CODEX: Measuring the Expansion of the Universe (and beyond)

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CODEX, a high-resolution, super-stable spectrograph to be fed by OWL, the most powerful telescope ever conceived, will for the first time provide the possibility of directly measuring the change of the expansion rate of the Universe with time … and much more. The concept of this instrument has been studied in a collaboration launched by ESO in July 2004 together with INAF – Osservatorio Astronomico di Trieste, the Institute of Astronomy, Cambridge University, and the Observatoire de Genève.*

The expansion of the Universe

The discovery of the expansion of the Universe in the late 1920s by Edwin Hubble was a major milestone in cosmology. It brought to an end the belief held by most physicists of the time including Albert Einstein that the Universe is static and not evolving. Hubble's discovery of the expansion of the Universe has been confirmed by a vast range of astronomical observations. It eventually led to the widely accepted Hot Big Bang Theory, which predicts that the Universe was very dense and hot at early times, and is an essential aspect of the cosmological standard model.

Einstein's theory of General Relativity (GR) led to the description of the Universe as a homogeneous and isotropic four-dimensional space time, the so-called Friedman-Robertson-Walker (FRW) Universe. In 1922 Friedman (and independently Lemaître in 1927) found that Einstein's original equations did not allow static solutions. Ironically this prompted Einstein to "spoil" his new theory of gravity by introducing a cosmological constant to allow static solutions in his field equations. This same cosmological constant, which Einstein in his later years considered as "the biggest blunder" of his life, has now become another pillar of the modern cosmological standard model.

In the Early Universe a large vacuum energy density acting like a cosmological constant is believed to have been responsible for the rapid expansion of the Universe in a phase called Inflation. Furthermore, recent observations of the luminosity distance of Type Ia supernovae have established the presence of a form of Dark Energy which appears to have an effect similar to that of Einstein's cosmological constant within the framework of a FRW Universe.

It is possible in principle to *directly* measure the change of the expansion rate of the Universe with time. If we consider in an expanding FRW Universe the light of a source which is emitted at time t_e and received at time t_0, the change of redshift z of the source with time can be expressed as: $\dot{z} = (1+z)H_0 - H(t_e)$. The time derivative of the redshift of light emitted by a source at fixed coordinate distance is thus related in a simple manner to the evolution of the Hubble parameter $H(t_e)$ between the epoch of emission and reception. The Hubble parameter is related to the energy content of the Universe as

$$H = H_0\left[\Omega_{mat}\left(\frac{a_0}{a}\right)^3 + \Omega_R\left(\frac{a_0}{a}\right)^4 + \Omega_{de}\left(\frac{a_0}{a}\right)^{3(1+w)} + (1-\Omega_{tot})\left(\frac{a_0}{a}\right)^2\right]^{1/2}$$

where $\Omega_{tot} = \Omega_{mat} + \Omega_R + \Omega_{de}$ and Ω_{mat}, Ω_R, Ω_{de} are the energy density of matter, radiation, and dark energy expressed in terms of the critical density, respectively, and a and a_0 are the scale factor at the time t_e and t_0. The dark energy density is characterised by an equation of state of the form $p_{de} = w\rho_{de}c^2$, and $w = -1$ corresponds to the case of a cosmological constant. Note that we do not know much about the dark energy term, and its redshift dependence could well be more complicated than parameterised here by a simple equation of state. At the redshifts here considered ($z \sim 2$–5) the radiation energy density is small $\Omega_R << \Omega_{tot}$ and can be neglected. The majority of astronomical observations, most prominently those of the CMB, supernovae, Lyα forest and the clustering of galaxies are consistent with a FRW Universe with no curvature and a cosmological constant which corresponds to an energy density about twice that of the matter at present.

It is important to characterise the physical effects of "dark energy" as completely as possible and in particular it is essential to establish whether the dark energy actually has the dynamical effects expected in GR. We recall that all observational constraints are basically geometric in nature as they mainly constrain the angular diameter distance to the last scattering surface (CMB) and the luminosity distance at moderate redshifts (supernovae). The constraints on actual dynamical effects of the cosmological constant as probed by the clustering of the matter distribution are coupled in a complicated way to geometrical constraints and are actually rather weak.

* See also the article by Sandro D'Odorico on page 6 in this issue of The Messenger.

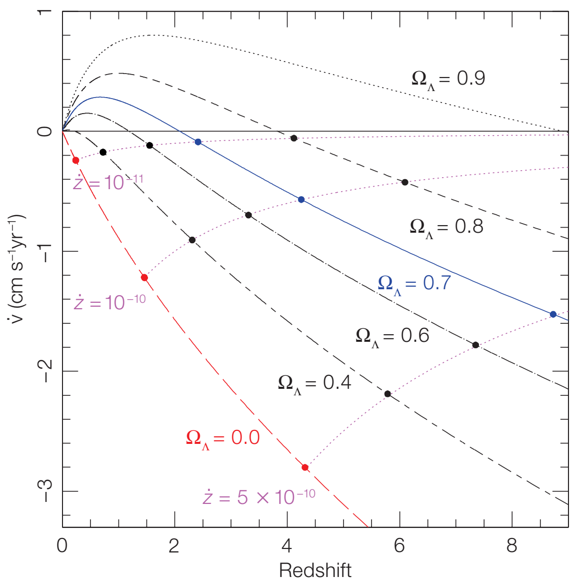
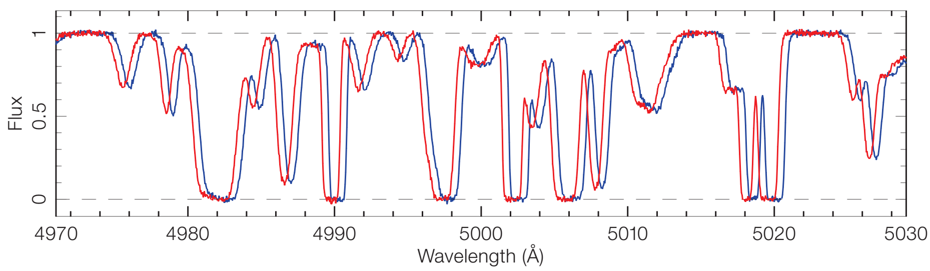


Figure 1 (left): Evolution of $\dot{v}$ as a function of redshift. The cosmological parameters have been fixed to $\Omega_{tot} = 1$, $H_0 = 70$ and different values of Ω_Λ have been considered. The $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$ cosmology is shown with a blue solid line, and the Einstein-de Sitter model is plotted with a red long-dashed line. The filled circles connected by dotted lines show loci of constant $\dot{z}$, in units of yr^{-1}.

Figure 2 (below): This figure shows the displacement of intergalactic absorption features caused by the evolution of the Universe's expansion rate. We show a small portion of the simulated Lyα forest in the spectrum of a $z \sim 3$ QSO as we would observe it today (blue line) and 10^7 years from now (red line). The time interval between the two observations is huge (10^7 years) for the sake of visualisation. In the real experiment it will be about six orders of magnitude smaller, as will be the displacement of the spectral features.



The CODEX experiment is conceptually very simple: by making observations of high redshift objects with a time interval of several years, we want to detect and use the wavelength shifts of spectral features of light emitted at high redshift to probe the evolution of the expansion of the Universe *directly*.

It is convenient to express the expected wavelength shift over a period Δt in terms of the velocity of the equivalent Doppler shift, $v = (\Delta\lambda/\lambda)c$. Figure 1 shows the expected change of Doppler shift for a range of FRW models with no curvature as a function of redshift. There are a few things to note. The wavelength shift has a very characteristic redshift dependence. At some redshifts the wavelengths are "stretched" while in others they are "compressed". The wavelength shift corresponds to a Doppler shift of about 1–10 cm/s over a period of 10 years.

This amount is extremely small, and brought Sandage (1962) to conclude that such a measurement was beyond our capabilities. Why do we think that this experiment is possible now? For three reasons: (1) Extremely Large Telescopes such as OWL should be capable of providing the huge number of photons required. (2) In the last two decades our capability of accurately measuring wavelength shifts of astronomical sources has dramatically improved (Mayor et al. 2002). (3) A suitable class of astronomical objects for this measurement has been identified: the Lyα forest lines, which are extremely numerous and beautifully trace the cosmic expansion with negligible peculiar motions (at least ten times smaller than the Hubble flow).

Measuring the wavelength shift in high redshift objects

A priori it is not obvious which objects and which spectral features are best suited for a precise measurement of $\dot{z}$. For a given energy flux the precision of the final measurements will increase with the sharpness of spectral features (less noise) and increasing wavelength (more photons). Another important consideration is the expected peculiar acceleration associated with peculiar motions relative to the Hubble flow, which will act as additional noise. The numerous absorption lines in the spectra of high-redshift QSOs, which make up the so-called Lyα forest, appear to be the most promising targets for a measurement of $\dot{z}$. The most striking feature of the Lyα absorption is the large number of lines in a single spectrum.

There are about one hundred suitable features in a single spectrum which have a typical width $\Delta\lambda_{line}$ of 30 km/s. With QSO absorption spectra we can probe a wide redshift range from $z \sim 1.5$ up to 4 and beyond. There is a generally accepted paradigm for the origin of the Lyα forest absorption and the associated metal absorption which has been established by extensive comparison of cosmological hydrodynamical simulations and analytical calculations with the exquisite data which have become available from 10-m-class telescopes (see Rauch (1998) for a review). The peculiar acceleration distribution as derived from state-of-the-art hydrodynamical simulations shows that for the vast majority of these systems the expected acceleration is indeed negligible. The Lyman series absorption lines are thus ideally suited to measure the global evolution of the Hubble parameter. Figure 2 illustrates the Lyα absorbers and the cosmic shift with time.

The simulations

In order to quantitatively assess the feasibility of the measurement, Monte-Carlo simulations have been carried out independently by several groups. The high-resolution spectra of QSO were simulated, noise added and the process repeated for the second epoch. The pairs of spectra so produced were compared and the 'measurement' performed. Figure 3 shows the difference expected among pairs of spectra, where the second epoch spectrum has been redshifted according to different cosmological models. The results of the simulations agree with the fact that, if the lines are resolved, the final accuracy of the experiment can be expressed as a function of signal-to-noise (S/N) ratio and redshift as:

$$\sigma_v = 1.4 \left(\frac{S/N}{2350}\right)^{-1} \left(\frac{N_{QSO}}{30}\right)^{-1/2} \left(\frac{1+Z_{QSO}}{5}\right)^{-1.8} \text{cm/s}$$

(where S/N refers to a pixel of 0.0125 Å). This implies that observing each epoch for (e.g.) 40 QSOs with a S/N ratio of 2 000 each, an accuracy of 1.5 cm/sec can be obtained. Figure 4 shows that for a QSO of magnitude 16.5 and 2 000 hours of observations, such a S/N ratio is within reach for some of the larger next-generation telescopes currently under consideration, provided that the whole system has an efficiency comparable to that of UVES at the VLT.

A sufficient number of bright QSOs is already available. Selecting objects from published catalogues, we find 91 QSOs brighter than m = 16.5, out of which 25 have redshifts between 2 and 4, and the number of suitable objects should increase with the large, all-sky photometric surveys planned in the coming years.

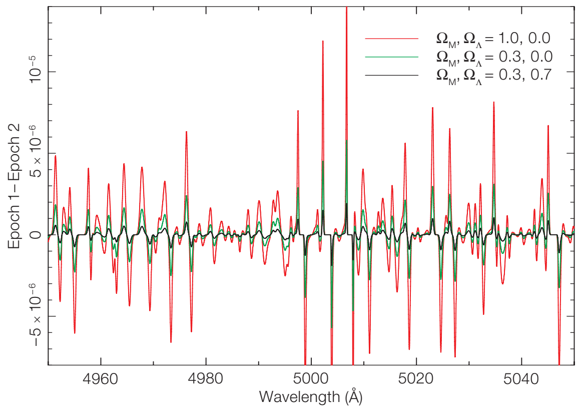


Figure 3: Flux difference of two simulated, noiseless Lyα forest spectra at z = 3.1 taken Δt = 10 years apart for different cosmological parameters as indicated and H_0 = 70 km/s/Mpc.

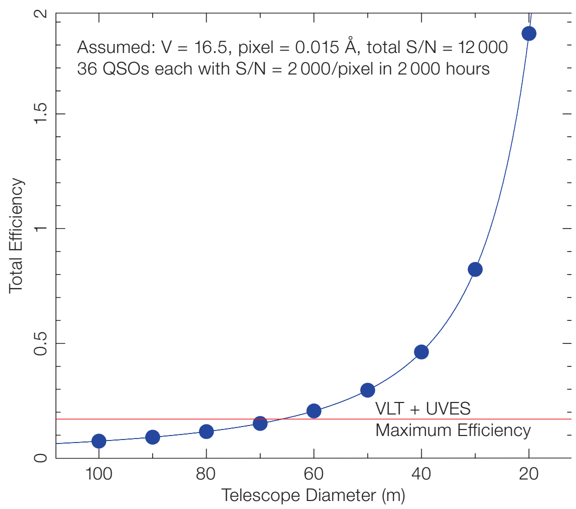


Figure 4: Telescope + CODEX efficiency versus telescope diameter, for a S/N ratio of 12 000, integration time of 2 000 hours and a QSO magnitude of V = 16.5. The plot shows the total efficiency that the system should have to reach the goal with the above assumptions. The red line is the UVES + VLT efficiency.

The instrument concept

We have therefore developed an instrument design concept with the characteristics given in Table 1. In order to obtain a resolving power of 150 000 on a seeing-limited ELT (1 arcsecond aperture on a 60-m telescope or 0.65 arcsecond on a 100-m), five identical spectrographs are foreseen. To obtain the highest stability, each spectrograph will be contained in a vacuum tank, hosted in a temperature-stabilised room nested in an environmentally quiet laboratory. In order to keep to a limited size for each spectrograph, several new concepts (pupil anamorphysm and slicing, special crossdisperser) have been adopted, and each spectrograph will have an echelle grating only twice the size of those of UVES, with an 8 k × 8 k detector.

While it is possible to predict the behaviour of the individual elements of CODEX, it will be extremely difficult to model the whole system, including, for instance, the complex interactions with the telescope. We therefore anticipate that a full CODEX unit, exactly similar to one of the five installed at OWL, has to be developed and operated for several years at the VLT, in order to gain the experience and to (im)prove the CODEX concept.

Chasing the systematics

When aiming at precise measurements which go almost a factor 100 beyond presently achievable performance, special care must be taken to account for subtle systematic effects. "Local" forms of noise are relevant; an evaluation of the barycentric correction terms is given in Table 2, which shows that the corrective terms are under control and within reach at present. One important number missing from Table 2 is the value of the acceleration of the Sun in the Galaxy, which is comparable to the amount of the cosmic signal. This important term can in principle be measured by CODEX observing QSOs well distributed in the sky, but it will be determined with superior accuracy by the ESA GAIA satellite at a level of 0.5 mm/sec/year – an accuracy ten times smaller than the cosmic signal.

The accuracy of the wavelength calibration is another concern (we shall recall that a shift of 1 cm/sec corresponds to

Table 1: Main characteristics of CODEX.

Acceptance aperture on the sky	1 arcsec for 60 m, 0.65 arcsec for 100 m
Location	Underground in nested thermally stabilised environment
Feed	Coudé feed
Peak DQE including injection losses (with GLAO)	14 % (Coudé feed)
Number of unit spectrographs	5 (11 for 100-m OWL and 1 arcsec aperture)
Unit Spectrograph dimensions	Diameter 2.4 × 4 m (vacuum vessel)
Spectral resolution	150 000
Wavelength coverage	446–671 nm in 35 orders
Spectrograph layout	White pupil
Echelle	41.6 l/mm, R4, 170 × 20 cm, 4 × 1 mosaic
Crossdisperser	VPHG 1 500 l/mm operated off-Littrow
Camera	Dioptric F/2.3, image quality 30 μm
Detector	CCD mosaic 8 k × 8 k, 15 μm pixels Stabilised to a few mK
Noise performance	Photon shot noise limited for $m_v = 16.5$ in 10 minutes
Sampling	4 pixels per FWHM

Table 2: Sensitivity matrix of the accuracy of the barycentric correction with regard to their input parameters.

Parameter	Induced error on the correction [cm s^{-1}]	Comment
Earth orbital velocity		
– Solar-system ephemerides	< 0.1	JPL DE405
Earth rotation		
– Geoid shape	~ 0.5	
– Observatory coordinates	< 0.1	Any location in atm.
– Observatory altitude	< 0.1	along photon path may
– Precession/nutation corrections	< 0.1	be chosen
Target coordinates		
– RA and DEC	?	70 mas ⟶ 1 cm s^{-1}
– Proper motion	~ 0	negligible
– Parallax	~ 0	negligible
Relativistic corrections		
– Local gravitational potential	< 0.1	
Timing		
– Flux-weighted date of observation	?	0.6 s ⟶ 1 cm s^{-1}

about 3 Å shift on the detector). Tests made with HARPS indicate that the Th-Ar lamps used in most spectrographs are not adequate for such accuracy, and that a new calibration system should be devised. In addition, such a novel calibration system must be perfectly reproducible and stable over the long term (20 years or more) of the duration of the experiment. We have been investigating with the Max-Planck-Institut für Quantenoptik (MPQ) the possibility of using new superb standards based on newly-developed laser frequency combs. The group at MPQ is led by Prof. Hänsch, one of the Nobel Prize Winners in Physics this year.

CODEX beyond the measurement of the cosmic signal

The scientific applications of CODEX, as a high-resolution spectrograph with extremely high performance fed by OWL, will go well beyond the main experiment proposed above. In the following we give a glimpse of three outstanding applications:

Search for variability of fundamental constants

Fundamental constants are supposedly universal and unvarying quantities. Any measured variations would have far-reaching consequences for the unified theories of fundamental interactions, for the existence of extra dimensions of space and/or time and for the existence of scalar fields acting in the late universe. Only astronomical observations hold the potential to probe the values of fundamental constants in the past, and in remote regions of space. In 2001, observations of QSO absorption lines brought the first hints that the value of the fine-structure constant α – the central parameter in electromagnetism – might change over time (Murphy et al. 2001), but more recent observations are consistent with a null result. An effective two to three order of magnitude precision gain is foreseen with a spectrograph with $R \approx 150\,000$ at OWL. The accuracy of the $\Delta\alpha/\alpha$ variation measurements will be a few times 10^{-9} – more precise than any other astronomical and geological measurement.

Search for other earths

Exo-planets and, in particular, terrestrial planets in habitable zones, will be one of the main scientific topics of the next decades, and one of the main OWL science drivers. CODEX with OWL will lead the discoveries in at least three main cases in exo-planetary science, providing with unique capabilities and observations: (i) discovery and confirmation of rocky planets, (ii) search for long-period planets, (iii) Jupiter-mass planets around faint stars.

The need for a ground-based follow-up facility capable of high radial velocity accuracy has been stressed in the recent ESO-ESA working group report on solar planets: a high-precision radial-velocity instrumentation for the follow-up of astrometric and transit detections, to ensure the detection of a planet by a second independent method, and to determine its true mass. For Jupiter-mass planets, existing instrumentation may be technically adequate; for Earth-mass candidates, special-purpose instrumentation (like CODEX) on a large telescope would be required. CODEX will also allow us to search for hot Jupiters around solar-mass stars in different environments and star-forming histories, such as globular clusters and nearby companions to the Galaxy.

Primordial nucleosynthesis

Standard Big bang nucleosynthesis presents a pressing cosmological conundrum. There is some evidence suggesting a cosmological origin for ^{6}Li, and the stellar value for primordial ^{7}Li does not agree with primordial Deuterium from QSOs and with Ω_b from WMAP. Although Li observations in low metallicity Galactic halo stars are plagued by possible systematic uncertainties due to modelling of stellar atmospheres and the treatment of convection, it is possible that both discrepancies can be reconciled with physics beyond the standard model during the Quark-Hadron phase. CODEX will provide the first observations of ^{7}Li and ^{6}Li in dwarf stars in galaxies of the Local Group and will make it possible for the first time to measure the interstellar ^{7}Li/^{6}Li ratio in unprocessed material of High-Velocity Clouds. The latter is a direct and robust probe of the yields of the Big Bang Nucleosynthesis yields, providing important insights on whether new physics is playing a role in the early Universe.

In addition to these selected applications, many other science cases have emerged over recent years. Stellar oscillations, the study of the most metal-poor stars in our Galaxy and in its local group companions, the use of cosmochronometers to determine the age of the Universe, the history of the metal enrichment of the Universe … all these cases (and surely many more) will receive a major boost from CODEX on OWL, far beyond what can be now conceived.

References

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Afterglows of Elusive Short Gamma-Ray Bursts

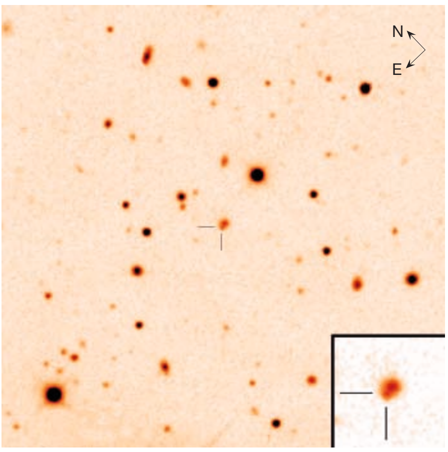
An international team of astronomers[1] has for the first time observed the visible light from a short gamma-ray burst (GRB). Using the 1.5-m Danish telescope at La Silla (Chile), they showed that these short, intense bursts of gamma-ray emission most likely originate from the violent collision of two merging neutron stars. The same team has also used the VLT to constrain the birthplace of the first ever short burst whose position could be pinpointed with high precision. The results were published in the October 6 issue of the journal *Nature*.

Gamma-ray bursts, the most powerful type of explosion known in the Universe, have been a mystery for three decades. They come in two different types, long and short. Over the past few years, international efforts have convincingly shown that long gamma-ray bursts (longer than about 2 sec) are linked with the explosion of massive stars. It is thought that short-duration GRBs may be due to the merging of two neutron stars; they have evaded optical detection for more than 30 years.

In the night of July 9 to 10, 2005, the NASA HETE-2 satellite detected a burst of only 70-millisecond duration and, based on the detection of X-rays, was able to determine its position in the sky. Thirty-three hours after, Jens Hjorth and his team obtained images of this region of the sky using the Danish 1.5-m telescope at ESO La Silla. The images showed the presence of a fading source, sitting on the edge of a galaxy.

The burst resides 11 000 light years from the centre of a star-forming dwarf galaxy that is about 2 400 million light years away and is quite young – about 400 million years old. From observations conducted until 20 days after the burst, the astronomers ruled out the occurrence of an energetic hypernova as found in most long GRBs. This supports the hypothesis that short GRBs are the consequence of the merging of two very compact stars.

(Based on ESO Press Release 26/05)



First image in the visible (more precisely, in the so-called *R*-band) of a short gamma-ray burst. The image was taken with the Danish 1.5-m telescope and the DFOSC camera at La Silla on July 11, 2005. It shows the gamma-ray burst to be situated on the edge of a low-redshift galaxy.

[1] Jens Hjorth (Dark Cosmology Centre – DARK, Niels Bohr Institute, University of Copenhagen), Darach Watson (DARK), Johan P. U. Fynbo (DARK), Paul A. Price (Institute for Astronomy, University of Hawaii), Brian L. Jensen (DARK), Uffe G. Joergensen (DARK), Daniel Kubas (ESO), Javier Gorosabel (Instituto de Astrofísica de Andalucía), Pàll Jakobsson (DARK), Jesper Sollerman (DARK and Department of Astronomy, Stockholm University), Kristian Pedersen (DARK), and Chryssa Kouveliotou (NASA/Marshall Space Flight Center). The team is part of the Gamma-Ray Burst Afterglow Collaboration at ESO (GRACE) carrying out gamma-ray burst afterglow studies.