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HIRES, the High-resolution Spectrograph for the ELT

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HIRES will be the high-resolution spectrograph at optical and near-infrared (NIR) wavelengths for ESO's Extremely Large Telescope (ELT). It will consist of three fibre-fed spectrographs providing a wavelength coverage of 0.4–1.8 μm (with a goal of 0.35–1.8 μm) at a spectral resolution of ~ 100 000. Fibre-feeding allows HIRES to have several interchangeable observing modes, including a single-conjugate adaptive optics (SCAO) module and a small diffraction-limited integral field unit in the NIR. It will therefore be able to operate in both seeing- and diffraction-limited modes. HIRES will address a wide range of science cases spanning nearly all areas of research in astrophysics and even fundamental physics. Some of the top science cases will be the detection of biosignatures from exoplanet atmospheres, finding the fingerprints of the first generation of stars (Pop III), tests on the stability of Nature's fundamental couplings, and the direct detection of the cosmic acceleration. The HIRES consortium is composed of more than 30 institutes from 14 countries, forming a team of more than 200 scientists and engineers.

Introduction

At first light, the ELT will be the largest ground-based telescope at visible and infrared wavelengths. The flagship science cases supporting the successful ELT construction proposal were the detection of life signatures from Earth-like exoplanets and the direct detection of the cosmic expansion re-acceleration, and it is no coincidence that both science cases require observations with a high-resolution spectrograph.

Over the past few decades high-resolution spectroscopy has been a truly interdisciplinary tool, which has enabled some of the most extraordinary discoveries spanning all fields of astrophysics, from planetary sciences to cosmology. Astronomical high-resolution spectrometers have allowed scientists to go beyond the classical domain of astrophysics and to address some of the fundamental questions of physics. In the wide-ranging field of research exploiting high-resolution spectroscopy, ESO has a long and successful tradition, thanks to the exquisite suite of medium- and high-resolution spectrographs offered to the community of Member States. The Ultraviolet and Visual Echelle Spectrograph (UVES), the Fibre Large Array Multi Element Spectrograph (FLAMES), the CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES), the medium-resolution spectrograph X-shooter and the High Accuracy Radial velocity Planet Searcher (HARPS) have enabled European teams to lead in many areas of research. The Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO), which is now joining this suite of very successful high-resolution spectrographs, is fulfilling its promise by truly revolutionising some of these research areas. The scientific interest and high productivity of high-resolution spectroscopy are reflected in the fact that more than 30% of ESO publications can be attributed to its high-resolution spectrographs.

However, it is becoming increasingly clear that in most areas of research high-resolution spectroscopy has reached the "photon-starved" regime at 8–10-m-class telescopes. Despite major progress on the instrumentation front, further major advances in these fields desperately require a larger photon collecting area. Given its inherently "photon-starved" nature, amongst the various astronomical observing techniques high-resolution spectroscopy is most in need of the collecting area of Extremely Large Telescopes.

When defining the ELT instrumentation suite, ESO commissioned two Phase A studies for high-resolution spectrographs, one to work at visible wavelengths and known as CODEX (Pasquini et al., 2010), and SIMPLE (Origlia et al., 2010) to work in the NIR. Both studies were started in 2007 and completed in 2010. These studies demonstrated the importance of high-resolution optical and NIR spectroscopy at the ELT and ESO therefore decided to include a high-resolution spectrograph (HIRES) in the ELT instrumentation roadmap. Soon after conclusion of the respective Phase A studies the CODEX and SIMPLE consortia realised the great scientific importance of covering both the visible and NIR spectral ranges simultaneously. This marked the birth of the concept of an X-shooter-like spectrograph with higher resolution, capable of providing *R* ~ 100 000 over the full visible and NIR wavelength range. Following a community workshop in September 2012 the HIRES Initiative prepared a White Paper summarising a wide range of science cases proposed by the community (Maiolino et al., 2013) and also prepared a preliminary technical instrument concept.

With the start of construction of the ELT, the HIRES Initiative decided to organise itself as the HIRES Consortium and recruited additional institutes that had expressed an interest in HIRES. The Consortium, strongly motivated by the unprecedented scientific achievements that the combination of such an instrument with the ELT would enable, was commissioned by ESO to perform a Phase A study. The Phase A study started in March 2016 and concluded successfully in May 2018. Following the conclusion of the Phase A study, other institutes in the USA and Canada joined the HIRES Consortium.

The HIRES Consortium[a] is now composed of institutes from Brazil, Canada, Chile, Denmark, France, Germany, Italy, Poland, Portugal, Spain, Sweden, Switzerland, the United Kingdom and the USA. The Italian National Institute for Astrophysics (INAF) is the lead technical institute. See Marconi et al. (2018) for more details on the Consortium structure and organisation.

Science goals

During the Phase A study, the HIRES Science Advisory Team (SAT), chaired by the Project Scientist, defined the science priorities for HIRES and determined the corresponding top-level requirements. These science cases, briefly described below, were then prioritised in order to define the instrument baseline design. Many other science cases are possible with HIRES, but they will not be mentioned here, where we focus on a few representative science goals. A description of the prioritisation process can be found in, for example, Maiolino et al. (2013) and Marconi et al. (2018).

Exoplanets and protoplanetary discs

The study of exoplanet atmospheres for a wide range of objects, from gas giants to rocky planets, and from hot to temperate planets, is a primary objective in the field for the next decade. In particular, the detection of components such as molecular oxygen, water and methane in Earth- or super-Earth-sized planets would be truly transformational, as they may be regarded as signatures of habitability or even signatures of life. Simulations of HIRES observations have been performed by Snellen et al. (2013, 2015) and Hawker & Parry (2019).

HIRES will be able to probe the atmosphere of an exoplanet in transmission during a transit in front of its host star. As an example, it will be possible to detect CO_2 absorption in Trappist-1b with a signal-to-noise ratio (S/N) of 6 in 4 transits of the planet, while O_2 absorption at 0.75 μm would be detected in only 25 transits of the planet, i.e., less than 30 hours of observation. HIRES will also be able to probe exoplanets directly, by spatially resolving them from their host star, focusing on their reflected starlight and taking advantage of the angular resolution of the ELT with AO-assisted observations. For example, it will be possible to detect the Proxima Centauri b planet in 4 nights of integration at a S/N of 8 with a relatively simple SCAO system similar to that used by other ELT first-light instruments. Figure 1, left, shows that HIRES will be able to detect O_2 from an exoplanet similar to Proxima b in 70 hours of integration.

Protoplanetary discs are a natural outcome of angular momentum conservation in star formation and are ubiquitous around young, forming stars. HIRES will be able to determine the properties of the gas in the inner star-disc region, where competing mechanisms of disc gas dispersal are at play. This will constrain, on the one hand, the mechanisms by which the forming star acquires mass and removes angular momentum, and, on the other hand, the initial conditions for planet formation.

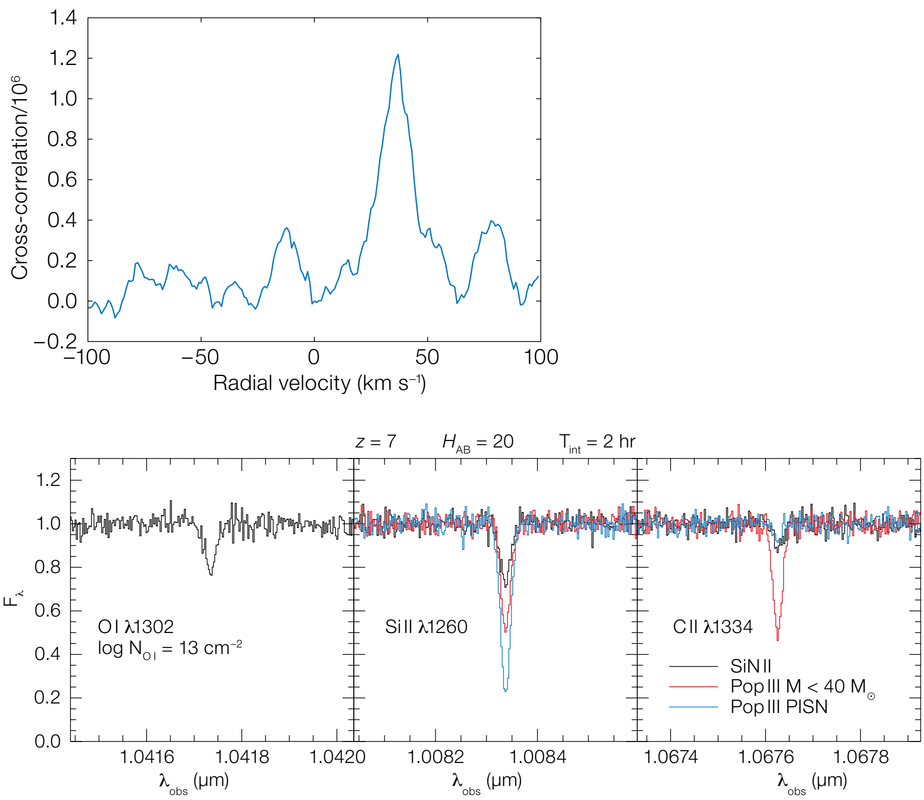

Figure 1. HIRES science highlights. Top: Cross-correlation signal indicating the clear detection of O_2 in a Proxima-b-like exoplanet in 70 hours of total integration (adapted from Figure 4 of Hawker & Parry, 2019). Bottom: Observations of a z = 7 quasar with H_{AB} = 20 and a total integration time of 2 hours showing HIRES's ability to distinguish IGM enrichment by normal SNII supernovae or by low mass and pair instability supernovae from Pop III stars (simulations by the HIRES Science Advisory Team).

Stars and stellar populations

The vast light-collecting power of the ELT will enable detailed high-resolution spectroscopy of individual stars, and in particular very faint red dwarfs and distant red giants in nearby galaxies, for which HIRES will be able to provide tight constraints on the atmospheric parameters. These constraints will be extremely important for characterising the stellar hosts of exoplanets.

HIRES will also expand our horizons by measuring the heavy-element abundances of the most primitive stars (with low mass and low metallicity) in our Galaxy and its satellites, helping us to understand what is the lowest metallicity

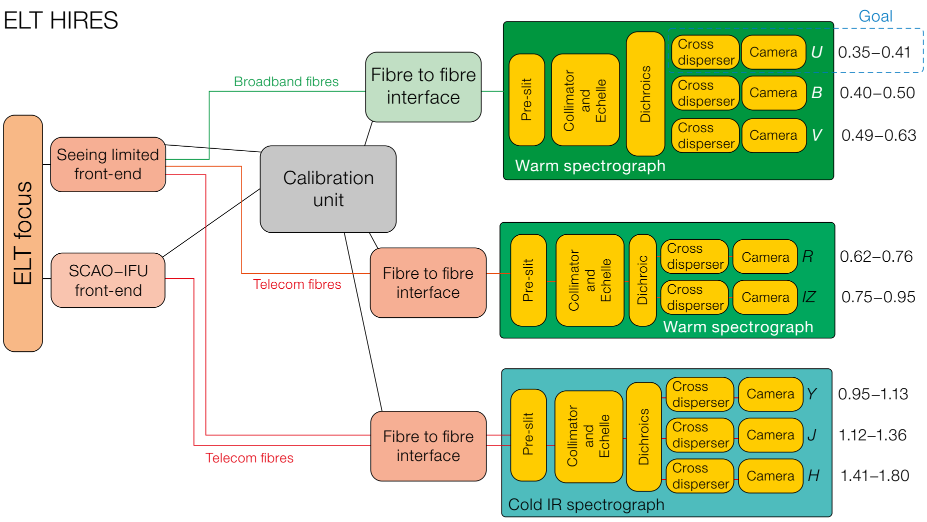

Figure 2. HIRES architectural design, outlining the instrument subsystems: Front-end (seeing-limited and AO assisted with SCAO unit), Fibre Link, Calibration Unit, VIS-Blue, VIS-Red and NIR (cold IR spectrograph).

at which gas can collapse to form low-mass stars, and what are the nature and yields of the very first generation of stars and their supernovae.

Last, but not least, the combination of very high spectral resolving power and diffraction-limited angular resolution makes the ELT a unique resource for deepening our understanding of the physics of stellar atmospheres and nucleosynthesis processes, by allowing us to spectroscopically resolve the effects of surface convection and to measure isotopic abundances of atomic species.

Galaxy formation and evolution, and the intergalactic medium

The detection of Population III stars and the observational characterisation of their properties are major objectives of extragalactic astrophysics. Protogalaxies hosting Pop III stars are expected to be too faint for direct detection, even with the JWST. However, the signature of Pop III stars can be detected through their nucleosynthetic yields, which can potentially be observed in the abundance patterns of very metal-poor absorption systems in the high-resolution, wide-range spectra of bright high-redshift sources provided by HIRES in the NIR (Figure 1, bottom).

The direct detection and characterisation of the beginning of the reionisation epoch is another very important goal in the study of galaxy formation. This process is believed to have been dominated by ultraviolet photons from the first generations of galaxies, most of which are too faint to be observed directly even with the JWST. By targeting bright quasars at high redshift as background continuum sources, HIRES will be able to study both transmission features in the Lyman-α forest and metal absorption lines associated with these reionisation-epoch sources, constraining the patchiness of the reionisation process, the properties of the ultraviolet background radiation and the chemical enrichment of the intergalactic medium (IGM) in this epoch.

Cosmology and fundamental physics

The observational evidence for the acceleration of the expansion of the Universe and the tensions that have been highlighted by different cosmological probes have shown that our canonical theories of cosmology or fundamental physics may be incomplete (and possibly incorrect) and that there might be unknown physics yet to be discovered. HIRES will allow us to search for, identify and ultimately characterise any new physics through several different but fundamentally inter-related observations which will enable a unique set of tests of the current cosmological paradigm.

HIRES will be able to constrain the variation of fundamental physical constants like the fine-structure constant α and the proton-electron mass ratio μ with the advantage, compared to laboratory measurements, of exploring variations over timescales of 12 Gyr and spatial scales of 15 Gpc. A detection of variation in the fundamental constants would be revolutionary: it would automatically prove that the Einstein Equivalence Principle is violated (i.e., gravity is not purely geometry), and that there is a fifth force.

HIRES will enable a test of the cosmic microwave background (CMB) temperature-redshift relation, $T(z) = T_0 (1 + z)$, which is a robust prediction of standard cosmology but one that must be directly verified by measurements. A departure from this relation can in turn reveal that the hypothesis of local position invariance (and thus the equivalence principle) is violated or that the number of photons is not conserved. HIRES measurements will greatly improve on the existing constraints on $T(z)$ compared to existing data.

The redshifts of cosmologically distant objects drift slowly with time — the so-called Sandage (or Sandage–Loeb) effect (see Liske et al., 2008). A redshift drift measurement is fundamentally different from all other cosmological observations; it can provide a direct detection of cosmic reacceleration, thus undoubtedly confirming cosmic acceleration and the existence of dark energy, and potentially providing evidence for new physics. HIRES will be capable of detecting the redshift drift in the Lyman-α forests of the brightest currently known QSOs (~ 6 cm s^{-1} $decade^{-1}$ at $z = 4$ for a Planck-like standard cosmology). The ELT may thus become the first facility ever to watch the Universe change in "real time".

Science priorities

These are just a few of the many science cases that can be addressed, a collection of which can be found in Maiolino et al. (2013). However, in order to define the instrument baseline design a prioritisation of the science cases was performed by the HIRES Science Advisory Team following criteria of scientific impact (transformational versus incremental), feasibility and competitiveness.

Then, if the top level requirements (TLRs) of the top priority science cases were also enabling other science cases, the latter were not considered any further in the subsequent prioritisation, being considered as accomplished together with the top priority science cases. The top science priorities and associated requirements are:

1. **Exoplanet atmospheres in transmission**, requiring a spectral resolution of at least 100 000, a wavelength coverage of at least 0.50–1.80 μm and a wavelength calibration accuracy of 1 m s^{-1}. The implementation of the above TLRs would automatically enable the following science cases:
   – reionisation of the universe,
   – characterisation of cool stars,
   – detection and investigation of near pristine gas,
   – the study of extragalactic transients.

2. **Variation of the fundamental constants of physics**, requiring an extension to 0.37 μm in addition to the TLRs of priority 1. At wavelengths less than 0.40 μm the throughput of the ELT is expected to be low as a consequence of the planned coating. However, even in the range 0.37–0.40 μm the system is expected to outperform ESPRESSO at the VLT, and a new coating is under study which may be available a few years after first light. This extension towards the blue would also automatically enable investigation of:
   – the cosmic variation of the CMB temperature,
   – the determination of the deuterium abundance,
   – the investigation and characterisation of primitive stars.

3. **Detection of exoplanet atmospheres in reflection**, requiring, on top of the TLRs of priority 1, the addition of an SCAO system and an integral field unit. Reflected-light spectra allow atmospheric emission to be traced from lower altitudes on the day side of the exoplanet. These additional TLRs would automatically also enable the following science cases:
   – planet formation in protoplanetary discs,
   – characterisation of stellar atmospheres,
   – searching for low-mass black holes.

4. **The Sandage test**, for which the additional TLRs are a wavelength range of 0.40–0.67 μm and a stability of 2 cm s^{-1}, also enabling:
   – the mass determination of Earth-like exoplanets,
   – radial velocity searches and mass determinations for exoplanets around M-dwarf stars.

Instrument concept

Following Phase A and further studies before the start of construction, the HIRES baseline design is for a modular instrument consisting of three fibre-fed cross-dispersed echelle spectrographs — VIS-BLUE (*UBV*), VIS-RED (*RIZ*) and NIR (*YJH*) — providing a simultaneous spectral range of 0.4–1.8 μm (with a goal of 0.35–1.8 μm) at a resolution of 100 000. Fibre-feeding allows several, interchangeable, observing modes, ensuring maximisation of either accuracy, throughput or spatially resolved information. Together with the SCAO module, the proposed baseline design is capable of fulfilling the requirements of the 4 top science cases.

The baseline design is summarised below but several alternatives were also evaluated during the Phase A study. Also, several add-ons made possible by the modular nature of the instrument have been considered (for example, a polarimetric module at the intermediate focus, or a wavelength extension out to the *K* band (2.0–2.4 μm). The overall concept is summarised in Figure 2. In the front-end the light from the telescope is split, via dichroics, into 3 wavelength channels. Each wavelength channel interfaces with several fibre bundles that feed the corresponding spectrograph module. Each fibre bundle corresponds to an observing mode and together they constitute the Fibre Link. All three spectrographs, VIS-BLUE, VIS-RED and NIR, have a fixed configuration, i.e., there are no moving parts, thereby fulfilling the stability requirements. They include a series of parallel entrance slits consisting of linear micro-lens arrays each glued to the fibre bundles. The split in wavelengths between the spectrographs is influenced, along with other parameters, by the optical throughput of the different types of fibre available on the market; the different modules can therefore be positioned at

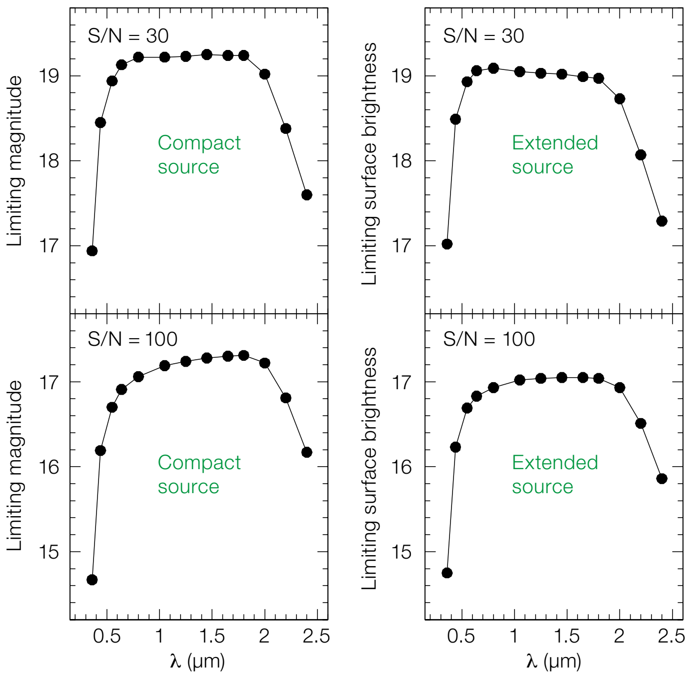

Figure 3. HIRES limiting magnitudes obtained from the Exposure Time Calculator for different S/N ratios (30 — top and 100 — bottom), and for compact and extended sources (left and right). Observations are in seeing-limited mode with *R* = 100 000 and a total exposure time of 1800 seconds.

different distances from the focal plane of the telescope.

The whole instrument should be placed on the Nasmyth platform, if enough volume and mass is available. If necessary, the fibre-feeding allows the VIS-RED and NIR modules to be placed in the Coudé Room, which can also host the Calibration Unit.

Performance

The Exposure Time Calculator (ETC), regularly updated to take into account modifications to the design, is maintained by INAF-Arcetri and can be run online[2]. The ETC can compute the limiting magnitude achievable at a given wavelength in a given exposure time and at a given S/N, or it can compute the S/N achievable at a given wavelength in a given exposure time and at a given magnitude. HIRES expected performances, computed with the ETC, are summarised in Figure 3.

Conclusions

The HIRES baseline design is for three ultra-stable and modular fibre-fed cross-dispersed echelle spectrographs providing a simultaneous spectral coverage of 0.4–1.8 μm (with a goal of 0.35–1.8 μm) at a resolution of 100 000 with several, interchangeable, observing modes ensuring maximisation of either accuracy, throughput or spatially resolved information. Overall, the studies conducted so far have shown that the HIRES baseline design can address the 4 top priority science cases, being able to provide ground-breaking science results with no obvious technical showstoppers.

The construction of HIRES involves the majority of the institutes in ESO Member States with expertise in high-resolution spectroscopy and will require an estimated 30 million euros for hardware (excluding contingencies) and about 500 full time equivalent personnel. Contingencies are expected to be low (5–10%) because the proposed baseline design is based on proven technical solutions and can benefit from heritage from HARPS and ESPRESSO and other earlier high-resolution spectrographs, for example the Potsdam Echelle Polarimetric and Spectroscopic Instrument (PEPSI) at the 11.8-m Large Binocular Telescope, the SPectropolarimètre InfraRouge (SPIRou) at the 3.6-m Canada France Hawaii Telescope and the Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs (CARMENES) instrument at the 3.5-m telescope of Calar Alto Observatory. Construction will take about 8–10 years, so with Phase B starting in 2021, HIRES could be at the telescope as early as 2030.

Overall, HIRES is an instrument capable of addressing ground-breaking science cases whilst being almost (telescope) pupil independent, as it can operate in both seeing- and diffraction-limited modes; the modularity ensures flexibility during construction and the possibility to adapt quickly to new developments in both the technical and the science landscapes.

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Links

[1] Instrument Web Page http://hires.inaf.it
[2] Exposure time calculator http://hires.inaf.it/etc.html

Notes

[a] Partners of the HIRES Consortium
(CI = Coordinating Institute within a country)
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