SIMPLE: A High Resolution Near-infrared Spectrograph for the E-ELT

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SIMPLE is an optimised near-infrared spectrograph designed to deliver a complete 0.84–2.5 μm spectrum with resolution up to R = 130 000 and limiting magnitudes to JHK ~ 20. Its most prominent science cases include the study of the intergalactic medium in the early Universe (at $z > 6$) and of the atmospheres of exoplanets transiting nearby low-mass stars.

Science drivers

High resolution infrared spectroscopy is one of the youngest branches of astronomical research with a huge scientific potential. It is opening new windows in our understanding of several hot topics of modern stellar and extragalactic astrophysics, and it will have a major impact in the JWST and ALMA era and beyond.

Quantitative spectroscopy of key absorption lines in intrinsically red (cool stars and planets), reddened (protoplanetary discs, stellar populations in the inner Galaxy) or red-shifted (high-z Universe) targets requires a spectral resolution R ~ 100 000 over the 0.84–2.5 μm spectral range. However, high spectral resolution of faint objects at optical and NIR wavelengths can only be performed using large telescopes. At a resolution of R ~ 100 000 the sky and thermal backgrounds are quite low, even in most of the K-band. Since the targets (either compact sources or sub-structures) are typically smaller than the spectrometer entrance aperture (which is about diffraction-limited) regardless of the telescope size, the limiting flux observable with a given signal-to-noise (S/N) scales with the square of the telescope aperture. This implies a limiting magnitude about 3.5 magnitudes fainter than any other current or planned NIR high resolution spectrometer at 8–10-metre telescopes.

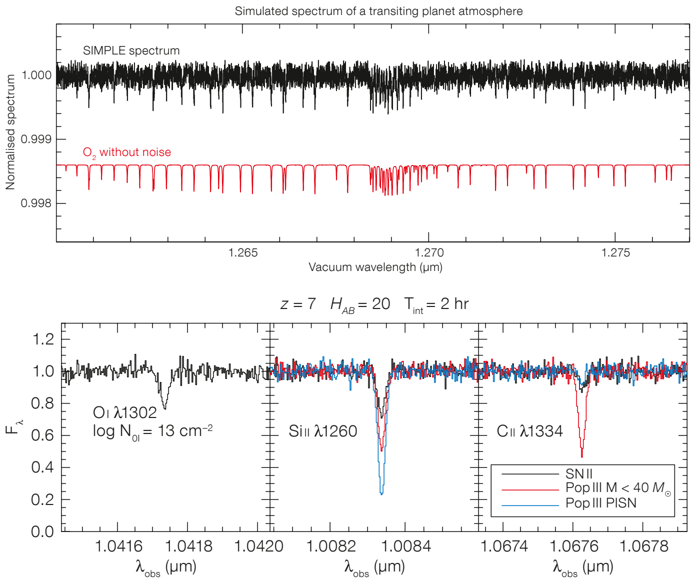

Figure 1. Top panel: expected J-band spectrum at R ~ 100 000 of the O_2 lines, for a transiting planet with an atmosphere cross-section of 6×10^{-4}. Bottom panel: SIMPLE 2-hour simulation of absorption systems at $z = 7$ in the foreground of a quasar with $H_{AB} = 20$, for different abundance patterns of the intervening proto-galaxy. The black line is for abundances typical of SN II; the red line is for abundances expected from Population III stars with masses $M < 40\ M_{\odot}$, while the blue line is for abundances from Population III Pair Instability SNe.

This huge jump in sensitivity will place a NIR high resolution spectrometer at the E-ELT at the forefront in the astronomical context of the next two decades. SIMPLE has two major aims:

1. To characterise the atmospheres of exoplanets and detect signatures of life. High spectral resolution studies can be performed on planetary systems with cross-sections exceeding 3×10^{-4} (see Figure 1), i.e. on planets with extended atmospheres (> 100 km) down to the Earth-size, or on massive planets (super-Earths, Neptunes) with less expanded (< 50 km) atmospheres. Small planets with more normal atmospheres (such as ocean planets or Earth/Venus planets) are most challenging, but the chemical composition of their atmospheres can still be investigated by applying an adaptive rebinning of the individual molecular lines in their high resolution spectra. A number of surveys are specifically dedicated to the search for transiting exoplanets and strong synergies are also expected with, e.g., Kepler, EPICS and CODEX for planet search and classification, and with METIS, which can provide complementary information from mid-IR spectra. A potential competitor is JWST, but according to simulations, SIMPLE outperforms JWST because of the much larger telescope aperture of the E-ELT and of the higher spectral resolution for measuring the intrinsically narrow lines.
2. To detect the signature of the "first light" sources in the early Universe i.e. Population III stars (see, e.g., Figure 1). SIMPLE will provide high S/N, high resolution absorption spectra of QSOs and GRBs at, or beyond, the reionisation epoch, thus tracing the early chemical enrichment and dust content of proto-galaxies along their line of sight. Targets (mostly QSOs at $z > 6.5$) will be provided by ongoing and planned NIR surveys (VISTA, PanSTARRS, Euclid/SNAP). While SIMPLE will be unique in detecting the chemical fingerprint of the first light galaxies in absorption, JWST and other ELT instruments (HARMONI and EAGLE) will provide complementary information by searching for Population III signatures in emission.

The high spectral and angular resolution, and high S/N delivered by SIMPLE will also be crucial to obtain: a) detailed chemical abundances of the key metals, and their isotopes, and kinematics with accuracy better than 1 km/s for cool stars and stellar clusters; b) accurate radial velocities down to 1m/s to search and characterise exoplanets (and in particular rocky planets) around low mass stars; c) spectro-astrometry of the inner structure of protoplanetary discs tracing the early phases of planet formation; d) magnetic fields and astro-seismology; e) molecular tracers of stratification in the atmospheres of Solar System moons. The much-reduced extinction in the IR also allows SIMPLE to pierce the dust embedding several Galactic and extragalactic objects, which are heavily obscured in the optical, and, for example, to characterise the stellar populations of the Galactic Centre, including the study of relativistic effects in the stars orbiting the supermassive black hole.

The scientific requirements of SIMPLE yielded an instrument concept that includes and optimises two distinct observing modes, namely:

1. Single-object. This mode must deliver the full 0.84–2.5 μm spectrum in a single exposure, providing the highest possible sensitivity, spectral quality and stability;

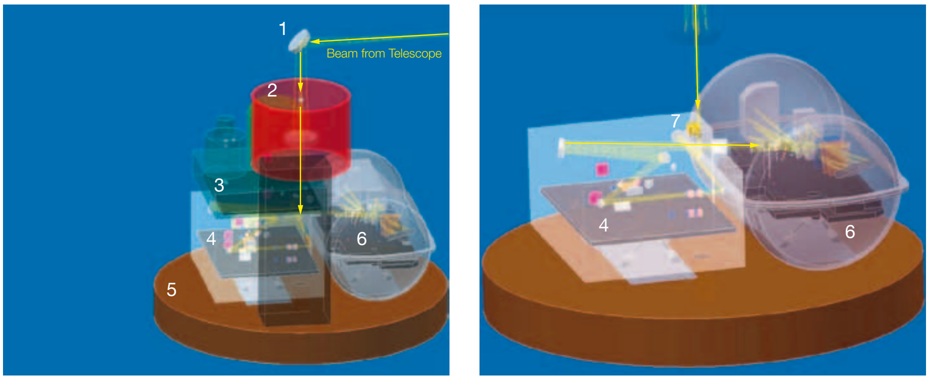

Figure 2. 3D views of SIMPLE identifying the subsystems, the optical path and the sub-modules of the pre-slit and spectrometer.

1 Fold mirror fixed relative to Nasmyth platform
2 Re-imager and guider module
3 SCAO–WFS module
4 Pre-slit module
5 Derotator
6 Cryogenic spectrometer
7 Calibration unit

2. Long-slit. This mode does not require full spectral coverage, but must provide optimised image quality along the slit with a spatial sampling of 9 mas/pixel or smaller.

While truly unique in terms of performance, capabilities and scientific expectations, the concept we propose is a relatively simple instrument (hence the name) exploiting known technologies, which translate into a relatively low risk facility, suitable for early operation at the E-ELT and capable of delivering major scientific results from the early operation phase onwards.

Instrument design concept

SIMPLE consists of a canonical cross-dispersed echelle spectrometer whose slit width is a few times the diffraction limit at the longer wavelengths (*K*-band), i.e. its design is independent of the telescope diameter (Oliva & Origlia, 2008). It is a single channel system with fixed, all-mirror optics. The collimated beam has a diameter of 180 mm and the disperser is a commercial R2 echelle grating. Therefore, the required resolving power of R = 130 000 is achieved with a slit width of 27 mas, equivalent to 2.5 × λ/D in the *K*-band. The spectrometer can cover the whole 0.84–2.5 µm range in one exposure because it employs prisms as cross-dispersers. It delivers a complete cross-dispersed spectrum on a mosaic of three 4k × 4k array detectors. The slit length in this mode is limited to 0.45 arcseconds, to avoid order overlap. The long-slit (4-arcsecond) mode requires a dedicated order-sorter device included in the pre-slit system. Four slits of different widths are available: 27 mas (R = 130 000); 36 mas (R = 100 000); 54 mas (R = 67 000); and 72 mas (R = 50 000). The slits are at a fixed position inside the spectrometer and are selected by sliding a dekker/mask, which is also used to switch between the long-slit and full-spectrum modes. The dekker unit is the only moving part at cryogenic temperatures.

The spectrometer requires a good level of AO correction to concentrate the light into the slit and maximise throughput. To properly quantify this requirement, we define the slit efficiency parameter (SLE), which measures the fraction of light falling within the 27 × 54 mas aperture used to extract the spectrum in the baseline observing mode with R = 130 000. SIMPLE on the E-ELT with a poor AO correction (SLE < 0.03) would achieve similar limiting magnitudes as the same spectrometer mounted on the VLT. Therefore, to take proper advantage of the telescope area, the minimum requirement is SLE > 0.1 over most of the wavelength range. LTAO/MCAO matches the requirements, while GLAO is unable to concentrate enough light, even when using an image-slicer. On-axis SCAO correction with 42 × 42 sub-apertures provides performance very similar to LTAO/MCAO down to *JH*-band limiting magnitude ~ 12.

The instrument design consists of subsystems (see Figure 2) that are well separated both from the logical and physical point of view:
- the spectrometer, which includes the slit and the optical elements necessary to collimate, disperse and re-focus the light onto the detector. It operates in a vacuum–cryogenic environment cooled by liquid nitrogen. It can be divided into two main modules, namely the cryostat and the optical bench carrying the spectrometer optics;
- the pre-slit, which is refrigerated to –30 °C and includes a pupil stop, an acquisition camera and slit viewer and selectable sub-modules for the different observing modes, i.e. an ADC, a fibre scrambler and a polarimeter;
- an infrared (0.9–2.1 µm) SCAO WFS that uses the light from bright (*JH*-band < 12) targets and includes a pupil-steering mirror, a viewing/tracking camera at an intermediate focus, a fast (up to 1 kHz) modulation mirror, and two selectable cameras to switch between the 42 × 42 and 84 × 84 sub-aperture modes. The splitting between scientific-light (transmitted) and WFS-light (reflected) is made by means of selectable beam splitters with parameters optimised for the different scientific cases;
- a calibration unit; and
- a re-imager and guider module, including a small (360 mm diameter) telescope, which creates an intermediate F/36 focal image 1 metre below its primary mirror.

The instrument is mechanically separated from the LTAO/MCAO module and collects the light far (~ 3 m) beyond the F/17.7 focus. The instrument can be positioned on the Nasmyth platform at any focal station. Should no LTAO/MCAO module be available at the beginning of E-ELT observations, SIMPLE can be mounted at a "naked-focus" and operate as a first-light instrument for all those observations that can be performed with SCAO–WFS correction. Notably, these include the scientifically prominent programme aimed at the detection of molecules in the atmospheres of planets transiting in front of their parent star (see Figure 1).

Performance

The total instrument efficiencies are remarkably high, ranging between 20 % (*I*-band) and 40 % (*K*-band), because the instrument optics is mostly composed of mirrors whose high throughput is guaranteed by protected Ag coating. A dedicated exposure time calculator for the instrument was developed and made publicly available on the SIMPLE web page[1]. Limiting *JHK*-band Vega-magnitudes of ~ 20–21 (S/N ~ 10) and 17–18 (S/N ~ 100) can be obtained with an on-source integration time of two hours at the maximum resolving power of 130 000.

References

Oliva, E. & Origlia, L. 2008, SPIE, 7014, 70141O

Links

[1] http://simple.bo.astro.it