		1.0-10.0	10^7-10^8	Few x100 in sky
Earth-like moons						
- Reflex velocity			few x10,000			
- Astrometric wobble	very small	diff. lim.		~1.0		
- Spectral detection			>10	1.0 - 5		
- Transits & eclipses				1.0 - 5		
Rings around extra-solar planets	single sources	0.01	100-1000	0.5 - 4	10^7-10^9	
Planets around young stars in the solar neighborhood	few arcsec	0.002	10-100	0.6 -10	10^8	Few x100 in sky
Free-floating planetary-mass objects	1-few arcsec	0.01	10-100	1.0 - 10		100s to 1000s in sky
Our Solar system	up to ~1'x1'	diff. lim.	TBD	Opt - therm-IR		
Stars & circumstellar disks						
Probing birthplaces	up to ~1'x1'	0.002-0.01	up to 100,000	1.0 - 5		Up to 300/sq "
"	"	0.02-0.04	"	10 to 20		"
Structure in inner disks	few arcsec	diff. lim.		2, 10 and 17	10^5 at 0.1"	
Embedded young stellar objects	few arcsec	diff. lim.	~100,000	5.0 - 20		
Jets and outflows		diff. lim.	~100 (NB imaging)	0.5 - 2		
Debris around other stars	3'x3'	diff. lim. (~1", no AO)	350-850		10^2 within 0.5"	All stars within 100pc

	FOV	Spatial Resolution (arcsec)	Spectral (R)	Wavelength (microns)	Dynamic Range	Target density
The lives of massive stars						
Early Phases		as high as possible		NIR & MIR		
Mature phase outflows		diff. lim.		NIR & MIR		
Normal and Peculiar stars	~1"x1"	diff. lim. S~0.9	up to 100,000	0.6 (Ha)		
Asteroseismology	30'	no AO needed	80,000		> few x 10^5	500 per field
Chemical composition : chronometry	30"x30"		30,000-150,000	0.3 - 0.7		
The Death of Stars						
Mass fn of black holes and neutron stars			~1000	NIR		
Isolated neutron stars	single sources		~100	Op		
Black holes in globular clusters	5"	~0.001	~5 and 20,000	Opt and NIR		Crowded fields
Microlenses			~100	1 - 2.5		
Stars and Galaxies						
The Interstellar medium						
Temperature and density probes			10,000 to 10^6	7 to 25		
Fine structure in the ISM						
High redshift	single sources			NIR		
Dust properties via polarimetry						
Heavily extinguished regions						

	FOV	Spatial Resolution (arcsec)	Spectral (R)	Wavelength (microns)	Dynamic Range	Target density
HIGHLIGHT CASE : Resolved Stellar Populations						
- Imaging	5"x5" or larger	diff. lim. (S TBD)	~5	V to K	TBD	Very crowded fields.
- Spectroscopy	few arcmin	0.002-0.02	3-8,000 & 20-40,000	V to K		in specific galaxies
Resolved stars in stellar clusters	~2"x2"	0.003	~25	0.4 - 0.6	TBD	Very crowded fields.
Spectral observations of star clusters		few mas	30,000			
The stellar IMF				1.0 - 10		
Extragalactic massive stars beyond the LG	~1'x1'	0.02-0.1	1000 - 10,000	V+R (+IJHK)		few tens / field
Stellar kinematic archaeology	few arcsec	diff. lim.	10,000 -100,000	V to K		many nearby galaxies
The intracluster stellar population	few tens of ″	diff. lim. (S TBD)	~5	NIR (J & K)		few tens / sq"
The cosmic SFR from supernovae	2'x2'	diff. lim. (S=0.5)	~ 5 and ~2,000	NIR (JHK)		4-8 per field per year
Young, massive star clusters	~2'x2'	0.03 - 0.04	> 40,000	>0.8		many nearby galaxies
Black Holes - monsters in Galactic Nuclei	5"x5"	few mas	few x 1000	Opt & NIR		

	FOV	Spatial Resolution (arcsec)	Spectral (R)	Wavelength (microns)	Dynamic Range	Target density
Galaxies and Cosmology						
Cosmological Parameters						
Dark Energy						
Type Ia SNe as distance indicators	2'x2'	diff. lim. (S=0.5)	~5 and ~2,000	NIR (JHK)		4-8 / field / year
GRBs as distance indicators	5'x5'		8,000 to 10,000	0.8 - 2.4		single targets
Expansion History						
From primary distance indicators						
CODEX: Cosmic Differential Expansion	single sources	0.2	>100,000 (400,000)	0.4 - 0.7		

	FOV	Spatial Resolution (arcsec)	Spectral (R)	Wavelength (microns)	Dynamic Range	Target density
HIGHLIGHT CASE: First Light - The First Galaxies and the Ionisation State of the Early Universe						
Galaxies and AGN at the end of reionisation	> 5' x 5'	0.01 - 0.02 50% EED	5,000-10,000			0.2 - 5 / sq'
- most distant sources	> 5' x 5'	0.1 - 0.2 50% EED	few x 100	1.0 - 2.4		"?
Probing the reionisation history	single sources	diff. lim.	1000 - 10,000	JHK		
Early chemical evolution of the IGM	single sources	Any (if imaged sliced)	10,000	0.4 - 0.9		
Evolution of galaxies						
Physics of high redshift galaxies - Req	2' diam.	0.05	5,000	0.5 - 2.5		0.1 to 10 /sq'
" - Goal	10' diam.	0.01 - 0.02	10,000	0.3 - 2.5		"
Assembly of galaxy haloes - Req	2' diam.	0.1	5,000	1 - 2.5		0.1 to 10 /sq'
" - Goal	10' diam.	0.05	10,000	0.7 - 2.5		"
The SFR over the history of Universe a)	3' x 3'	0.1	~5	0.5 - 2.2		few tens /sq'
b)	10' x 10'	0.05	~5	0.3 - 2.2 + FIR		few per unit z / sq'
Fundamental Constants	single sources	< 0.01	300,000	Opt		

Table 3-7 Requirements from the main science cases (adapted from Hook [120])