European Organisation for Astronomical Research in the Southern Hemisphere

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

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APPLICATION FOR OBSERVING TIME   LARGE PROGRAMME   PERIOD: **80A**

Important Notice:

1. Title   Category: **A–8**

Monitoring the redshift-drift of the Lyman-alpha forest – a direct measurement of the dynamical evolution of the Universe

2. Abstract / Total Time Requested

Total Amount of Time: 3750h   Total Number of Semesters: 16 (30)

We propose to monitor the redshift drift of the Lyα forest and associated metal lines towards a sample of 20 very bright QSOs in the redshift range $2 < z < 4.2$ with the ultra-stable high-resolution optical spectrograph on the E-ELT over a period of 15 yr (with observations spread over 8 yr). The redshift drift is sensitive to the difference of the expansion rate today and the expansion rate at the redshift of the absorbing structures and is directly related to the de- or acceleration of the Universe. With the proposed observations we can achieve an overall measurement accuracy of 3.5 cm/s. By monitoring the drift of the Lyα forest over a wide redshift range we will measure the instantaneous expansion rate of the Universe today and the expansion rate at high redshift. The measurement of the expansion rate and its evolution at high redshift will be an important test of General Relativity. The measurement of the instantaneous expansion rate will test whether the Universe expands today at the rate expected from other observations which, generally, measure the expansion rate averaged over a hundred Myr or more. The observations proposed can be used as a first epoch measurement for more accurate measurements by a future generation of astronomers and will thus represent a long-lasting legacy. The acquired spectra will also represent a unique resource for a wide range of other QSO absorption line studies.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	80	UVES	234h	any	d	$\leq 0.8''$	PHO	s

4. Principal Investigator: **L. Pasquini** (ESO, ESO, lpasquin@eso.org)

CoI(s): M. Haehnelt (IoA, UK), J. Liske (ESO, ESO), on behalf of the CODEX team (OTHER, OTHER), and the E-ELT SWG (OTHER, OTHER)

5. Description of the proposed programme

A) Scientific Rationale: The universal expansion was the first observational evidence that general relativity might be applicable to the Universe as a whole. Since Hubble's (1929) discovery much effort has been invested into completing the basic picture of relativistic cosmology. It is generally accepted that the observable Universe is homogeneous and isotropic and can be described by the Robertson Walker metric. Whether the evolution of its scale factor can, however, be accurately described by general relativity in four spacetime dimensions as we know it is still completely uncertain. The observational result of the mid-late 1990s that the expansion of the Universe has recently begun accelerating came as a big surprise. Within standard relativistic cosmology such an acceleration can be accommodated by modifying the stress-energy tensor of general relativity to include a new component with negative pressure. In its simplest incarnation this so-called dark energy is the cosmological constant already introduced by Einstein and all observational evidence so far is consistent with this interpretation. The unexpected deviation from the Einstein-de Sitter model favoured for a long time by many theoreticians may, however, be the smoking gun of the necessity for a more radical paradigm shift. A model-independent approach to mapping the expansion history as a function of redshift in detail appears therefore prudent. Using SNIa to measure the luminosity distance as a function of redshift has been the most successful attempt of this kind so far. The caveats are that distance is 'only' related to the expansion history through an integral over redshift and that one still requires a prior on the spatial curvature of the Universe.

We propose here to instead directly measure the expansion history of the Universe with a method first suggested by Sandage (1962). Sandage pointed out that the evolution of the expansion rate causes the redshifts of objects partaking in the Hubble flow to change slowly with time:

$$\dot{z} = (1+z)H_0 - H(z) \tag{1}$$

This implies that the expansion history can be determined, at least in principle, by means of a straightforward spectroscopic monitoring campaign. The signal is, however, very small. Fig. 1 shows the redshift drift as a function of redshift as expected in standard relativistic cosmology for three different sets of cosmological parameters. For a monitoring period of 10 yr the redshift drift at $z = 3$ lies in the range of 3-30 cm/s, depending on the choice of cosmological parameters, and is hence well within reach of what can be measured with the ultra-stable high-resolution optical spectrograph at the E-ELT in terms of accuracy and stability of the wavelength calibration.

As originally proposed by Loeb (1998) and discussed in detail by Liske et al. (2007), monitoring of the absorption spectra of bright QSOs with their large number of spectral features offers the best prospects for a measurement of the redshift drift. Note that the measurement of $\dot{z}$ for spectral features covering a range of redshift will allow us to measure the instantaneous present-day expansion rate as well as the expansion rate at high redshift averaged over about a Gyr. The measurement of the expansion rate and its evolution at high redshift will be an important test of general relativity and will – if general relativity is the correct theory of gravity on large scales – contribute significantly to characterizing the nature and evolution of dark energy. The measurement of the instantaneous expansion rate today will test whether the Universe expands today at the rate expected from other astronomical measurements of the present-day Hubble constant which generally constitute a measurement of the expansion rate averaged over hundred Myrs or more.

Finally, we point out that our data may also serve as a first epoch measurement to be supplemented with similar or superior data in the (distant) future in order to yield a much more accurate measurement of the redshift drift. Hence, these data will have a long-lasting legacy value.

B) Immediate Objective: We will obtain a series of extremely high S/N absorption spectra of a sample of about 20 very bright QSOs with the ultra-stable high-resolution optical spectrograph. In order to monitor the redshift drift the series of spectra will be taken over two periods of four years, separated by a further seven years, so that the total duration of the experiment is $\Delta t = 15$ yr.

Radial velocity measurements of the effect of planets with the ultra-stable high-resolution optical spectrograph have demonstrated that its design goal of a stable wavelength calibration with an accuracy of 1 cm/s is achievable over (arbitrarily) long periods of time. This superb accuracy of the wavelength calibration and wavelength stability means that the accuracy of our proposed measurement will be photon-noise limited (Pasquini et al. 2005; Liske et al. 2007). We have performed detailed simulations using mock absorption spectra to establish how well the redshift drift can be measured in the photon limited case using the method of Bouchy et al. (2001) originally developed for the detection of planets (Liske et al. 2007). In the photon noise limited case the accuracy with which the redshift drift can be measured depends only on the total number of photons collected and the number and sharpness of the spectral features. This accuracy can be conveniently parameterized as

$$\sigma_v = 1.4 \left(\frac{S/N}{2370}\right)^{-1} \left(\frac{N_{\rm QSO}}{30}\right)^{-0.5} \left(\frac{1+z_{\rm QSO}}{5}\right)^{-1.7}, \tag{2}$$

5. Description of the proposed programme (continued)

where N_{QSO} and z_{QSO} are the number and redshift of the QSOs. S/N refers to the S/N ratio per 0.0125 Å pixel in a single epoch measurement. The first two terms in equation (2) describe the dependence on the number of photons collected while the third term is an approximation based on our extensive simulations of mock absorption spectra that take into account the evolution of the flux distribution in the absorption spectra. Since the number of absorption features increases with increasing redshift the measurement error decreases.

Choosing the sample of target QSOs requires to find the best compromise between a sample that is as large as possible in order to optimize redshift and RA coverage and to check for systematic uncertainties, and a sample that contains only the very brightest QSOs in order to maximize the total number of photons collected. Here we fix the number of target QSOs at 20. Based on currently known QSOs accessible from the southern hemisphere (i.e. with DEC $< 35°$) we have chosen those 20 QSOs with the most favourable combination of magnitude and redshift, in the sense that this sample will give the best total accuracy (σ_v) that is possible for any sample of 20 QSOs and a fixed amount of observing time. The selected sample covers the redshift range $2 < z < 4.2$ and provides a wide coverage in RA to facilitate observations all year round.

At the time of our measurement the number of suitable bright QSOs should have increased and it should be possible to choose a larger sample of QSOs with a similar number of photons collected in the same amount of time. An additional benefit of a large sample of QSOs is the increased amount of additional science which can be expected to be done with these spectra.

Fig. 2 shows a Monte Carlo simulation of the expected outcome of the experiment using our sample of 20 QSOs, where the data have been split into four redshift bins. With an overall, total experiment accuracy of ~ 3.5 cm/s the redshift drift should be just about measurable.

The CODEX study has identified and investigated a number of possible systematic uncertainties, most notably peculiar accelerations of the absorbing structures and changes in the density, temperature and ionization state of the absorbers. The additional error components that are induced by these effects were all found to be at least two orders of magnitude smaller than the error due to photon noise. Hence, the uncertainties due to peculiar motions and the evolution of the physical state of the absorbers is not expected to limit our ability to measure the redshift drift.

Finally, we note that the unprecedented S/N of the spectra collected for the redshift drift measurement will also make them extremely valuable for a number of other QSO absorption line studies addressing fundamental questions. For example, the dataset should increase the accuracy with which one can test for the variability of physical constants by two orders of magnitude compared to present-day data.

C) Telescope Justification: The measurement is photon noise limited and requires the large aperture of the ELT and the accuracy and the stability of the wavelength calibration of the ultra-stable high resolution optical spectrograph. Proper correction of the earth motion requires that the photon barycenter of the time of the observation must be determined to better than 0.6 s. In order to minimize this effect and other possible sources of instability (e.g. airmass variations, instrument instabilities), the integration time of each exposure should be as short as possible. In order to reach the photon noise-limited regime in the total measurement each individual observation must be photon noise limited. This further adds to the necessity for the large photon collection area of the ELT. A S/N ratio of 30 per pixel is obtained in just 11 minutes for an object of magnitude 18.5. Hence there should be no problem with using reasonably short integration times (e.g. 20 minutes) with the ELT.

D) Observing Mode Justification (visitor or service): The observations are standard and are distributed over a large number of targets with a wide range of RA. Service mode is therefore the preferred option.

5. Attachments (Figures)

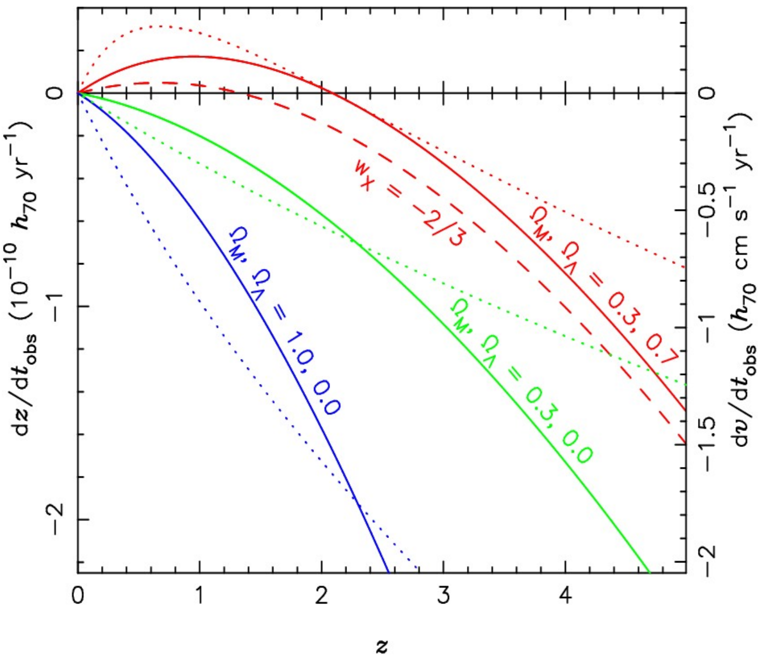

Fig. 1: The solid (dotted) curves and left (right) axis show the redshift drift $\dot{z}$ ($\dot{v} = c\,\dot{z}\,(1+z)^{-1}$) as a function of redshift for various combinations of $\Omega_{\rm M}$ and Ω_Λ as indicated. The dashed curve shows $\dot{z}$ for the case of dark energy with an equation of state parameter $w_X = -\frac{2}{3}$ (and $\Omega_{\rm M}, \Omega_X = 0.3, 0.7$).

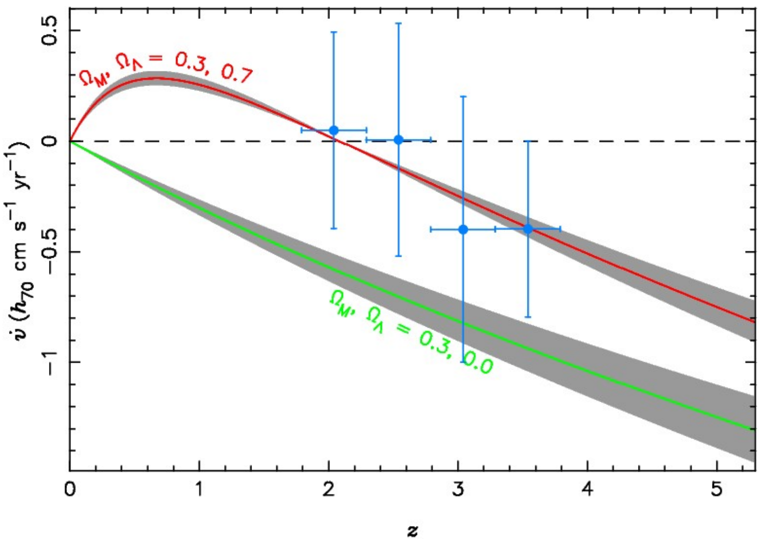

Fig. 2: Monte Carlo simulation of a $\dot{z}$ measurement using our sample of 20 bright QSOs in the redshift range $2 < z_{\rm QSO} < 4.2$. The time between the first and last observations was assumed to be $\Delta t = 15$ yr, with observations carried out during years 1–4 and 12–15. The blue points show the simulated data in bins of 0.5 and the expected error bars. The overall accuracy of this experiment is $\sigma_v = 3.5$ cm/s. The solid red curve shows the expectation for the input cosmological model of $H_0 = 70$ km/s/Mpc, $\Omega_{\rm M} = 0.3$ and $\Omega_\Lambda = 0.7$. For comparison the green curve shows the expectation for a model without a cosmological constant. The grey shaded areas result from varying H_0 by ± 8 km/s/Mpc. The discovery of any QSOs in the southern hemisphere that are brighter than any of the ones in our sample would increase the total accuracy of the experiment at a fixed total observing time.

6. Experience of the applicants with telescopes, instruments and data reduction

The expertise in the CODEX team covers all aspects of the project. The applicants have ample experience with using (and building) echelle spectrographs and team members have pioneered the precision measurement of radial velocities based on an accurate wavelength calibration. The team further has considerable experience with the reduction and analysis of QSO absorption spectra. The theoreticians on the team are familiar with all theoretical aspects of the project and will ensure an adequate interpretation of the data.

7. Resources available to the team, such as: computing facilities, research assistants, etc.

The proposing team has sufficient resources to perform the required data analysis. Following the positive experience with HARPS, the development of an optimized data reduction pipeline should have been part of the instrument development plan and we assume here the availability of such a pipeline. The final reduced data and intermediate data products will be made available to the community.

8. Special remarks:

The proposal assumes that the ultra-stable high resolution optical spectrograph reaches its design wavelength calibration accuracy of 1 cm/s over long periods of time and has adequate wavelength coverage. This puts the following requirements on the telescope

- availability of a gravity-stable Coudé focus
- plate scale stability: 0.02–0.05 arcsec centering
- wavelength coverage: 0.38–0.7 μm

Note that the instrument is seeing limited and that the anticipated aperture is 1 arcsec. The measurement would nevertheless benefit from GLAO in order to maximize the amount of energy in the fibre aperture. In this case it would have the following AO requirement: 80% EE in 1 arcsec.

9. Justification of requested observing time and lunar phase

Lunar Phase Justification: The reflected solar spectrum contains many spectral lines, which would produce a variable contaminating radial velocity signal in our QSO spectra. We have discussed this in detail in Pasquini et al. (2005: CODEX concept study, page 80). In order to limit the shift produced by an individual contaminating absorption line to 30 cm/s or less, its contrast with respect to the science target has to be larger than 10^4. This clearly calls for observations in dark time. How much moon light can be tolerated will be investigated in future using detailed simulations.

Time Justification: (including seeing overhead) We have used the ELT ETC for the high-resolution spectrograph (R=100000). The ETC results have been treated in the following way: First, the number of photons per pixel has been reduced to bring the ETC pixel size to that of our own detailed simulations (eq. 2, 0.0125 Å) which we consider an adequate pixel size for the ultra-stable high-resolution spectrograph. Secondly, we undid the ETC's application of an "aperture" loss factor. Depending on the selected spatial pixel scale and number of pixels the ETC uses simulated PSFs to calculate the fraction of the flux ensquared by the selected area. However, we expect the high-resolution spectrograph to be built with a 1 arcsec aperture so that aperture losses should be minimal. The current version of the ETC does not allow for this possibility, hence the correction.

The total exposure time was selected so as to achieve a total, overall accuracy of the experiment of 3.5 cm/s, resulting in an overall time request of 3750 hours. This time will be split among the targets in such a way as to achieve a similar overall S/N for each object.

Assuming that on average 1 night per week will be available for CODEX observations (or 26 nights per semester) it will take 4 years to complete each of two epochs. Separating the end of the first epoch and the start of the second epoch by 7 years results in a total, overall experiment duration of 15 years.

We reiterate that with the advent of future large surveys, a substantial addition to the list of bright QSOs is expected, especially in the southern hemisphere, enabling us to either reduce our time request or to obtain stronger results.

Calibration Request: Standard Calibration

10. Report on the use of ESO facilities during the last 2 years

N/A

11. Applicant's publications related to the subject of this application during the last 2 years

Pasquini L. and the CODEX Team, 2005, ESO publication OWL-CSR-ESO-00000-0160: OWL Instrument Concept Study: COsmic Dynamics EXperiment

Pasquini L. and the CODEX Team, 2005, The Messenger, 122, 10: CODEX: Measuring the Expansion of the Universe (and beyond)

Liske J. and the CODEX Team, 2007, MNRAS, submitted: Cosmic dynamics in the era of Extremely Large Telescopes

12. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	Q 0016-357	00 18 40.80	-35 29 11.9	11	r=15.21		z=3.1900	
A	PKS 0858-279	09 00 40.07	-28 08 23.6	4	g=14.56		z=2.1520	
A	B 1422+231	14 24 38.11	+22 56 00.3	26	i=15.99		z=3.6200	
A	PG 1247+268	12 50 05.72	+26 31 07.5	7	g=15.01		z=2.0420	
A	KP 1623.9+26.8	16 25 57.76	+26 44 44.2	14	r=15.54		z=2.6070	
A	B2 1225+31	12 28 24.96	+31 28 37.5	10	r=15.32		z=2.2190	
A	Q 0049-3936	00 52 09.28	-39 19 45.7	12	r=15.42		z=2.3000	
A	Q 0031-3939	00 33 32.66	-39 22 45.4	11	r=15.40		z=2.2000	
A	TON 1530	12 25 27.42	+22 35 13.2	10	g=15.43		z=2.0580	
A	Q 0158-3731	02 00 23.35	-37 17 23.9	13	r=15.54		z=2.2500	
A	CTS A33.02	05 54 45.80	-33 05 17.1	15	r=15.71		z=2.3600	
A	PSS J0926+3055	09 26 36.32	+30 55 04.9	66	i=16.96		z=4.1900	
A	HE 0940-1050	09 42 53.50	-11 04 26.2	31	r=16.36		z=3.0540	
A	1208+1011	12 10 57.04	+09 54 27.0	56	i=16.80		z=3.8030	
A	Q 0038-3416	00 41 15.10	-34 00 12.7	15	r=15.69		z=2.2000	
A	SDSS J120006.25+312630.8	12 00 06.25	+31 26 30.9	32	r=16.40		z=2.9889	
A	CTS C15.05	23 50 34.26	-43 25 59.7	29	r=16.33		z=2.8850	
A	Q 0000-26	00 03 22.95	-26 03 18.4	76	i=17.11		z=4.1110	
A	Q 1101-264	11 03 25.30	-26 45 15.8	15	g=15.87		z=2.1450	
A	Q 0025-4047	00 27 42.83	-40 31 00.8	16	g=15.94		z=2.1800	

Target Notes: All targets were chosen to lie south of $+35°$. The exposure time is in hours and refers to the time requested per year. To obtain the total exposure time multiply the given value by 8 (i.e. the plan is to perform identical observations for 4 years for each of two epochs). The total exposure time of 3750 hours was distributed among the targets so as to achieve similar S/N for all of them.

12b. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If yes, explain why the need for new data.

No

13. Scheduling requirements

14. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
80	UVES	A	BLUE	Standard setting: 346