THE COSMOLOGICAL DYNAMICS EXPERIMENT

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ABSTRACT

The expansion of the Universe, discovered by Hubble in 1929, remains one of the fundamental observational cornerstones of contemporary relativistic cosmology. The sheer photon collecting power of future Extremely Large Telescopes will allow us, for the first time, to directly probe the *history* of the expansion: by observing a systematic drift of the redshifts of cosmologically distributed sources over the timescale of a few decades we will be able to map out the expansion velocity as a function of cosmic epoch. This fundamental physics experiment is as elegant as it is observationally and technically challenging. Here we describe the experiment in detail and outline an ongoing effort to devise an instrument capable of meeting the challenge: CODEX.

Key words: Cosmology; ELT.

1. INTRODUCTION

When applied to cosmology Einstein's theory of General Relativity (GR) predicted an evolving Universe. Hubble's discovery of the universal expansion confirmed this prediction and hence represented the first observational evidence that GR might be applicable to the Universe as a whole.

Since Hubble's discovery much effort has been invested into completing the basic picture of cosmology. The central question is: What is the stress-energy tensor of the Universe? Assuming homogeneity and isotropy reduces this question to: What is the density and equation of state of each mass-energy component of the Universe? Since these parameters determine both the geometry *and* the dynamics of the metric one can use a measurement of either to infer their values. Over the past decade the successes on this front have reached their (temporary) culmination: observations of the Cosmic Microwave Background [1], type Ia supernovae [2], the large-scale galaxy distribution [3] and others now provide answers of such convincing consistency and accuracy that the term 'precision cosmology' is now commonplace, e.g. [4]. However, all of these experiments essentially measure the Universe's *geometry* (as well as the clustering of density perturbations) but not its *dynamics*. A direct, purely dynamical measurement of the history of the Hubble expansion has never been attempted. The combination of independent measurements of the geometry *and* the dynamics would allow us to test whether both are indeed determined by the 'same' stress-energy tensor, an assumption inherently built into GR.

The theoretical possibility of measuring the dynamics was first pointed out by [5] and most recently reviewed by [6] in the context of currently existing observational technology, concluding that a measurement was presently out of reach. Recently, ESO has initiated CODEX, a concept study carried out in collaboration with Geneva Observatory, INAF Trieste and the IoA Cambridge to investigate the impact of the next generation of 60-100m optical telescopes (Extremely Large Telescopes [ELTs]).

2. EVOLVING REDSHIFTS

How can we directly measure the dynamics of the Universe as a function of cosmic epoch? The evolution of the Universe is usually expressed in terms of the scale factor of its metric, $a(t)$. We observe the expansion by its wavelength-stretching effect on photons traversing the Universe. A photon emitted at t_e and observed at t_0 suffers a redshift of

$$1+z=\frac{a(t_0)}{a(t_e)}. \tag{1}$$

However, since we do not know t_e this does not allow us to measure $a(t)$. The trick is to also measure $\mathrm{d}a/\mathrm{d}t=\dot{a}$. Knowing both $a(z)$ and $\dot{a}(z)$ one can reconstruct $a(t)$. Differentiating equation (1) with respect to t_e we find

$$\frac{\dot{a}(t_e)}{a(t_e)}\equiv H(z)=(1+z)H_0-\dot{z}(z). \tag{2}$$

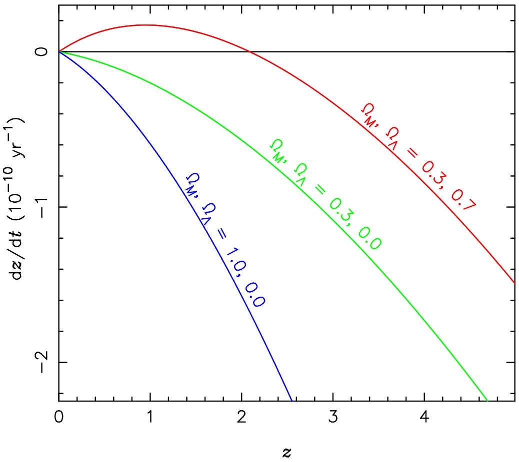


Figure 1. The redshift drift $\dot{z}$ as a function of redshift for different cosmological parameters as indicated and $H_0 = 70$ km/s/Mpc. The existence of a point where $\dot{z} = 0$ is the hallmark of $\Omega_\Lambda \neq 0$.

$\dot{z}$ is a small, systematic drift in the redshifts of cosmologically distant sources as a function of time: an object measured at z today will be found to have a slightly different redshift a few years later. This effect is induced by the de- or acceleration of the expansion, i.e. by the change of the Hubble parameter H. Since H_0 is known, this drift is a direct measure of the expansion velocity at epoch z. Hence a measurement of $\dot{z}(z)$ amounts to a purely dynamical reconstruction of the expansion history of the Universe, $a(t)$.

How large is this redshift drift? That depends on the cosmological model. In standard relativistic cosmology H is related to the densities of matter and vacuum energy, Ω_M and Ω_Λ, by

$$H(z) = H_0\sqrt{\Omega_\Lambda + (1+z)^2\Omega_k + (1+z)^3\Omega_\mathrm{M}}, \quad (3)$$

where $\Omega_k = 1 - \Omega_\Lambda - \Omega_\mathrm{M}$. In Fig. 1 we plot the expected signal for various different cosmological parameters. For an interval of $\Delta t = 10$ yr we have $\Delta z \approx 10^{-9}$ at $z = 4$. In velocity and wavelength units the shift is $\Delta v \approx 6$ cm/s and $\Delta\lambda \approx 10^{-6}$ Å. It is truly a *tiny* signal!

3. WHERE CAN WE MEASURE $\dot{Z}$?

The smallness of the expected signal places two competing constraints on the objects that could potentially be used to measure $\dot{z}$. On the one hand they should faithfully trace the Hubble flow or else the cosmic signal will be swamped by random peculiar accelerations. On the other hand they should have sharp spectral features. However, these require cold material which is generally found in dense regions inside deep potential wells, which in turn generate large peculiar accelerations. These considerations rule out masers and molecular absorption lines as possible candidates.

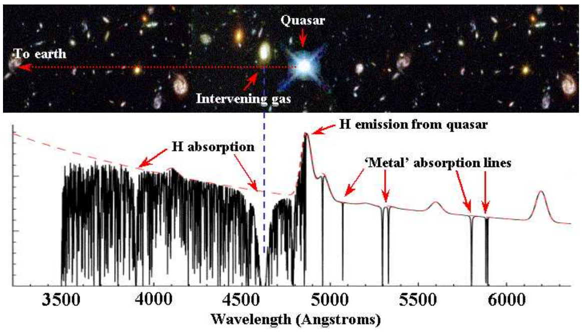


Figure 2. A schematic diagram of a QSO spectrum. The broad emission line near 4900 Å is the QSO's Lyα emission line at $z \approx 3$. The numerous absorption features on the blue side of this line are Lyα lines due to intergalactic gas along the line of sight to the QSO. Figure courtesy of John Webb (UNSW).

One possible solution for dealing with the conflicting requirements is to choose a class of objects that traces the Hubble flow and to compensate the associated lack of sharpness of spectral features by their number density:

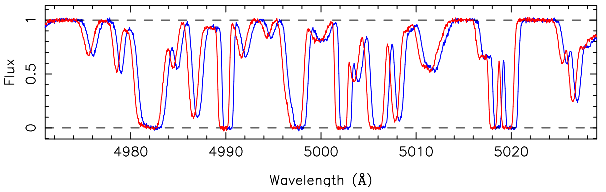
4. THE LYMAN α FOREST

The term 'Lyα forest' refers to the plethora of absorption lines observed in the spectra of all QSOs on the blue side of the Lyα emission line. The lines are due to the Lyman α transition of neutral hydrogen and arise in the intervening intergalactic medium between us and the QSO (cf. Fig. 2). The Lyα forest is a well-studied phenomenon, both observationally and theoretically. Its intergalactic nature implies shallow potential wells and hydrodynamic simulations yield peculiar accelerations a factor of 10 below the cosmic signal. Hence the Lyα forest reliably traces the Hubble flow. The trade-off lies in the relatively large line widths of 15-50 km/s. However, this is mostly offset by the fact that each QSO spectrum at $z > 2$ shows on the order of ~100 absorption features. Nevertheless, it remains a formidable challenge to detect the redshift drift in the Lyα forest (cf. Fig. 3).

5. SIMULATIONS

Fig. 1 shows that a 3σ detection of the redshift drift at $z = 4$ in $\Delta t = 10$ yr requires a radial velocity accuracy of order $\sigma_v \approx 2$ cm/s. Given the properties of the Lyα forest, how many spectra of which resolution and signal-to-noise ratio (S/N) are required to achieve this accuracy? How does σ_v depend on redshift? To answer these questions we have performed Monte Carlo simulations using an empirical parametrisation of the Lyα forest. We find:

$$\sigma_v = 2\left[\frac{\mathrm{S/N}}{1650}\right]^{-1}\left[\frac{N_\mathrm{QSO}}{30}\right]^{-\frac{1}{2}}\left[\frac{1+z_\mathrm{QSO}}{5}\right]^{-1.8}\ \mathrm{cm/s} \quad (4)$$



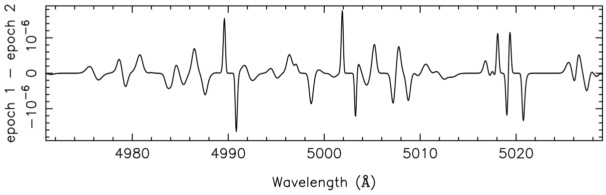


Figure 3. Top: The redshift drift in a simulated Lyα forest spectrum for $\Delta t = 10^7$ yr. Bottom: Flux difference of two simulated, noiseless Lyα forest spectra taken $\Delta t = 10$ yr apart.

where the S/N is per 0.0125 Å pixel. Note that σ_v does not depend on the spectral resolution as long as the absorption lines are resolved, i.e. $R \gtrsim 50\,000$. The z-dependence is the result of (i) the density evolution of the Lyα forest, (ii) the broadening of absorption lines in wavelength space and (iii) the increase of a spectrum's useful fraction with $(1+z)$. The functional form above is only valid for $z_{\rm QSO} \lesssim 4.5$ beyond which the sensitivity saturates due to severe line blanketing.

In Fig. 4 we show the result of a simulated $\dot{z}$ measurement. The (binned) 'data' points come from 30 simulated spectra of S/N $= 2000$, where the background QSOs were randomly assigned a redshift in the range $2 < z_{\rm QSO} < 4.5$, and we assumed $\Delta t = 20$ yr. The deviations away from $\Delta z = 0$ are clearly visible at $z > 3$ and in this particular case the cosmic signal is detected at the $> 99\%$ confidence level.

6. CAN WE COLLECT ENOUGH PHOTONS?

The S/N that is obtained in a given observation critically depends on four factors: the target flux, the telescope size, the telescope and instrument efficiencies and the integration time. Does a feasible combination of these parameters exist that allows us to achieve the S/N required for a detection of the redshift drift? In Fig. 5 we fix the target flux at $m_{\rm QSO} = 16.5$ mag and the total integration time at 1000 h and ask what overall telescope/instrument efficiency is required to attain a 3σ detection of the redshift drift as a function of telescope size. The horizontal line shows the currently achievable efficiency of the UVES spectrograph on ESO's VLT. This may be considered an upper limit to the efficiency of any future ELT/spectrograph combination. We can read off the plot that we require a telescope of $\gtrsim 70$ m diameter for this experiment to be feasible over a timescale of 10 years.

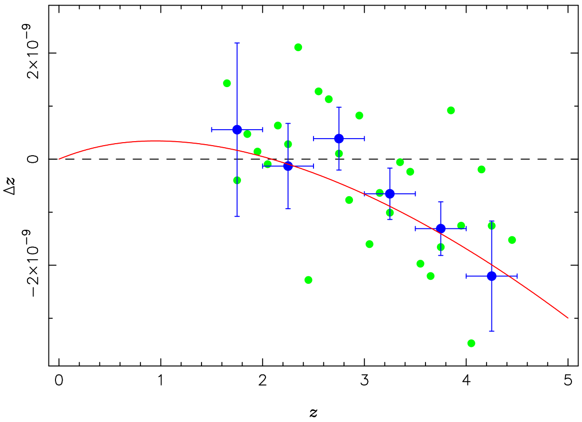


Figure 4. Monte Carlo simulation of a $\dot{z}$ measurement using 30 pairs of Lyα forest spectra with S/N $= 2000$ in the range $2 < z_{\rm QSO} < 4.5$, and $\Delta t = 20$ yr. The green and blue points with error bars show the same data but differently binned. The solid line shows the expectation for the input cosmological model of $H_0 = 70$ km/s/Mpc, $\Omega_{\rm M} = 0.3$ and $\Omega_\Lambda = 0.7$.

So is the assumption of $m_{\rm QSO} = 16.5$ mag at $z = 4$ justified? In other words, are there enough photons in the sky? In Fig. 6 we plot the brightest objects from a recent QSO compilation in the magnitude-redshift plane, along with lines of constant σ_v, for which we have assumed a 100m telescope with 10% overall efficiency and 1000 h integration time per epoch. Several QSOs lie on or below the $\sigma_v = 2$ cm/s line. This means that the photon flux from QSOs is indeed high enough to allow us to collect enough photons in a total of 200 nights using a 100m telescope to achieve the radial velocity accuracy necessary for a detection of the redshift drift.

7. SPECTROGRAPH REQUIREMENTS

A $\dot{z}$ measurement using the Lyα forest obviously requires a high-resolution spectrograph on an ELT. Here we identify four key requirements for such an instrument:

1. *Resolution*: As discussed above, the sensitivity of the experiment to the redshift drift does not depend on spectral resolution as long as the Lyα forest absorption lines are resolved, imposing a lower limit of $R \gtrsim 50\,000$. However, other absorption lines in QSO spectra, due to heavier elements, have substantially smaller line widths. In addition, the accuracy to which the wavelength scale of a spectrum can be calibrated depends on resolution, resulting in a requirement of $R \approx 150\,000$.
2. *Wavelength coverage*: In principle, we wish to observe the redshift drift over as large a redshift range as possible. However, beyond $z \approx 4.5$ the Lyα forest begins to saturate, while at $z \lesssim 2$ it is very sparse. Furthermore, the atmosphere and telescope transmissions decrease rapidly below ~400 nm. Hence we require a wavelength coverage of 400–680 nm.
3. *Efficiency*: From Fig. 5 we have seen that the overall telescope/instrument efficiency should not fall much

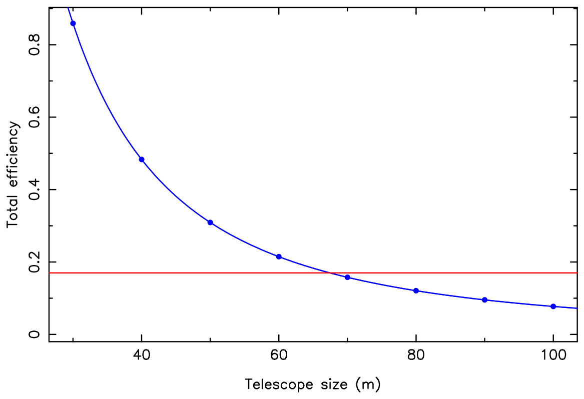


Figure 5. For a given telescope size we show the total efficiency required for a 3σ detection of the redshift drift in a 16.5 mag QSO at $z = 4$ in 1000 h integration time per epoch ($\Delta t = 10$ yr). The horizontal line shows the efficiency currently achieved with VLT/UVES.

below 10%. This includes the quantum efficiency of the detector.
4. *Stability*: To avoid large corrections we aim for a stability of a few cm/s over the timescale of ∼0.5 h. An even more stringent stability requirement can be avoided through the use of a novel wavelength calibration system: a mode-locked femtosecond-pulsed laser [8] produces a spectrum of equally spaced lines ('frequency comb') whose *absolute* wavelengths are known to an accuracy limited only by the atomic clock used to control the laser. This system will deliver an unprecedented wavelength calibration accuracy and it will allow us to monitor the long-term stability of the instrument.

8. CONCLUSIONS

Performing a direct and purely dynamical measurement of the expansion history of the Universe is a fundamental physics experiment which has never been attempted. A direct route towards this measurement is to monitor the redshifts of cosmological sources as a function of time. The expected drift in these redshifts is a direct consequence of the de- or acceleration of the Universe's expansion. In principle this experiment does not assume or rely on any astrophysics, such as the evolution of the objects involved.

Its ubiquity and intergalactic nature have led us to suggest the Lyα forest in the spectra of high-redshift QSOs as a suitable target for this experiment. Based on the properties of the Lyα forest and the photon flux from known QSOs, we have concluded that a high-resolution optical spectrograph on a next-generation ELT of size $\gtrsim$ 70m is indeed capable of detecting the redshift drift.

A number of issues relevant to a $\dot{z}$ measurement remain to be investigated in more detail. Examples include the impact of QSO continuum variations, changes in the absorber ionisation structure and the accuracy of the heliocentric correction. However, preliminary analyses of these issues suggest that none render the experiment unfeasible.

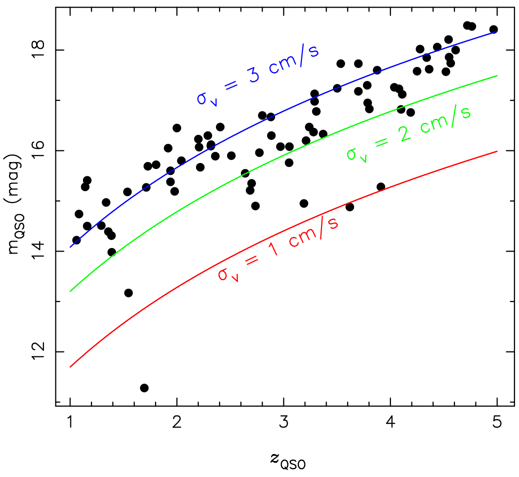


Figure 6. The brightest objects from the most up-to-date QSO catalogue [7]. We also show lines of constant σ_v as indicated, assuming: 100m telescope, 10% effciency, 1000 h integration time per epoch.

Finally we point out the tremendous legacy value of any data collected by CODEX. The accuracy of its absolute wavelength calibration will make these data a valuable resource for any future CODEX-like follow-up experiment.

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