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L. Cambrésy, F. Martins, E. Nuss and A. Palacios (eds)

HIRES: A HIGH-RESOLUTION ECHELLE SPECTROGRAPH FOR THE E-ELT

L. Origlia[1] on behalf of the HIRES Consortium[2]

Abstract. HIRES is the study of a High Resolution Spectrograph for the E-ELT. Flagship science cases include the characterization of exoplanet atmospheres with the prospect of the detection of signatures of life on rocky planets, the chemical composition of planetary debris on the surface of white dwarfs, protoplanetary and proto-stellar disks, detailed stellar physics and evolution over the full space of stellar parameters, Galactic archaeology out to the Local Group and beyond, the chemical fingerprints imprinted by population III stars on the Inter-Galactic Medium (IGM) during the epoch of reionization, evolution of galaxies no longer restricted to strongly star-forming and/or very massive galaxies, primordial black holes, and the exciting possibility of paradigm-changing contributions to fundamental physics. Flagship science drivers demands for a stable instrument with a spectral resolution of R≈100,000 and broad, simultaneous spectral coverage extending from 0.37μm to 2.5μm. Most science cases to not require spatially resolved information, and can be pursued in seeing-limited mode, although some of them would benefit of the E-ELT diffraction limited resolution. Some multiplexing as well as some polarimetric capabilities would also be beneficial for a number of the science cases. These various requirements can be met with a highly modular instrument concept that foresees independent and optimized fiber-fed spectrographs, enabling different observing modes and giving access to different wavelength ranges.

Keywords: spectroscopy, high-resolution, science case, instrument concept

1 Introduction

High-resolution spectroscopy is a general definition that applies to R=20,000 domain as well as to the R=100,000 and higher, and in a specific instrument it is tailored to the specific science cases and specialised to different wavelength domains. High resolution spectroscopy has been, during the past twenty years, a rapidly expanding area enabling major, fundamental progresses in most fields of astrophysics, but also in more general areas of fundamental physics.

European astronomers have been leading several of these fields as well as many of the major discoveries thanks to the four high-resolution spectrographs at the VLT (UVES, CRIRES, FLAMES, X-Shooter, covering the full wavelength range from the near-UV at the atmospheric cut-off to 2.5 μm) and HARPS at the 3.6m telescope. This suite of instruments is soon to be joined by the Laser Frequency Comb-calibrated high-fidelity spectrograph ESPRESSO.

This impressive high-resolution capability of the ESO telescopes has delivered excellent science in a wide range of fields from the discovery of exoplanets and the characterization of their atmospheres, stellar chemical abundances, star and planet formation, Galactic Archaeology in our own Galaxy and in the Local Group, the study of supernovae and GRBs, galaxy evolution and the physical state of the IGM, and to interesting constraints on the nature of dark matter and the variation of fundamental constants.

It is clear that in the area of high-resolution spectroscopy, where "photon starving" is the main limiting factor, the discovery space enabled by larger telescopes will be huge. Indeed, ESO had commissioned nine phase A studies for E-ELT instrument concepts that included one optical (CODEX, Pasquini et al. (2010)) and one near-IR (SIMPLE, Origlia et al. (2010)) high-resolution spectrographs.

Based on the result of these phase A studies, the currently applicable E-ELT instrumentation plan will offer a High Resolution Spectrograph as part of its suite of instruments soon after the first-light set of Adaptive

[1] INAF - Bologna Observatory, Via Ranzani 1, 40127 Bologna, Italy
[2] http://www.hires-eelt.org

Optics (AO) modules and Scientific Instruments. This responds to the need to exploit the unprecedented photon-collection power of the E-ELT in the spectral resolution domain.

In this context, HIRES is currently a joint initiative by nine interested partners from Chile, France, Germany, Italy, Portugal, Spain, Sweden, Switzerland and United Kingdom, with the goal of contributing to the definition of a sounded and disruptive science case and of an instrument concept of proven feasibility to implement it.

2 Science Case

The Science Case of HIRES is described in a *white book* (available on the HIRES website) in continuous evolution and constantly updated by the HIRES Science Team. It is built on the experience of the high-resolution community with the suite of VLT high-resolution spectrographs, which has been tremendously successful, and on the Phase A studies of CODEX and SIMPLE. This section summarizes the main science topics detailed in the *white book.*

- Exoplanets are one of the outstanding key science cases for HIRES. Since the discovery almost 20 years ago of the first giant planet outside of the solar system (Mayor & Queloz 1995), the study of exoplanets has become reality and spawned a real revolution in astronomy. Since first discoveries we know more than 800 exoplanets and 2300 additional transiting candidates provided by the Kepler satellite (Batalha et al. 2013). A large fraction of solar-type stars host hot Neptune or super-Earth mass planets, the frequency of multiple planetary systems seems to be very large, and most of smaller planets are observed in multi-planetary systems. With the goal of advancing our understanding of planet formation, evolution, and habitability, the focus of exoplanet science in the E-ELT era will be on the characterization of their atmospheres in terms of chemical composition, stratification and weather. A wide range of planetary masses, from Neptune-like down to Earth-like including those in the habitable zones, need to be explored. The ultimate goal is of course the detection of signatures of life. Such a science goal can be performed by means of transmission spectroscopy during planetary transits. The main instrument requirements of this science case are 1) spectral resolution R=100,000 or higher to separate telluric and exoplanet line systems, to maximize the contrast of narrow molecular lines (hence probing different atmospheric layers), as well as to be sensitive to planet rotation and atmospheric circulation; 2) Simultaneous 0.38-2.40 μm spectral coverage to measure all the interesting features almost everywhere in the visible/near-IR range. The blue limit is set by the inclusion of the Ca II H&K lines for monitoring of stellar activity, while the K-band is desirable for the presence of strong CO bands at $\approx$2.3 μm.; 3) high Point Spread Function stability ($\approx$1/100 of a pixel), pointing towards a fiber-fed instrument in a stable, gravity-invariant environment, with a fixed spectral format and no moving parts inside the spectrograph; 4) good detector stability during planetary transits and high-precision flat-fielding (better than 0.1%). A polarimetric mode would further enhance the exoplanet diagnostic capabilities of HIRES, especially for the detection of bio-signatures.

- In the context of exoplanet science, another hot topic is the chemical characterization of planetary debris (i.e. the building blocks of planetary systems), by the observations of metal-enriched white dwarfs. An E-ELT aperture is critical to observe statistical significant samples of these faint stars and high spectral resolution, high signal to noise in the blue are mandatory to measure the chemistry of the debris.

- The spectroscopic study of protoplanetary and proto-stellar disks in young stellar objects, will provide fundamental information on the dynamics, chemistry and physical conditions in their innermost regions, on the physics of star formation, jet launching mechanisms and planet formation. Such a study requires a near-IR high-resolution (R$\approx$100,000) spectrograph exploited with spatially resolved information (possibly with an IFU mode) at nearly the diffraction limit of the E-ELT. This science case would also benefit from a polarimetric mode, which would provide information on the magnetic field in the inner regions of the accretion disk.

- Our current knowledge of dynamical phenomena and phases of stellar evolution is still very limited and mostly based on studies in the solar neighbourhood. Although new theoretical simulations of stellar convection, differential rotation, stellar activity, mass loss, and interior mixing, as well as star formation and the interaction of stars with protoplanetary disks and planets, are being developed, these efforts are to a considerable degree depending on simplifications and unknown initial conditions, and on free parameters. This primitive state of our knowledge leads to severe limitations of using stars as probes in the empirical study of the evolution of planetary systems and galaxies, and well in cosmology. New, high-quality observations of stars with different stellar parameters, in different evolutionary stages and located in different environments are urgently needed. When compared to the current generation of ground-based 8-10m class telescopes, the considerably larger aperture of the E-ELT leads to a substantial gain in sensitivity. With an E-ELT and an efficient high-resolution spectrometer covering the full optical and near-IR range, it will be possible to obtain spectra at R≈100,000 and very high signal to noise, thus enabling a detailed determination of the stellar atmosphere structure, physics and chemistry for solar-type and cooler dwarf stars out to distances of several kpc, thus sampling most of the Galactic disk and bulge, or sub-giants and red giants in the outer Galactic Halo and in the neighbouring dwarf galaxies. However, in order to reach the goal, it is fundamentally important that the spectra are not only nominally of high-resolution and have high signal to noise but also very well calibrated (in terms of wavelength, flux, flat-fields, etc.). Some spectro-polarimetric capabilities to probe magnetic fields in a number of stellar conditions, evolutionary stages and environments are also highly desirable.

- An instrument like HIRES on the E-ELT will provide truly revolutionary results in Galactic archaeology out to the Local Group and beyond. At a spectral resolution R≈100,000 and with a broad spectral coverage (0.37-2.5 μm), it will enable the detailed chemical mapping of multiple elements and isotopes, thus revealing the origin and the formation history of ancient stars belonging to different Galactic components. This will be especially crucial for the extremely low metallicity stars, whose photospheres may trace the chemical abundances resulting from the enrichment of the first population of stars (PopIII). HIRES will also be an extremely efficient machine to trace the metal enrichment pattern and dynamics of extragalactic star clusters and resolved stellar populations in other galaxies, if enabled with some multiplexing capability (≥10 objects over a FoV of a few arcmin) with intermediate spectral resolution (R≈20,000) sampling the full spectral range from 0.37-2.5 μm.

- In the context of galaxy formation and cosmology, one of the most exciting prospects for HIRES is the detection of elements synthesized by the first stars in the Universe. HIRES will probably be the first facility that will detect the fingerprint of PopIII stars by measuring the chemical enrichment typical of this population in the IGM and Inter-Stellar Medium in the foreground of Quasars, GRBs and Ultraluminous Supernovae at high redshift, probing in this way the epoch of reionization. The high spectral resolution of HIRES will also allow astronomers to trace in detail the history of the reionization process of the Universe and the subsequent thermal history of the IGM. To reach these outstanding science goals requires a spectral resolution R>50,000 and a spectral coverage extending from about 0.6 to 2.5 μm. If enabled with some multiplexing capability (5-10 objects), HIRES will also be able to obtain a three-dimensional map of the cosmic web of the IGM at high redshift, by probing absorption systems towards multiple lines of sight on scales of a few arcminutes. Most importantly, if the simultaneous wavelength coverage extends from 0.4 to 2.5 μm HIRES will have the unique and exceptional capability of obtaining a three-dimensional map of the distribution of metals in the IGM, which would be a unique probe of the enrichment process of the Universe. For this science case a spectral resolution in the range 10,000-15,000 is optimal.

- The same intermediate spectral resolution, wide simultaneous spectral coverage and multiplexing of 5-10 over a field of view of a few arcminutes are also required to investigate the processes driving the evolution of massive early type galaxies, during the epochs of their formation and assembly (z=1-3), which is still a major unsolved puzzle beyond reach of current facilities.

- If equipped with an IFU sampling the E-ELT diffraction limit, HIRES, with its high spectral resolution (R≈100,000) will be the only tool to measure the low mass end of supermassive black holes in galactic nuclei, which bears signature of primordial black hole seeds.

- Most excitingly perhaps, HIRES will be an instrument capable of addressing issues that go beyond the limited field of Astronomy, breaking into the domain of "fundamental physics". In particular, HIRES will provide the most accurate constraints on a possible variation of the fundamental constants of nature, and in particular of the fine structure constant and of the proton-to-electron mass ratio μ. This measurement will be enabled by a spectral resolution R≈100,000, and high efficiency in the blue part of the spectrum. HIRES will also deliver the most accurate measurement of the deuterium abundance that, compared with the value obtained from the CMB measurements (from Planck), will provide stringent constraints on models of non-standard physics. By measuring the redshift drift-rate dz/dt of absorption features in distant QSOs, HIRES will be the only instrument capable of obtaining a direct, non-geometric, completely model-independent measurement of the Universes expansion history (the ”Sandage test”). This should be regarded as (the beginning of) a legacy experiment, lasting several decades, giving substantial additional value to projects primarily targeting the physics of the IGM with QSO absorption spectra. However, in addition to high-spectral resolution (R≈100,000), this measurement requires a very accurate absolute wavelength calibration of a few cm/s (which can be achieved with laser comb technology and high fiber scrambling efficiency) as well as excellent stability, of the order of a few cm/s, over the duration of an observing night.

3 Instrument Concept

The various science requirements can be met through a highly modular instrument concept, where optimized independent modules enable different observing modes and give access to different wavebands. A modular concept has several advantages.

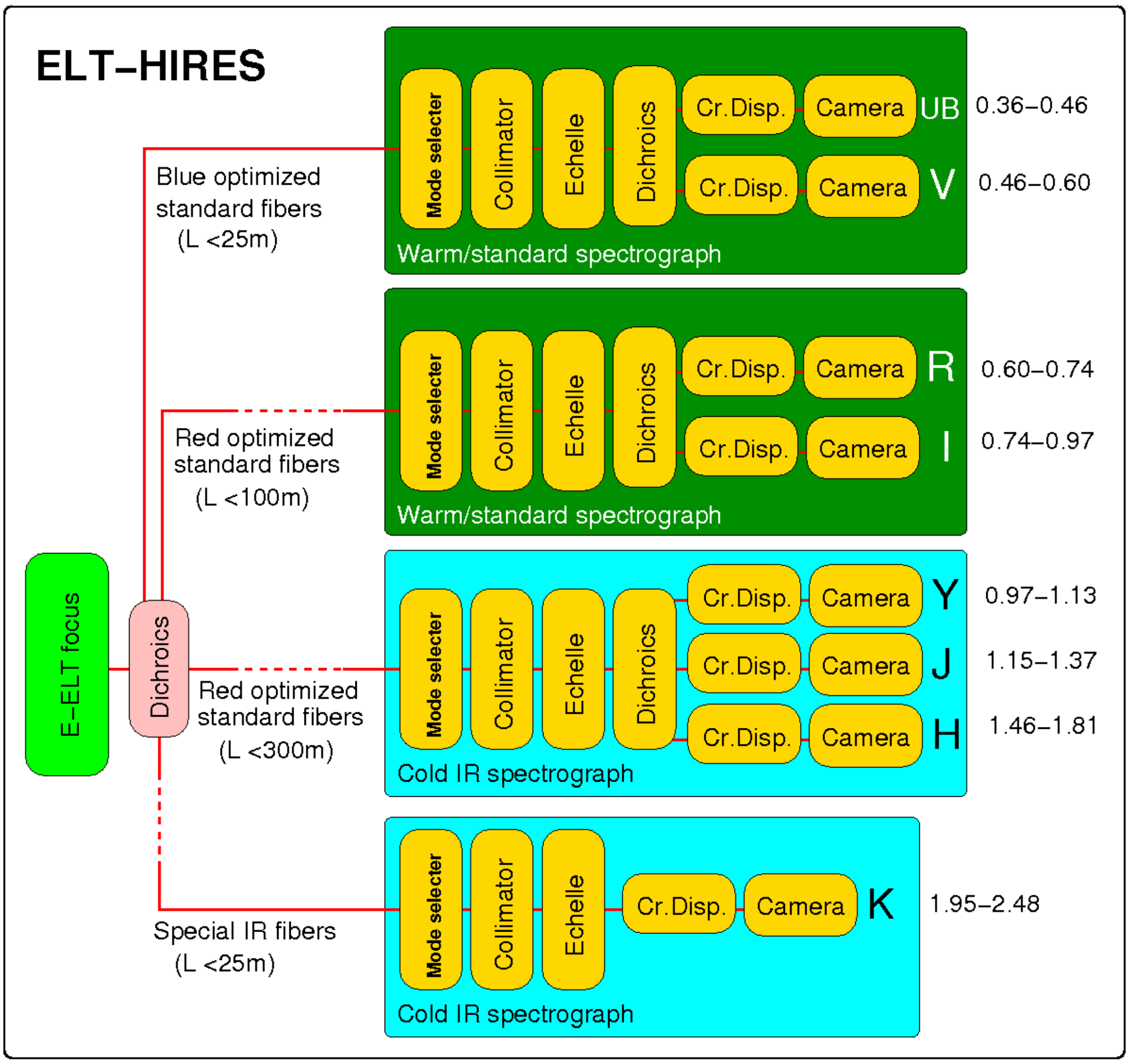

Fig. 1. Possible scheme showing the distribution of the spectroscopic modules for HIRES.

It can be developed in sequential stages, starting with the essential and highest-priority modules, and later upgrading of the instrument with additional less time-critical modules, depending on budget and resources. It reduces the overall risks associated with the project. Technical problems associated with an individual module do not delay the delivery of the other independent modules and their implementation as well as their manteinance at the telescope. Similarly, shortfalls of funding or resources experienced by one of the consortium partners will only affect the respective module this partner is involved in, and does not prevent the other partners to keep to the delivery schedule of the other modules.

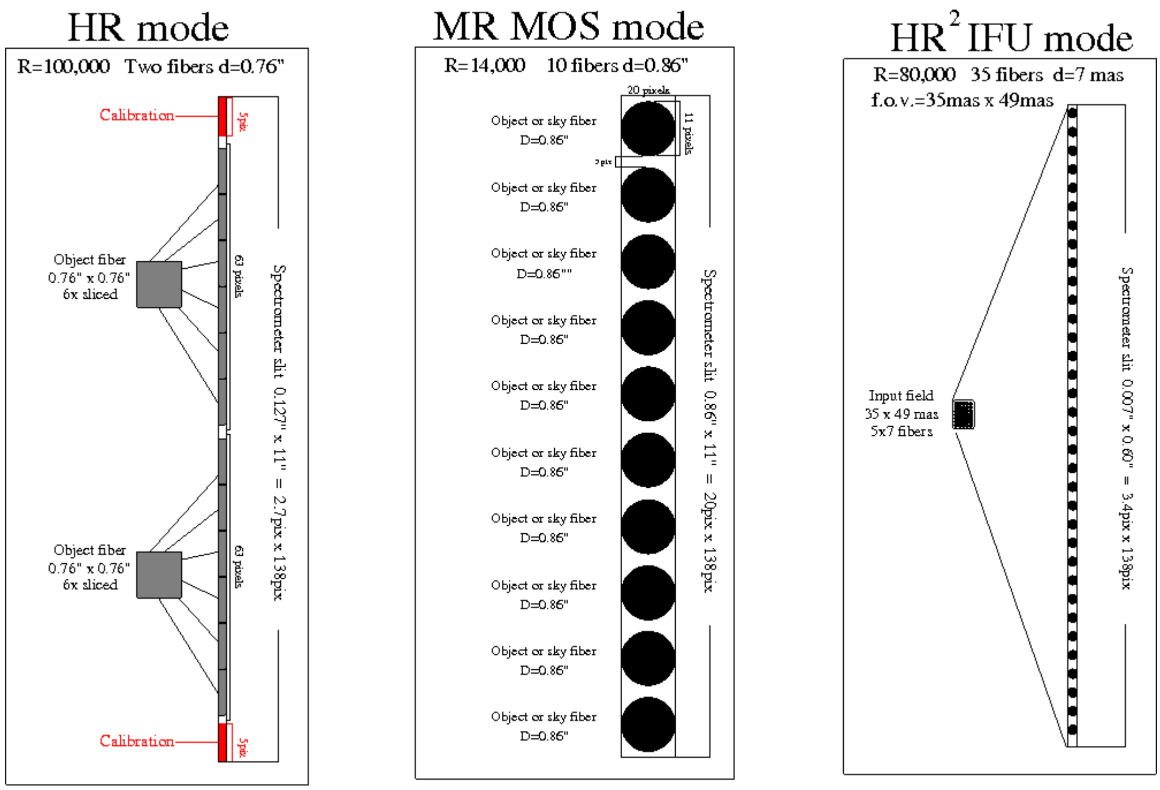

Fig. 2. Illustration of the different possible illuminations of the spectrometer pseudo-slit through different set of fibers.

We propose here that such a modular and versatile system can be realized by a system of fibers that feed simultaneously (through dichroics) different, independent spectrometers optimized for different wavebands. Each spectrometer is fed by fibers optimized for the respective wavelength range.

Such a fiber-fed design provides a natural solution for the implementation of the different observing modes discussed in the science case (high-resolution, moderate multiplexing at intermediate resolution and high spectral and spatial resolution with an IFU assisted by AO. The different modes are obtained by feeding the pseudo-slit in the focal plane of the spectrometers with systems of fibers deployed in different spatial configurations.

Fig. 1 shows a possible scheme of the modular concept: up to four, totally independent spectrometers, optimized in the UB+V and R+I bands and (cryogenic) in the Y+J+H and K bands, fed by a set of optimized fibers. We note that the standard telecommunication (low-OH) fibers in the YJH bands (0.9-1.8 μm) are so transparent that they can be up to 300m long, without affecting the performance of the system. Hence this spectrometer can be accommodated nearly anywhere in the telescope enclosure. The fibers for the blue and K bands, instead, need to be shorter than about 25m to have good throughput, implying that these spectrometers would probably have to sit on one of the Nasmyth platforms.

Fig. 2 shows how the different observing modes can be realized leaving the optics and gratings within the spectrometers fixed, by simply changing the pseudo-slit illumination through a different deployment and feeding of the fibers.

In the basic "high-resolution mode", the light is collected from the telescope by two ≈0.8 arcsec fibers, one for the object and the other for the sky or calibration (a three fibers system can be envisaged, with two fibers allocated for the sky, so to reduce the sky photon noise). A calibration spectrum is always simultaneously recorded at the top and bottom of the pseudo-slit. The light from the fibers is sliced into 2x6 rectangular images aligned along the spectrometer pseudo-slit. Only with the slicing technique is it possible to achieve the required spectral resolution (R≈100,000) with a relatively "small" grating (≈1.2m in size) because the observations are seeing-limited.

In the medium-resolution mode with moderate multiplex the light is collected from the focal plane of the telescope by 10 fibers (≈0.9 arcsec in diameter), without any slicing. The fibers images are directly arranged onto the pseudo-slit of the spectrometer. Without changing anything within the spectrometer, this setup automatically delivers a spectral resolution of about 15,000. The ten fibers can be all allocated to targets or, for faint objects, half of them can be allocated to the sky. This mode, because of its simultaneous full spectral coverage from U to K, is eventually complementary to the observing modes foreseen by the E-ELT MOS instrument.

A high spectral and spatial resolution IFU mode can be realized with a bundle of fibers fed at the focal plane of a dedicated Single Coniugate AO module, or at the focus of an already existing AO module (e.g. MAORI). The size of the individual fibers would match the diffraction limit in the preferred near-IR band. Inside the spectrograph, the images of the individual IFU fibers would be deployed along the pseudo-slit of the spectrograph. This mode, because of its high spectra resolution (R≈80,000) is eventually complementary to the observing modes foreseen by the E-ELT IFU instrument.

The different observing modes can be selected by a system of two mirrors that relay the light from the different set of fibers to the pseudo-slit of the spectrometer. The system can be realized in such a way that the basic high-resolution mode is the one feeding directly the spectrometer without any relay-mirror. This guarantees that the stability of this basic mode is not affected by the presence of the other observing modes. The other two modes (medium-resolution with moderate multiplexing and IFU+AO), which do not have stringent stability constraints, are enabled by swapping relay mirrors into the beam.

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