# TOWARDS INSTRUMENTATION FOR ELTS: THE OWL CASE

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## ABSTRACT

Based on expected Science Drivers for a 60 to 100-m diameter OWL-class telescope, we derive the basic instrumental capabilities that are needed to address them effectively. They come in three flavors –viz. an extremely high-contrast fully diffraction-limited spectro-imager, a cryogenic AO-assisted imager and multi-integral field spectrometer. Their highest priority wavelength range lies in the near-IR. In terms of size and technical requirements, these instruments belong to a quite similar class than instruments currently being developed for the 8-10 m telescopes. This places them hopefully in the feasible category, even if already rather challenging. A big caveat however is that enlarging the imaging field or the spectrometer multiplex would require large clusters of these basic "bricks". The requirements on the adaptive optics correction are stringent and call for a close and careful integration between the telescope adaptive optics systems and the instruments. We also introduce here, as a relevant example of a new observational strategy, an instrument focused on a specific scientific program – the direct measurement of the acceleration of the Universe at different epochs via the Lyα forest in QSO spectra. Being able to host dedicated facilities of this type, used for a specific observing programs in a CERN experiment-like fashion, is deemed essential to ensure that the giant telescopes of the future get and stay at the cutting edge of research in the next decade and beyond. Finally, we comment briefly on the articulation between the development of generic instrument concepts for ELTs in the frame of the European ELT Design Study and their adaptation to the OWL case.

Keywords: Extremely Large Telescopes, OWL, Adaptive Optics, Instrumentation

## 1. INTRODUCTION

The concept of a 100-m class OWL optical and near-infrared telescope emerged in 1998 [1], in response to science objectives mainly driven by HST and JWST. Our starting goal was to enable spectroscopic follow-up in the visible and near-IR of the faintest objects detected by the HST, thus complementing the JWST capabilities in the thermal domain. This raised two major challenges, viz. getting this huge collecting area and simultaneously an exquisite image quality down to the diffraction-limit, for the most possible "bluish" wavelength. Both ought not only to be technically feasible, but also should be achieved at an affordable cost (< 1 B€) and in a reasonable time span (< 12 years).

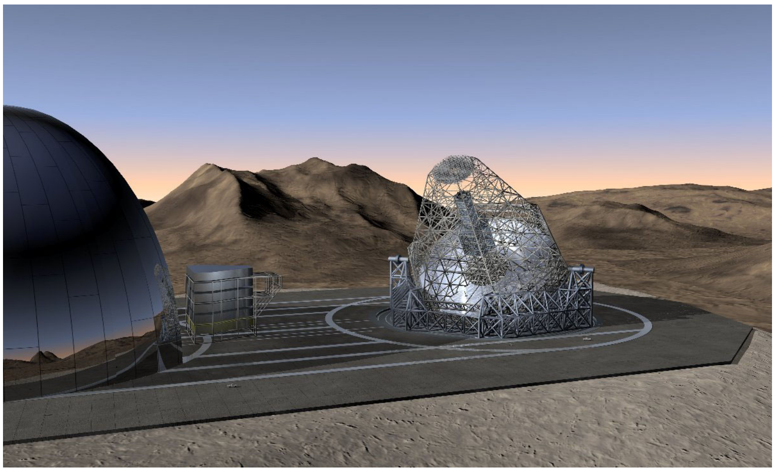

**Figure 1.** Layout of **OWL.**

OWL's conceptual design (Fig. 1) is now well advanced, with the final review scheduled at the end of 2005. In essence we have already essentially validated the first challenge of building such a large collecting area, largely through industrial studies and owing to innovative optical and mechanical concepts [2]. On the other hand, still much work remains on the wavefront control aspect. Two particularly difficult areas are to evaluate (and if needed correct) the detrimental effects of wind on such a large structure, as well as establish the cost and timescale required to get wavefront correction to the diffraction limit, including at short wavelengths. These two points are being aggressively pursued. At this stage, it was essential to revisit the major science drivers for OWL and start to iterate on their implications on the telescope design and on its feasibility. The paper is an early report on this first step. It successively addresses the main OWL science goals and their needs in terms of observational parameters, the telescope baseline design, insofar as its impact on instrumentation design and capabilities is concerned, and finally the basic instrumental package required in order to pursue them.

## 2. SCIENCE OBJECTIVES AND OBSERVATIONAL PARAMETERS

Evaluation of the Science case for ELTs is a continuing work in progress by European Scientists under the OPTICON umbrella and in close liaison with their American counterparts. In November 2003, during a Meeting in Marseilles, a small set of highest priority science cases for ELTs were identified, with particular attention towards discriminating between a 30-m TMT-like case and a 60-100 m OWL-class facility (http://www-astro.physics.ox.ac.uk/%7Eimh/ELT/). Being able to address them effectively is considered as a critical feasibility item for such a project.

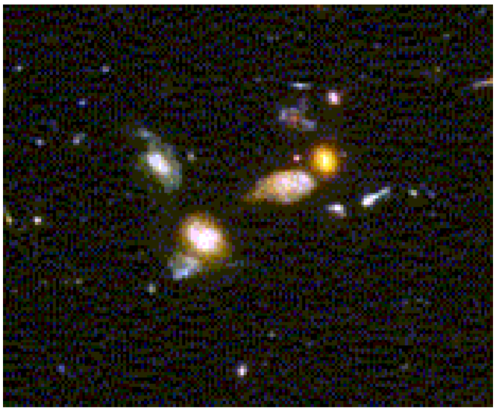

**Figure 2** A small section of the HST Ultra-Deep Field. Spectroscopy of the faintest galaxies in such an image is one primary scientific goal for ELTs.

The selected OWL science drivers fall in three outstanding –and challenging- domains: imaging and characterization of exo-solar planets, possibly down to earth-like objects; probing of the early Universe in particular from up to z~10 core-collapse Supernovae and possibly from Population III clusters; understanding of stellar populations through the photometry of individual stars in external galaxies and in particular in the closest giant ellipticals.

In terms of preferred wavelength domain, two of the main science targets (exo-solar planets and cosmological bodies) require in priority to work in the near-IR, while the third (stellar populations) could also profit from that domain, even if best ultimate performance would ultimately require working in the visible range. Actually, in the cosmological case, while the near part of the IR band (J, partially H) would be optimum for a 30-m, the superior light gathering of a 60-100 m would allow to push earlier in time, through H and K band observations. In view of the very steep increase in adaptive optics requirements with decreasing wavelength, or alternatively the steep decline in performance for any given AO system, this is heartening news for the next generation of telescope and AO systems builders!

All three science drivers come with the strong requirement that near 100% sky coverage be achieved. This is a non-issue for exo-solar planet searches, with a central star always bright enough to permit high-Strehl AO correction – actually much too bright with respect to its putative planets. On the other hand, this is a tough requirement for both the two other cases for which a close bright enough star is an exception, and even more if observing in the visible range.

In terms of basic observational modes, exo-solar planets detection requires achieving a huge contrast between the central star and its surroundings. One attractive option to do so is detecting/using specific spectral signatures from the putative planets, with the added bonus of going beyond mere detection to actually learning about their physical states. A differential spectro-imaging mode is thus strongly favored [3]. To probe the early Universe, detailed observing modes do vary according to the type of objects searched and/or studied, from the search and identification of distant SN, population III clusters and gamma-ray bursts to the study of the early phases of galaxy assembly. Two observational regimes are however recurrent, imagery in as large a field as possible (minutes of arc squared) and deep spectroscopy, often of multiple targets in large (again arc minutes squared) patrol fields. While imagery should be done preferably near the diffraction limit of the telescope, spectrographic investigations require a careful tradeoff between spatial resolution, number of objects and low surface brightness detection, pushing for intermediate spatial resolution, roughly of the order of 6 times the diffraction limit, but still very much larger than even the very best natural seeing. Resolving stellar populations calls for similar diffraction-limited imagery than above, albeit ultimately at shorter wavelengths.

## 3. OWL BASELINE DESIGN AND INSTRUMENTATION

OWL optical design (Fig. 3) is based on two very large collectors, a spherical primary and a plane secondary, followed by a corrector composed of four 8.15 to 2.5-m diameter mirrors.

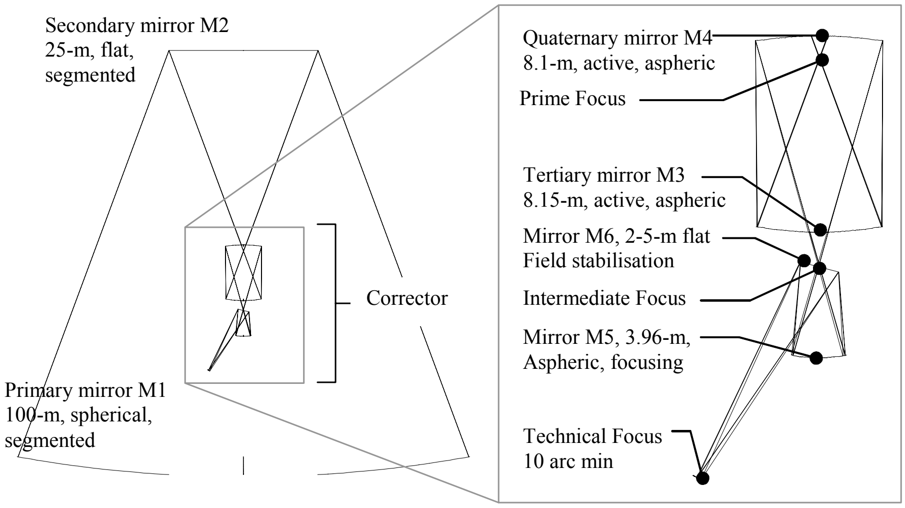

**Figure 3** Layout of OWL Optical Design

The F/6 focus offers a fully diffraction-limited science field of 2 arc minutes diameter. Optical image quality is good enough in a 6 arc minutes diameter field to permit using Natural Guide Stars (NGS), while applying only small aberration offsets to the Adaptive Optics system. Detailed simulations by Le Louarn et al. [4] show that one gets ~ 80% sky coverage at the Galactic poles with NGS bright enough to achieve a high K-band Strehl ratio ~ 75% in the K-band for good (0".5 at 0.5 µm) seeing conditions (Fig. 4). Such a Strehl would actually be good enough for exo-planet searches [5]. A fair correction (Strehl ~ 35%) is still attained in the J-band, albeit with much smaller sky coverage, except for extremely good seeing conditions.

The M5/M6 corrector mirrors are ideally placed –respectively conjugated at 8 km and to the ground- to act as the deformable mirrors for a two-conjugate Adaptive Optic System. OWL base optical system is thus well configured to provide this major AO capability, essential to achieve some critical science drivers as we will see below. Reversing the argument, building an NGS-based, high sky coverage, AO system for a 100-m, entails such a huge "étendue", viz. 180 mm x radian for the required ~ 6 arc minutes patrol field, that the use of deformable mirrors at least in the 1 to 2 m range is mandatory[i]. An NGS-only MCAO system with a wide (6' diameter) patrol field and two large deformable mirrors in the corrector is one essential baseline AO system for OWL. We have therefore launched a long-term R&D program for the development in successive steps of large adaptive mirrors, based on the technique successfully developed for the MMT [6], with increasing size and number of actuators.

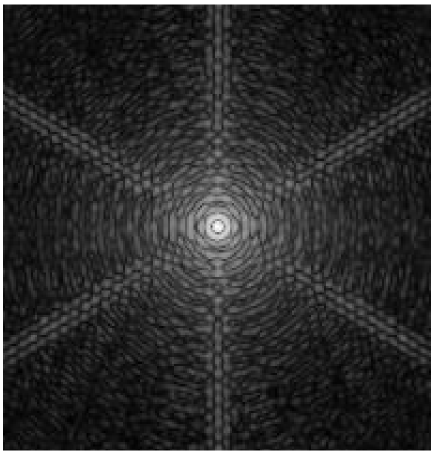

**Figure 4.** 100-m OWL K-band PSF. 80 cm actuator pitch; 0".5 seeing at 0.5 µm; 76% Strehl.

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[i] The guide stars pick-up arms in the patrol field could be used in principle to reduce the étendue, by enlarging the stellar images and/or sending the beams towards the field centre, before injecting them on –much smaller- deformable mirrors. Unfortunately this would at the same time destroy any multi-layer conjugation and could only be applied to Single Conjugate Adaptive Optics Systems.

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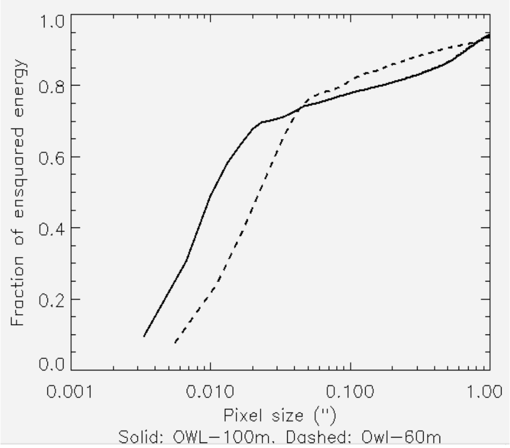

**Figure 5**. Fraction of K-band ensquared energy versus pixel size. AO parameters: 80 cm actuator pitch; 0".5 seeing at 0.5 μm.

For (integral field) spectroscopy, the relevant criterion is not anymore the Strehl ratio, but better the ensquared energy provided by the AO correction. Detailed simulations [4] show that one can get ~70% of the energy (the Jacquinot criterion, well adapted to low light-level detection, as with spectroscopy between the airglow lines) in the K-band inside a 24 mas square pixel, or 40 mas for a 60-m (Fig. 5).

A similar simulation in the J-band has shown a still respectable 50% ensquared energy in the same conditions. However, J sky coverage is considerably lower than the 80% (at galactic poles) K coverage and would reach good values only in the very best observing conditions.

## 4. OWL MAIN INSTRUMENTATION PACKAGE

Translated into instrumental requirements, the three science drivers selected for OWL require extreme contrast near-IR AO spectro-photometry in a small field; Multi-Conjugate Adaptive Optics (MCAO) assisted near-IR imagery at the diffraction limit and, finally, multi-integral field near-IR spectroscopy in a large patrol field, again MCAO assisted, but with a significantly coarser sampling. High sky coverage is needed. As seen above, this is automatically provided by the science target only in the exo-solar planet case, and for the other two, in a first phase in the near-IR, by an MCAO system fully integrated with the telescope.

The exo-solar planet search case is discussed elsewhere [5] and will not be repeated here in detail. One particularly important result is that, at equal adaptive optics performance, detectivity scales steeply with the diameter D of the telescope, viz. as $D^4$. Studies are currently being conducted by Institute Consortia in the frame of VLT 2nd generation instrumentation to develop a high contrast "Planet Finder" for the VLT. Advanced coronagraphic and speckles multi-wavelength suppression techniques are being studied. Some of these new components have actually been retro-fitted into the NACO adaptive-optics based IR camera at the VLT, with very significant contrast gains, up to ~ 40. On the pure instrumental side, i.e. not taking into account the AO system, such a Planet Finder is virtually scale-free with respect to the telescope diameter. A major difficulty however is the need to fully integrate the instrument and its AO system, to establish extremely accurately the aberration mismatch between the central star beam sensed by the AO wavefront sensor and the surrounding field "spectro-imaged" on the instrument detector.

In instrumental terms, a relatively near K-band diffraction-limited imaging camera for OWL would be quite similar in principle to the wide-field IR cameras being currently developed for smallish telescopes, like the 4-m diameter VISTA. One issue with an ELT is the need for accurate cancellation of atmospheric dispersion even in the IR. Another is the large amount of -costly- detector real estate needed to cover a sizable field. At a rather coarse 6 mas (1 pixel) sampling with a 100-m, an F/6 camera with a 1'x1' field would be already quite powerful for e.g. the detection of very high-z supernovae. It would require however $10^8$ infrared (18 μm) pixels, with an, at least present, prize tag over 10 M€. Equivalent to 4 VISTA cameras, this would be quite a formidable system. Also, the cryogenic camera and the wavefront sensor systems (fed with pick-up arms, addressable mirrors, kickbots) should maintain a few microns stability over the 1-m diameter patrol field during typically 30 minutes exposures, a non trivial metrological feat indeed.

An F/3 IR cryogenic spectrographic camera samples adequately (70% energy in 2 x 2 18 μm pixels) the delivered energy concentration in the K-band, at a 2 x 2 pixels spatial resolution of 24 mas on the sky, or~ 6 times the diffraction limit. As in the imagery case, this leads to an 8-m class "only" instrument, similar in principle to the KMOS multi-integral field spectrometer being presently developed for the VLT [7]. Like for KMOS, two hard technological feats are the development of cryogenic IR pickers (to select the objects) and cryogenic image slicers (to inject them inside the entrance slit). As in imagery, except with requirements relaxed by a factor two or more, atmospheric dispersion must be compensated and a very high stability should be maintained inside the MCAO system and with the cryogenic, instrument. An optical diagram of the baseline spectrometer is shown in Figure 6. With a spectral resolution ~ 6,000, in order to provide optimum airglow suppression and with the 4k x 4k detector array, the J, H and K band could be each covered in a single exposure. However, with individual objects field of 0".3 x 0".3, only 6 objects could be injected on the spectrometer long-slit at a given time. So, while the spectrometer itself looks reasonable (100 mm diameter pupil, 1.3 m total optical height) even for such a fully cryogenic system, getting a higher multiplex could quickly lead to a huge cluster of this building brick.

Ultimately, limits in terms of such huge instrument clusters will be set by the available volume, weight and cost. Preliminary definition of the OWL focal plane environment [2] foresees six temperature-controlled enclosures, each with a ~ 60 m$^3$ usable volume and a maximum instrument weight of 15 tons. While this allocation may seem quite generous, a large part could be already taken by a gimbaled platform for those instruments which require to be gravity invariant. One important step ahead is to iterate between the instrument package definition and that of the focal plane environment.

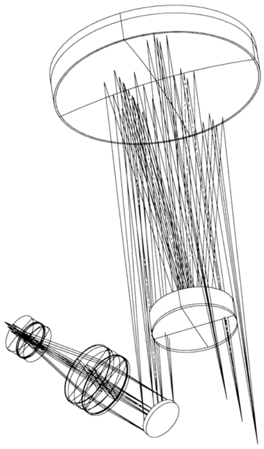

Figure 6. OWL long-slit spectrometer optical design (courtesy B. Delabre). 100 mm grating; F/3 camera; 4k x 4k 18 µm pixel IR array. Total optical length: 1.3 m.

## 5. AN ELT EXPERIMENT TO MEASURE THE TIME VARIATION OF COSMIC EXPANSION

Three main OWL instrument concepts have been outlined in the previous section, namely a high contrast IR spectro-imager, an IR camera and a multi-object IR spectrograph. They have been defined from the most important science drivers, but could also be considered as general facilities to exploit the unique advantages of an ELT, particularly the photon collecting power and the angular resolution, on many astrophysical programs, no doubt including some very high priority ones not yet identified at this time. In the following subsections we want to introduce the example of an instrument of a very different category, which could actually be better identified as a physical experiment. Its aim is to collect over at least a decade observations of the Lyman α forest of several Quasi-Stellar Objects (QSOs) at high redshift to obtain a direct measurement of the variation of the expansion velocity of the universe.

### 4.1 High resolution spectroscopy of QSOs to measure cosmic acceleration at different epochs

The so called "standard model" of the universe had its greatest success with the correct prediction of the existence and shape of the Cosmic Microwave Background. Several observational approaches have been used since then to determine the values of the key cosmological parameters which describe the content in matter and energy of the universe. The possible use of high resolution spectrographs on large telescopes to make direct measurements of the variation of expansion velocity on Lyman alpha clouds has been put forward by Loeb [8] and detailed by Grazian et al [9]. Friedmann equations can then be used to relate directly the variation of redshift with time to the cosmological parameters which describe the density of matter $\Omega_M$, vacuum $\Omega_\Lambda$ and the Hubble constant. Measurements of $\Delta z/\Delta t$ at different redshifts permit a bias-free determination of the cosmological parameters. The basic concept calls for measuring at different epochs over at least a decade the radial velocity of Lyman α clouds detected in the spectra of distant bright QSOs at redshift between 2.5 and 5 approximately. At smaller redshift, the lines in the forest become too sparse; at $z > 5$ the forest is to crowed to permit this type of measurements. The best redshift range is probably around $z = 3.5$ that is in the V band (see Fig. 7) but it is crucial to carry out the measurement at as different redshifts as possible. This direct measurement has advantages with respect to other approaches to measure the cosmological parameters which have been successfully used most recently. With respect to the measurements of the microwave background anisotropies, it explores a different range of redshifts. It is independent on the possible evolutionary effects which could affect the SNe type Ia measurements.

In the last few years three advances have contributed to bring this tantalizing goal within reach. First, two powerful high resolution spectrographs at the Keck and at the VLT, HIRES and UVES respectively, have observed with high signal to noise and resolution ~40,000 more than one hundred QSOs fainter than 17 magnitude with redshifts between 2 and 5.

From these observations we have acquired a detailed knowledge of the properties of the Lyman α forest. They can be used to carry out advanced simulations of the measurement and to select optimally the targets for the different redshift ranges we want to explore. Secondly, the drive to discover planets orbiting around nearby stars from the periodic wiggles in the plots of radial velocity of the stars over time, has brought the long term stability of this type of spectrographs down to the 1m/s range. In a joint project with ESO, the Observatoire of Geneva has recently installed a spectrograph of this class at the 3.6m telescope in La Silla [10] which can actually reach a 1m $s^{-1}$ stability over 5 years and 0.1 m $s^{-1}$ over a few hours. Thirdly, the possibility to build in the not too far future telescopes of diameters up to 100-m could provide the bonanza of photons which are needed to make these measurements at the required resolution and high pixel sampling. These developments have led ESO, the Observatoire of Geneva in Switzerland and INAF-Osservatorio di Trieste in Italy to initiate a concept study to revisit this scientific goal and to explore the feasibility of the corresponding instrument for an ELT.

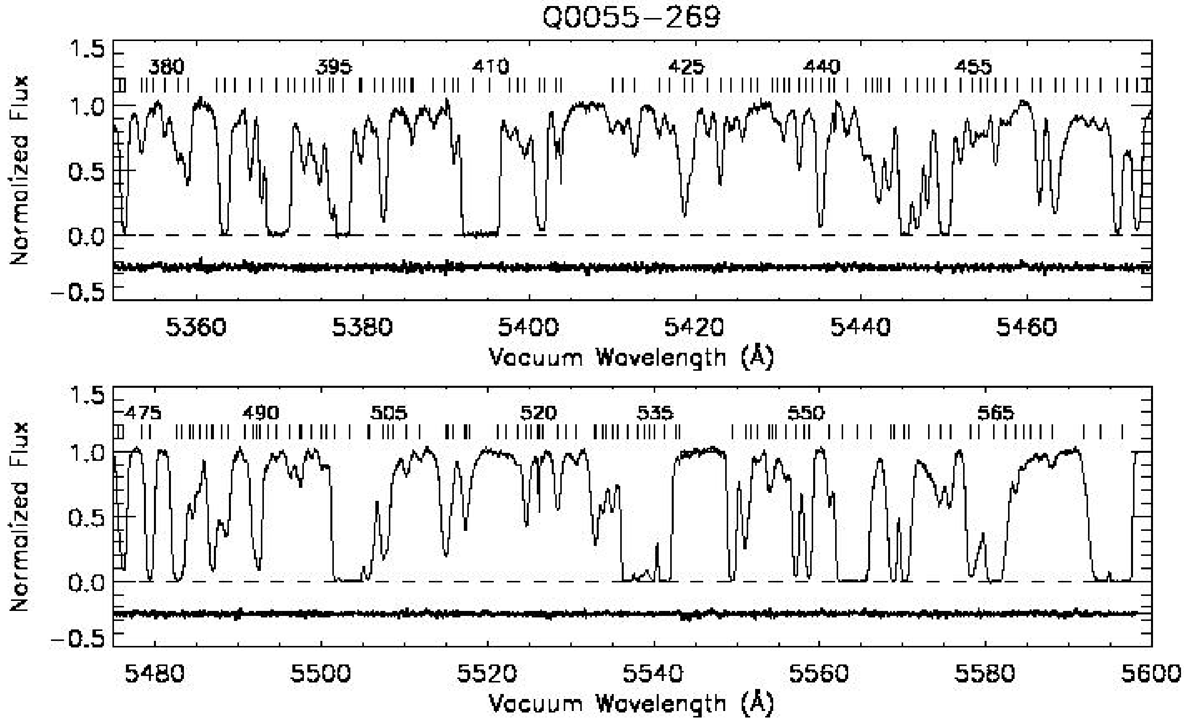

**Figure 7.** The Lyman alpha forest in the direction of the QSO 0055-269 as observed with the UVES spectrograph at the VLT at $\Re$ = 40,000. The section shown (25nm) encompasses the redshift range z = 3.4-3.6.

### 4.2 Instrument requirements and starting considerations for a concept study

In order to define the required stability of the spectrograph we will need to consider: i) the predicted magnitude of the effect on a single source as derived from the Friedman equations, as computed e.g. by Grazian et al [9], ii) how to optimally use all the information in the forest to measure the change in the frame overall velocity and iii) the use of many lines of sight (→ QSOs) over which the results can be averaged.. The simulations to verify the interplay between these parameters and the finally required instrument stability will be part of the concept study. For example they will tell us whether we should better use, in the cross-correlation between the observations at different epochs, a number of selected lines in the forest or the global information contained in the spectral profiles. As a requirement to guide the predefinition of the instrument concept, we have taken on the basis of simple considerations a goal of 5 cm $s^{-1}$ over ten years. This should guarantee a very clear detection of the expansion rate and of its variation with time in the z=2-5 redshift range. This is a factor of 20 improvement with respect to the accuracy which is expected from the HARPS spectrograph on long-term observations of a single object at an ESO 3.6m telescope. This appears as a very challenging but not impossible task.

An important goal of the concept study now under way is the verification of the interface of this instrument with the opto-mechanical layout of the telescope. The demanding requirement on long term stability of the instrument calls for a focal station which is gravity-invariant (an active correction systems seems unlikely to provide the required accuracy in this application). The second key requirement is the quality of the image in the visual-red region of the spectrum. While full adaptive optics will not be implemented in OWL at visual-red wavelengths at the start of operation, the use of AO at infrared wavelengths and tip-tilt correction should deliver in good seeing conditions the required concentration of energy. It is tentatively assumed for the instrument definition that 80% of the energy is within 0.6 arc second diameter at 600nm. Table 1 summarizes the initial requirements on the spectrograph.

**Table 1** Initial Requirements of the High Resolution Spectrograph at an 80m ELT

| | |
|---|---|
| Interface to the Telescope | Acquisition , calibration units & fiber feed in the focal plane |
| Spectrograph slit | Defined by an image slicers, 0.05 x 7 arc sec approx. |
| Resolution | 1.5 x $10^5$ goal ($10^5$ minimum) |
| Sampling | Resolution element sampled by 6-10 pixel |
| Spectral Coverage | 450-730 nm (goal) 500-600nm (minimum) |
| Stability of $\lambda$ scale | 5cm $s^{-1}$ over 10 years |

By simply adapting the UVES concept to a telescope of the 50-100 m class, these requirements call for an Echelle spectrograph with a beam size at least twice as large, the use of an image slicer and a detector mosaic of 4-10 4Kx4K CCDs.

Taken the required stability, the goal of the concept study is to identify the optimal values of resolution, sampling and spectral range to optimize this type of measurements. The study must demonstrate that the proposed instrument is doable with the proper scaling of current technology , it can be properly interfaced to the telescope and is maintainable with the required accuracy over a decade.

## 6. DISCUSSION

It is comforting that the –admittedly already ambitious- AO implementation strategy presented by E. Brunetto et al. [2], and largely based on projected technological availability even if still very challenging, matches reasonably closely the needs the three initial science drivers selected for OWL. One caveat is the study of stellar populations for which the next generation OWL (MC)AO should be able to reach good Strehl ratios with reasonable sky coverage in the visible domain. These are tough requirements for a 60 to 100-m telescope, calling *inter alia* for new laser guide stars concepts compatible with the relatively low altitude of the Na layer, like the PIGs discussed at the Conference by Kellner and Gaessler [11] and Bonaccini et al. [12].

The post-AO instrumentation, in terms of physical scale and metrological accuracy, could be actually quite similar to corresponding so-called VLT 2nd generation instruments presently under development: the Planet Finder for the exo-solar planets science case; KMOS for the early Universe spectroscopy; the VISTA IR camera for the early Universe imaging and the first step towards resolving external galaxies into stars. Here, we have taken ESO-centered examples for convenience, but a similar analysis would very well apply to e.g. Gemini 2nd generation instruments.

This relative easiness holds true however only for “reasonable” demands in terms of field (for imaging) and multiplex (for multi-integral field spectroscopy). Specifically, the basic integral-field spectrometer presented here would allow only ~ 6 objects at the same time; the already very large IR imager would cover ~ 1’x1’ at ~ 3 times the diffraction limit or ~ 20”x20” only at the diffraction limit. More ambitious facilities could be developed by “simply” multiplexing these basic bricks, but at obvious cost in volume, weight, complexity and human and financial resources. One clear additional complexity in any case for an ELT is the need for accurate atmospheric dispersion compensation [13]. Another is that, like for the VLT Planet Finder, but unlike VLT-KMOS and VISTA-IRCAM, OWL AO sensing should be fully integrated with basically any AO-assisted instrument.

It must be stressed that while this first set of highest priority scientific facilities has been defined from relatively narrow, if exciting, scientific fields, AO-assisted near-IR imagery and multi-object (with an integral field flavor) spectroscopy are quite generic investigation tools, with much broader appeal. The imager for instance could also provide regular meteorological (or volcanic for Io) surveys of various solar system bodies; the spectrometer would be ideal to produce a deep census of super-massive black holes in the center of galaxies.

Given the long time span needed to build an ELT, especially if driven by funding, no science driver could be cast in stone right from the start of the project. Furthermore, with these new giant facilities, we expect a growing emphasis in developing and using ad hoc facilities (a custom-built instrument, always complemented by a dedicated data reducing and analysis package) to answer very specific scientific questions through a well-defined observing strategy. That could be a single burst of say 6 full months of telescope access, e.g. to make a full census of Supernovae explosions at any z, or regular observations over more than a decade, as in the cosmic acceleration experiment presented above.

On the programmatic aspect, a very significant coordinated European astronomical R&D effort is underway, with ELT wavefront control and instrumentation a major component. A very significant part of the OPTICON Framework Program 6 which started beginning 2004 is geared towards developing enabling technologies for 8-10 m class instrumentation (AO components & systems; smart focal planes in particular). These are also the first step towards ELT AO systems and instruments. The ELT Design Study proposal has been recommended to the European Commission and we expect to start this effort beginning 2005. Again it contains major developments towards cutting edge AO concepts, systems and Instrument point designs [13], geared towards generic ELT needs. In parallel and close coordination, ESO is conducting, with the help of its community, the feasibility study of the particular OWL ELT flavor. We will strive to get maximum cross-fertilization between these studies, particularly, but not only, in the field of AO/Instrumentation, and continue to develop close collaborations with our American counterparts.

## ACKNOWLEDGEMENTS

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