CODEX: An Ultra-stable High Resolution Spectrograph for the E-ELT

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CODEX is the proposed optical high resolution spectrograph for the E-ELT. Designed to make the most of the unique light-gathering power of the E-ELT and to obtain superb stability, CODEX will open up a new parameter space in astrophysical spectroscopy. The wide-ranging science case has a large discovery potential in stellar, Galactic and extragalactic astronomy as well as in fundamental physics.

Science drivers

The concept and science case for an ultra-stable high resolution spectrograph at a giant telescope was first analysed in the context of an OWL study (Pasquini et al., 2005). It was found that photon-hungry high-precision spectroscopy will particularly benefit from the enormous light-collecting power of the E-ELT and will enable some new, truly spectacular science. In the Phase A study for CODEX, a science case and instrument design have been fully developed. Five scientific showcases that highlight the abilities of CODEX and cover a wide range of subject areas are presented; a more exhaustive description of CODEX capabilities is on the web[1].

– *Detecting and measuring the cosmological redshift drift of the Lyman-alpha forest — a direct measurement of the accelerating expansion of the Universe.* The cosmological redshifts of spectroscopic features originating at large distances are the signature of an expanding Universe. As the expansion rate changes with time, a corresponding change in redshift is expected. This is a very small effect, but measurable with CODEX if the collective signal in a large number of absorption features is monitored for 30 years (see Figure 1). The most favourable target is the multitude of absorption features making up the Lyman-alpha forest in quasar absorption line spectra.
– *Detection of Earth twins in the habitable zone of solar-type stars.* The search for extra-solar Earth-like planets that could sustain life catches the imagination of scientists as well as that of the general public. The 2 cm/s accuracy of CODEX constitutes a factor of about 20 improvement compared to current instruments. With this accuracy it will be possible to assemble and study sizeable samples of Earth-like planets in the habitable zone of their parent stars (see Figure 2).
– *Galactic archaeology: unravelling the assembly history of the Milky Way with nucleochronometry.* How did galaxies assemble and come to look the way they do? Much has been learned from our own Galaxy, which we can study in fine detail. Weak features of rare isotopes in stellar spectra can be studied to new limits with CODEX, and nucleochronometry — the equivalent of dating materials on the Earth using radioactive nuclides — will become an accurate quantitative tool yielding precise age determinations of stars.
– *Probing the interplay of galaxies and the intergalactic medium from which they form.* The formation of the first autonomous sources of radiation, stars and black holes, led to the heating, reionisation and pollution of the intergalactic medium (IGM) with metals. The sensitivity of CODEX to trace amounts of metals in the low density IGM thus opens a window into this important period in the history of the Universe, enabling the study of the interplay of galaxies and the IGM from which they formed in unprecedented detail.
– *Testing fundamental physics — taking the test of the stability of fundamental constants to new limits.* It has long been speculated that the fundamental constants vary in space or time or both. The discovery of such variations would be a revolutionary result leading to the development of new physics. The current evidence for small variations of the fine structure constant on cosmological timescales from studies of QSO absorption line spectra is intriguing but rather controversial. CODEX will enable tests of the stability of fundamental constants to greatly improved new limits.

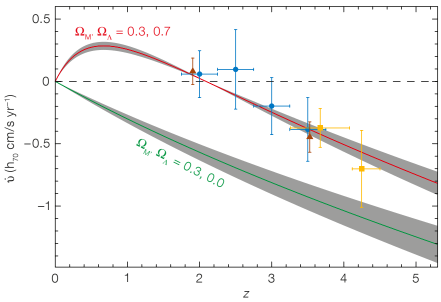


Figure 1. Monte Carlo simulations of three different implementations of a redshift drift experiment. Plotted are values and errors of the "measured" velocity drift $\dot{\upsilon}$, expected for a total experiment duration of 30 yr and a total integration time of 4000 h. See Liske et al. (2008) for more details.

A high Strehl ratio imager at the E-ELT will be capable of directly detecting some of the more massive planets discovered by CODEX. The combination of these instruments will provide the E-ELT community with a full characterisation of the planetary orbits as well as atmospheres, true masses and temperature. CODEX will also follow up Earth-sized exoplanet candidates discovered by space missions and ground-based transit searches. Confirmation of the planetary origin of the photometric transit and accurate measurements of the mass of the transiting body require a radial velocity (RV) precision of a few cms^{-1}, which CODEX will provide. Gaia will provide accurate physical stellar parameters enabling the positions of stars in the Hertzsprung–Russell diagram to be compared with those derived by CODEX from nucleochronometry and asteroseismology. Also high-redshift molecular rotational absorption lines discovered by ALMA and H I 21 cm absorption detected by SKA can be compared to optical metal lines observed with CODEX to constrain various combinations of constants involving the fine structure constant (α), the proton-to-electron mass ratio (μ) and the proton *g*-factor.

Instrument design concept

The top-level technical specifications have been derived from the requirements set by the main science cases (see Table 1). Given the high-precision aim of the instrument, the spectrograph should be located at the coudé focus, as this is the quietest (mechanically and thermally) environment available. At the coudé focus a guiding and tip-tilt correcting system accurately centres the object light into the 500 μm diameter fibre core, which guides the light into the spectrograph vessel. In the fibres the light is scrambled in order to make the output signal independent of variations at the

Figure 2. Expected planet population detected by Doppler spectroscopy with HARPS on the ESO 3.6-metre (precision 1 ms^{-1}; left), ESPRESSO on the VLT (precision 10 cms^{-1}; middle) and CODEX on the E-ELT (precision 1 cms^{-1}; right). CODEX is required to detect Earth-like planets in the habitable zone of solar-type stars (green rectangle).

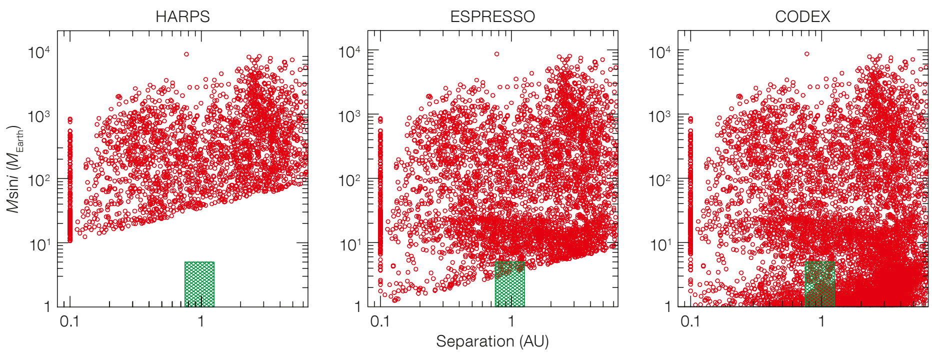
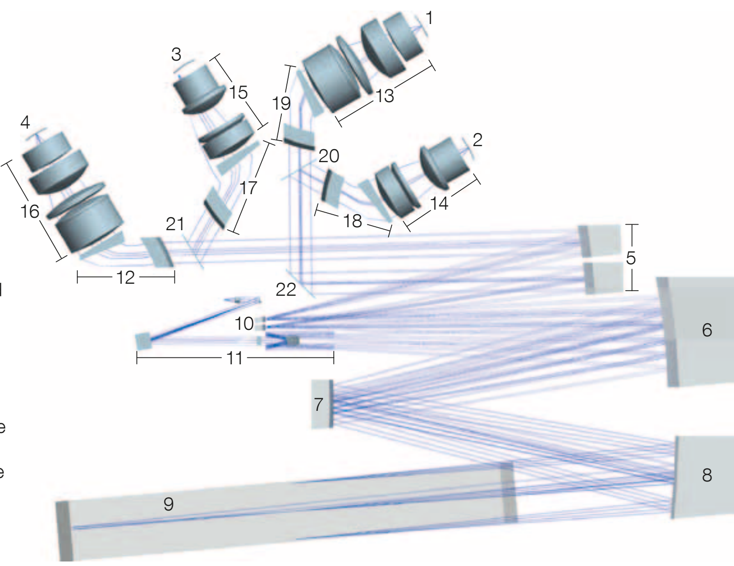


Table 1. Brief summary of CODEX characteristics.

Aperture on the sky	0.82 arcsecond, with a 500 µm fibre
Wavelength range	370–710 nm, in two arms: Blue 370–500 nm; Red 490–710 nm
Doppler precision	< 2 cms^{-1} over 30 years
Wavelength precision	< 1 ms^{-1} (absolute)
Resolving power	120 000 for square fibre, ~ 135 000 for circular fibre
Echelle	R4, 41.6 l /mm, 1700 × 200 mm, 4 × 1 mosaic
Detector focal plane	Four CCDs (9k × 9k 10 µm pixels) (2 in Blue Camera, 2 in Red Camera)
Total efficiency	28.8 % (max.), 14.5 % (min.) slit losses not included

Figure 3. Optomechanical design of CODEX is shown.

1 Red Detector 1
2 Blue Detector 1
3 Blue Detector 2
4 Red Detector 2
5 Mount (T2–1&2)
6 Mount M1
7 Mount M2
8 Mount M3
9 Mount Echelle
10 Mount (T1–1&2)
11 Anamorphic Pupil Slicer Unit (mount)
12 Mount (T3/21 + Red VPGH/2)
13 Red Camera 1
14 Blue Camera 1
15 Blue Camera 2
16 Red Camera 2
17 Mount (T3/22 + Blue VPGH/2)
18 Mount (T3/12 + Blue VPGH/1)
19 Mount (T3/11 + Red VPGH/1)
20 Dichroic 1
21 Dichroic 2
22 Fold mirror



entrance. In the spectrograph the pupil is made highly anamorphic and sliced into six parts, which pass through the 1.7-metre long echelle and the collimating system of the spectrograph, after which they are divided into two separate paths (Blue and Red). Each path is imaged onto two cameras, each equipped with 9 × 9 cm CCDs. Figure 3 shows the optomechanical concept. The cross-dispersed format enables the whole range, 380–710 nm, to be covered simultaneously with 60 echelle orders and 4-pixel sampling per resolution element. Two fibres will be available, one for the object and one for the sky or simultaneous calibration. The fibres are separated by 30 pixels on the detector, which is also the minimum separation between adjacent orders.

The mechanical concept of CODEX builds on the HARPS (Mayor et al., 2003) experience to obtain the highest mechanical and thermal stability. The thermal environment is designed to be progressively more stable with 10 mK variations within the spectrograph and 1 mK variations at the CCD. No movable parts are allowed in the spectrograph vessel. The optical system is mounted on three optical benches, enclosed in a large vacuum vessel. A full scientific pipeline and a very competitive set of analysis tools will be part of the set of deliverables, allowing the main science goals of CODEX to be achieved.

Performance

The uniqueness of CODEX stems from the combination of photon-collecting capability, high resolving power and unprecedented Doppler precision. We have analysed the causes of instability in HARPS and they have been extensively addressed in our R&D programme.

- Any instability of the reference source will translate directly into radial velocity errors. The commonly used Th–Ar lamps are not sufficient for the required precision. Laser frequency combs would be the ideal calibrators. A development in collaboration with MPQ has produced very encouraging results in tests with HARPS (Wilken et al., 2010).
- The input from the astronomical source must be kept very homogeneous and stable, and a combination of accurate centring and scrambling is required. Our R&D programme on fibres has shown that square fibres produce high scrambling with minimal loss of light.
- Photons from the simultaneous calibration and from the astronomical objects are not detected by the same CCD pixels. Differential motions between pixels in the detector can produce RV errors. By testing the HARPS detectors we have shown that thermal control of the cryostat can reduce this effect to insignificant levels.

The expected signal-to-noise ratio (including slit losses of 20 %) is of 86 for V = 19 and 12 for an object with V = 22 with one-hour long observations. More than one billion potential targets will therefore be available to the CODEX user community.

References

Pasquini, L. et al. 2005, The Messenger, 122, 10
Liske, J. et al. 2008, MNRAS, 386, 1192
Mayor, M. et al. 2003, The Messenger, 114, 20
Wilken, T. et al. 2010, MNRAS, 405, L16

Links

[1] http://www.iac.es/proyecto/codex/