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ANDES, the high-resolution spectrograph for the ELT: Project overview, future developments and science goals

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Summary. — ANDES is the high-resolution spectrograph for the ESO ELT. It comprises three fiber-fed spectrographs (UBV, RIZ, YJH), providing a spectral resolution of approximately 100000 with a minimum simultaneous wavelength coverage of 0.4–1.8 μm (goal 0.35–2.4 μm). ANDES operates in both seeing- and diffraction-limited conditions, with various, interchangeable observing modes, including a diffraction-limited integral field unit in the near-infrared. The ANDES project encompasses a wide range of groundbreaking science cases spanning almost all areas of astrophysics and even fundamental physics including the detection of biosignatures from exoplanet atmospheres, the identification of the fingerprints of the first generation of stars, tests on the stability of Nature's fundamental couplings, and the direct detection of the cosmic acceleration. The ANDES project is spearheaded by a large international consortium, led by INAF, comprising 35 institutes from 13 countries, forming a team of nearly 300 scientists and engineers. This team represents the majority of the scientific and technical expertise in the field among ESO member states.

1. – Introduction

At first light in 2028, the European Extremely Large Telescope (ELT) will emerge as the largest ground-based telescope, equipped to observe visible and infrared wavelengths. The ELT's construction was supported by two groundbreaking scientific cases: the detection of life signatures in Earth-like exoplanets and the direct observation of the cosmic expansion's reacceleration. Both cases demands high-resolution spectroscopy. Moreover, the European Southern Observatory (ESO) community has a rich experience in this field, evident in the suite of instruments developed at ESO, including UVES, CRIRES, and ESPRESSO. ESO therefore decided to include a High-Resolution Spectrograph (HIRES) in the ELT instrumentation roadmap. HIRES aimed to provide a resolution of $R \sim$100000 across the entire UV, optical, and near-infrared (NIR) wavelength range. In 2016–2018, the HIRES Consortium conducted a successful Phase A study for ESO, paving the way for several pre-Phase B activities. These activities culminated in the ESO Council's approval of the Construction of HIRES in December 2021. The instrument underwent a name change to ANDES (ArmazoNes high Dispersion Echelle

Spectrograph, `https://andes.inaf.it`). ANDES commenced Phase B in September 2022, and construction officially started in June 2024 with the ultimate goal of delivering ANDES to the ELT in 2032.

2. – Science goals

2·1. *Exoplanets and protoplanetary disks.* – The primary objective of ANDES in the study of exoplanets is to characterize their atmospheres. By leveraging its high-resolution and wide simultaneous spectral range, ANDES will detect molecules such as O_2, CH_4 and H_2 that can provide crucial insights into a planet's composition, climate, and potential for biological processes, which indicate potentially habitable environments and signs of life. During transits, transmission spectroscopy will isolate these molecular signatures in starlight filtered by an exoplanet's atmosphere. Crucially, ANDES's ability for diffraction-limited spatially resolved ovservations also enables the detection of reflected starlight from non-transiting planets. Small, rocky planets such as TRAPPIST-1 and Proxima Cen b represent high-priority targets for transmission and reflection spectroscopy, and molecules can be detected in short amounts of times, from a few hours to several days. The instrument will further shed light on protoplanetary disks, the birthplaces of planets. By resolving forbidden lines of atomic and ionized species, ANDES will trace gas in inner disk regions and differentiate bound disk gas from outflows. Such observations will advance our knowledge of disk evolution and dissipation, crucial for understanding planet formation timelines. A detailed description of the science objectives in this field is provided in the white paper by Palle *et al.* [1].

2·2. *Stars and stellar populations.* – ANDES, with its high spectral resolution and broad wavelength coverage, is crucial for studying stellar populations. It will enable the detection of faint spectral lines, determine stellar ages, and map the age distribution across the Galactic bulge. ANDES will also provide insights into the formation and evolution of the first stars and the progenitors of supernovae in dwarf galaxies. This comprehensive approach to stellar archaeology will refine our understanding of early cosmic epochs, galactic assembly, and stellar evolution as shown by Roederer *et al.* [2].

2·3. *Galaxy formation and evolution and the intergalactic medium.* – ANDES will revolutionize our understanding of galaxy evolution and of the intergalactic medium (IGM). During the Epoch of Reionisation, the neutral hydrogen in the universe became ionized by the first luminous sources. By measuring Lyman-α and Lyman-β forest features with unprecedented sensitivity in the spectra of high-redshift quasars and gamma-ray bursts, ANDES will map the distribution of ionized and neutral regions, revealing the topology of reionisation and the role of early galaxies and stars. In addition, ANDES's ability to detect metal absorption lines at high redshift will illuminate the chemical enrichment history of the IGM, showing how elements produced in the first supernovae spread through the young universe and revealing the signatures of the elusive Pop III stars. Beyond reionisation, ANDES will study extragalactic transients, such as superluminous supernovae and gamma-ray bursts, shedding light on the extreme environments of early galaxies. These breakthroughs will substantially deepen our understanding of the universe's formative epochs, see D'Odorico *et al.* [3] for a detailed description of these science cases.

2·4. *Cosmology and fundamental physics.* – ANDES will push the boundaries of cosmology and fundamental physics: first, it will refine Big Bang Nucleosynthesis constraints

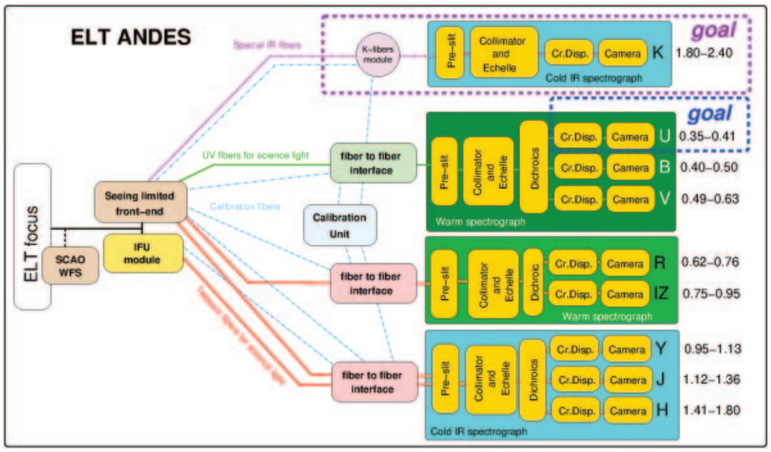

Fig. 1. – ANDES architectural design, outlining the instrument subsystems: Front End (seeing-limited and AO assisted with SCAO unit), Fibre Link, Calibration Unit, UBV, RIZ, YJH and K (cold spectrographs).

by precisely measuring abundances of light elements, such as deuterium and helium, to test the Standard Model and probe new physics. Second, ANDES will measure the CMB temperature evolution at different redshifts, checking for deviations that hint at novel phenomena or varying physical constants. Indeed, a central goal is to test the stability of key constants, like the fine-structure constant and proton-electron mass ratio, by comparing atomic transitions in distant absorbers. Any detected variation would challenge current physical theories. ANDES also enables long-term monitoring of redshift drift (the Sandage-Loeb test), offering a direct, model-independent look at cosmic expansion acceleration. By measuring tiny changes in quasar absorption lines over decades, it will tighten constraints on cosmological models, as shown by Martins *et al.* [4].

3. – Instrument concept

The ANDES baseline design is for a modular fiber-fed cross-dispersed echelle spectrograph with three ultra-stable spectral arms: (U)BV, RIZ, and YJH. These arms provide a simultaneous spectral range of 0.4–1.8 μm at a resolution of ∼100000. The goal is to extend the wavelength range to 0.35–2.4 μm by adding a U extension and an additional K spectral arm. The instrument can operate in both seeing-limited and SCAO (Single Conjugated Adaptive Optics) modes. The seeing-limited mode will be unique among the ELT suite of instruments and will allow observations even in poor atmospheric conditions or with poor phasing of the ELT mirrors. In SCAO mode, the instrument uses a small IFU with at least two selectable spaxel scales (only in the YJH arm, with the RIZ arm as a goal). The expected limiting magnitude for seeing-limited observations is $m_{AB} = 20$ in 1 hour with a signal-to-noise ratio (SNR) of 10 per resolution element. Simulations can be performed using the live exposure time calculator (ETC) maintained by INAF-Arcetri at `https://andes.inaf.it/instrument/exposure-time-calculator/`.

The proposed baseline of the system is depicted in fig. 1, which offers a simplified representation of the functional architecture and highlights the modularity level selected for the instrument. The primary subsystems that make up the instrument are presented as boxes, connected by fibers or fiber bundles that facilitate the transmission of light from the ELT focus and from the Calibration Units (CUs) to the various Spectrographs sit-

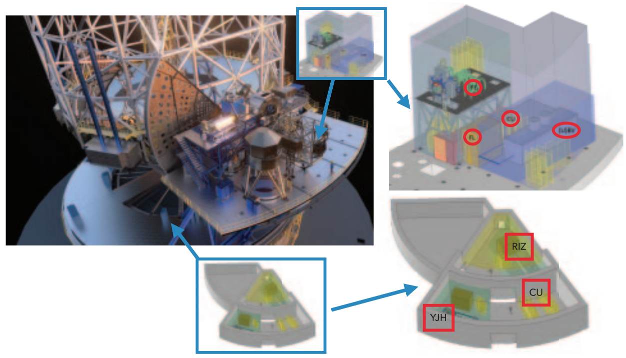

Fig. 2. – Overall and detailed views of ANDES Nasmyth and Coudé parts in the case the instrument is not entirely placed on the Nasmyth platform.

uated in different locations within the Telescope Infrastructure, the Nasmyth Platform, and the Coudé room. If sufficient volume and mass are available, the entire instrument can be accommodated on the Nasmyth platform. Alternatively, the (U)BV and K modules can be placed on the Nasmyth platform, while the remaining modules will be housed in the Coudé Room (as illustrated in fig. 2).

4. – Consortium, cost estimates and schedule

The ANDES Consortium comprises institutes from 13 countries, including Brazil, Canada, 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 institution. The complete list of institutes is available at `https://andes.inaf.it/consortium/`. In total, the consortium comprises 35 institutes. The large number of institutes involved in the Consortium reflects the widespread scientific and technical interest in a high-resolution spectrograph for the European Large Telescope (ELT) among the astronomical community globally. Notably, the Consortium comprises the majority of the high-resolution community in ESO member states. Furthermore, Consortium Institutes have a proven track record in building high-resolution spectrographs, including most of the institutes that constructed the high-resolution spectrographs for ESO telescopes.

The current estimate of the overall hardware costs, excluding contingencies, is around 45 MEUR. The project will require approximately 650 FTEs, including contingencies, to complete. The FTEs will be compensated with 65 nights of GTO, while hardware costs will be compensated with a minimum of 60 GTO nights. These GTO nights will be utilized for joint Consortium science programs. The current Project schedule anticipates that ANDES will be available at the telescope in 2032. It is worth noting that the Consortium will conduct subsystem reviews in October 2024 to March 2025 to prepare a PDR in October or November 2025, thereby minimizing potential delays.

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