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Spectrographs and spectroscopists for the Sandage test

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Abstract. The redshift drift is a small, dynamic change in the redshift of objects following the Hubble flow. Its measurement provides a direct, real-time, model-independent mapping of the expansion rate of the Universe. It is fundamentally different from other cosmological probes: instead of mapping our (present-day) past light-cone, it directly compares different past light-cones. Being independent of any assumptions on gravity, geometry or clustering, it directly tests the pillars of the Lambda CDM paradigm. Recent theoretical studies have uncovered unique synergies with other cosmological probes, including the characterization of the physical properties of dark energy. At the time of the original proposal by Sandage (1962) the expected change in the redshift of objects at cosmological distances appeared to be exceedingly small for reasonable observing times and beyond technological capabilities. In the last decades progress in the spectrographs (e.g. ESPRESSO), in the collecting area of telescopes and in the samples of cosmic beacons, enabled by new datasets and new machine-learning-based selections, have drastically changed the situation, bringing the Redshift Drift Grail within reach. As a consequence, this measurement is a flagship objective of the Extremely Large Telescope (ELT), specifically of its high-resolution spectrograph, ANDES.

Key words. Cosmology: observations, Spectroscopy

1. Introduction

Let me begin this contribution with a little tribute to Margherita Hack, recalling an episode of my adolescence. My interest in Astronomy had just awakened, but in the 70s and in a provincial town it was not so easy to find material to study it. In practice there was just a magazine, Coelum[1] and few popular books, among which I recall "Modern Cosmology" (Sciama 1971) and "Beyond the Moon" (Maffei 1973). So I wrote various letters to famed Italian astronomers asking for help, and Margherita was kind enough to send me her Astronomy course (Hack 1973), which I eagerly read. Therefore she has some responsibility for instilling in me love for Astrophysics and in particular for spectroscopy. She would not miss the opportunity to emphasize that *"the study of the spectra of celestial bodies has been of fundamental importance for the birth of astrophysics. It is only thanks to the analysis of the radiations emitted by celestial bodies that it was possible to determine their surface temperature and density, their chemical composition, the motions of gases in stellar atmospheres and of stars in galaxies..."*(Hack 1998, Ch.2), which was not a trivial statement when she started her career. In fact, *"there had been an eclipse of Astrophysics and the eleven Italian observatories (Turin, Milan, Padua, Trieste, Bologna, Florence, Rome, Teramo, Naples, Catania and Palermo), plus the Carloforte station, were practically all directed by mathematicians who, in addition to doing research that was obsolete, were also very autocratic… The positions of the stars, the constellations, the measurements of the parallaxes were studied. There was nothing physical."* [2] The enthusiasm for spectroscopy was reiterated during my thesis at the Asiago observatory by Augusto Mammano, one of the discoverers of the signature of the first microquasar in SS433 (Mammano et al. 1980) as well as an avid competitor in Margherita's volleyball matches(Hack 1998, Ch.3).

[1] http://www.coelum.com/

[2] L. Bonolis, "Colloquio con Margherita Hack", 8 aprile 2003

2. Optical Spectrographs (an ESO-biased view)

So be it, Spectroscopy: from the Boller & Chivens Spectrograph at the Asiago Observatory (Barbieri et al. 1977, 1980), to Boller & Chivens Spectrographs at the La Silla Observatory (Zeilinger 1991). In La Silla I had the privilege to witness and participate in the "fast and furious" growth (D'Odorico 2018) of new instruments, in particular spectrographs, in the two decades 1978-1998: the Coudé Échelle Spectrograph (Enard & Andersen 1978, CES) in the Coudé room of the 3.6m telescope, initially fed by the 1.4m Coudé Auxiliary Telescope (CAT) and, a few years later, by an optical fibre from the 3.6m, CASPEC (D'Odorico et al. 1983), an efficient crossdispersed echelle spectrograph, and the ESO Faint Object Spectrograph & Camera (Enard & Delabre 1984; D'Odorico et al. 1986, EFOSC) and the ESO Multi-Mode Instrument (Dekker et al. 1986, EMMI) at the New Technology Telescope. The high efficiency of the optics, coupled with the high quantum sensitivity of the newly introduced CCDs, boosted the performance of these instruments and, for the first time, gave European astronomers the possibility of competing on crucial observing modes with their colleagues at other 4m-class telescopes worldwide (D'Odorico 2018). Multiple-object spectroscopy (MOS) was inaugurated on relatively small fields with EFOSC thanks to the masks of the PUMA punchmachine(D'Odorico & Dekker 1987) and on larger fields taking advantage of optical fibers with the Fibre Optics Multi-Object Spectrograph (Enard et al. 1983; Cristiani et al. 1987, OPTOPUS), both at the Cassegrain focus of the 3.6m telescope.

The list is non-exhaustive and limited to 1998; later on more (high-resolution) spectrographs would arrive in La Silla, such as FEROS (Kaufer & Pasquini 1998) and HARPS (Mayor et al. 2003) (and in the future SoXS Schipani et al. (2022) will come). More details on these and many more ESO instruments can be found in Madsen (2012).

In 1999 the VLT era began and a new panoply of powerful spectrographs gradually became available, making Paranal the most productive ground-based observatory: FORS (Appenzeller et al. 1998), UVES (Dekker et al. 2000), FLAMES (Pasquini et al. 2002), VIMOS (Le Fèvre et al. 2003), X-shooter (Vernet et al. 2011), MUSE (Bacon et al. 2010), ESPRESSO (Pepe et al. 2021).

An innovative pattern for the construction of ESO instruments was devised, with the majority of them built by consortia of institutes, within a set of standardized specifications. Institutes were rewarded for the costs incurred by them both in terms of staff and sometimes also in terms of hardware with observing nights (called Guaranteed Time Observations, GTO).

These collaborations provided advantages for both ESO and the national institutes, enabling an ambitious instrumentation programme, giving access to unique expertise nurtured in national institutes and fostering a sense of ownership of the VLT program in a significant fraction of the astronomical community. For the institutes it led to the creation of competent, multidisciplinary instrument teams around an ambitious project, and made it easier to obtain funding from national agencies to develop the necessary infrastructure, including integration and testing facilities (D'Odorico 2018). The momentum gained in this way extends to the future, as shown by the presentations at this conference about CUBES at the VLT (Covino et al.) and ANDES at the ELT (Marconi et al.).

3. The Sandage Test of the Redshift Drift (a personally biased view)

Around 2000 at ESO Garching two post-docs, Andrea Grazian and Eros Vanzella, triggered by a conversation with Luca Pasquini, approached me, asking about the possibility of using UVES spectra to measure the variation of the expansion rate of the Universe. I told them that it was an interesting idea, that more than a decade before Peter Shaver and I had fancied about applying radio observations to measure the effect, that it was instructive to work out the math, but the final result would be that the expected signal was beyond the possibility of detection with the technology of the time.

Andrea and Eros did their homework,

$$\frac{dz}{dt_o} = (1 + z)\, H_o - H(z) \tag{1}$$

and stubbornly continued to think about ways to perform this measurement, for example taking advantage of the delay time caused by gravitational lensing. We found that in 1998 Loeb had written a fundamental paper (Loeb 1998) proposing to use the Lyman Forest observed in quasar spectra for this measurement and also that the original idea dated back to 1962 with a seminal paper by Sandage (1962). It was only few months later, under a shower and with my subconscious nourished by the visionary proposal of OWL (Gilmozzi & Dierickx 2000), that I suddenly realized: "I told Andrea & Eros the detection is not possible with the **present** technology, but what about **future** technology? Particle physicists are building the LHC, we may have OWL". In this way we got into the Redshift Drift business, joining other enthusiasts of this experiment. To carry it out a new spectrograph, CODEX, was envisaged for OWL (Pasquini et al. 2005) and indeed the redshift drift became one of the four key scientific cases of the new European Extremely Large Telescope (E-ELT). 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 Cristiani et al. (2007); Liske et al. (2008). Being independent of any assumptions on gravity, geometry or clustering, the redshift drift directly tests the pillars of the Lambda CDM paradigm. Recent theoretical studies have uncovered unique synergies with other cosmological probes, including the characterization of the physical properties of dark energy Martins et al. (2016); Esteves et al. (2021). The signal has units of acceleration and is expected to be extremely small (ca. 5 cm s^{-1}per decade) but grows linearly with time. Its detection

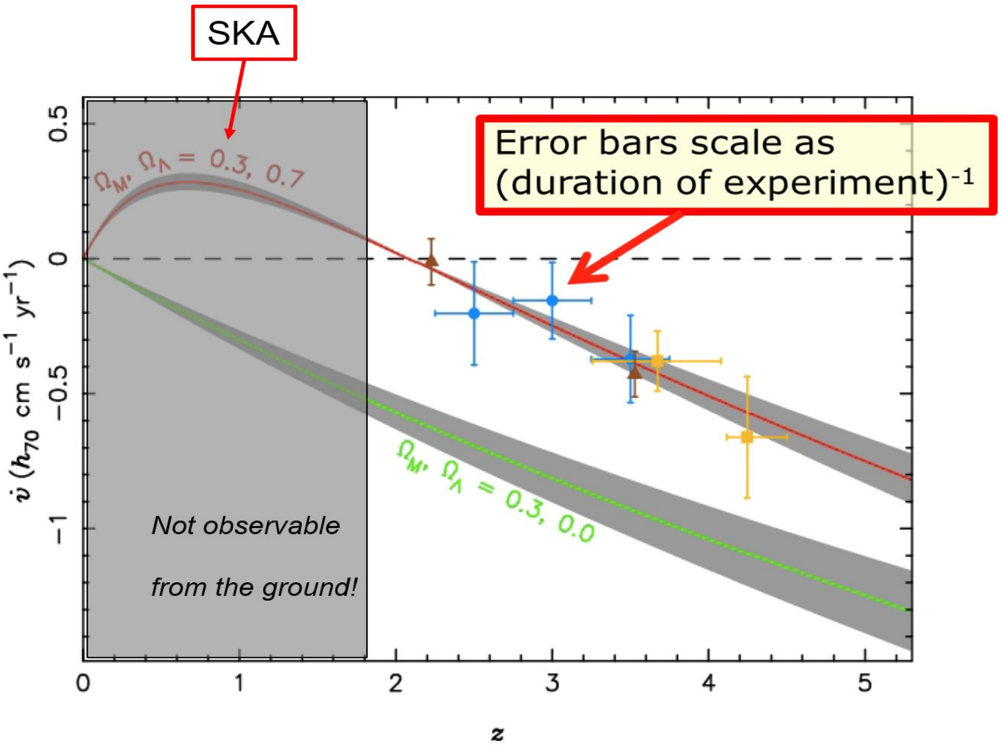

Fig. 1. Simulations of the Sandage test of the redshift drift using different example implementations of the experiment over an interval of time of 20 yr with a 42-m telescope. Blue dots: 20 quasars, binned into three redshift bins, equal time allocation, that provide the most precise measurement of $\dot{z}$. Yellow squares: selection of two higher redshift bins, 10 quasars maximizing the significance of the detection of a non-zero drift. Brown triangles: 2 quasars at lower redshift that provide the best combined constraint on Ω_Λ. The grey shaded areas result from varying Ho by ±8 km s^{-1}Mpc^{-1} (Adapted from Liske et al. (2008)).

requires several epochs of observations, extremely stable wavelength calibration ($\Delta\lambda/\lambda \sim 10^{-10}$ or, equivalently, 3 cm s^{-1}per decade), and high signal-to-noise (SNR) observations. Accuracies not far from what we need for detecting the cosmic signal are being reached in the observations of radial velocity perturbations induced by extra-solar planets in stellar spectra (e.g. ESPRESSO Pepe et al. (2021)). We want to do the same but with objects that are hundred thousand times fainter than the extra-solar planets targets, and on timescales of decades. An extremely large light bucket is needed and an absolute calibration source accurate on long time scales, the Laser Frequency Comb (Murphy et al. 2007, LFC).

The Liske et al. (2008) paper concluded that a 42-m telescope is capable of unambiguously detecting the redshift drift over a period of ~ 20 yr using 4000 h of observing time and, on the basis of detailed simulations, that a precision of

$$\sigma_v = 1.35 \text{ cm s}^{-1} \times \times \left(\frac{\text{S/N}}{2370}\right)^{-1} \left(\frac{N_{\text{QSO}}}{30}\right)^{-\frac{1}{2}} \left(\frac{1+z_{\text{QSO}}}{5}\right)^{-1.7} \quad (2)$$

can be achieved, depending on the redshift and the number of quasars, observed at a given SNR, taking advantage of various features observed in absorption in the spectra of bright, high-redshift quasars.

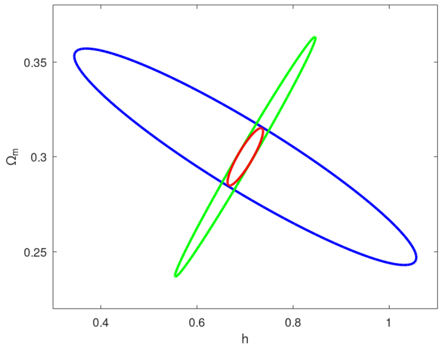

Fig. 2. Illustrating the synergy of redshift drift measurements by ELT/ANDES (blue) and the SKA Observatory (green): the plot shows the constraints from redshift drift measurements alone: a flat Lambda CDM fiducial model was assumed, but there are no external priors. The red contour is the combined constraint.

4. The QUBRICS Survey

Four thousand hours of observation of the ELT are a considerable investment and since 2008 the ELT shrank to 39.3 m, making the experiment even more daunting. Besides, observations in the Southern hemisphere, where the ELT is located, risk to be hampered by the lack of luminous targets with respect to the North, historically due to the dearth of surveys for bright quasars in the South. This was the motivation that originated the survey QUBRICS (Calderone et al. 2019; Boutsia et al. 2020, QUasars as BRIght beacons for Cosmology in the Southern hemisphere), taking advantage of the availability of several new multi-wavelength databases: Skymapper (Onken et al. 2019), Gaia (Gaia Collaboration et al. 2021), 2MASS (Skrutskie et al. 2006), WISE (Wright et al. 2010), PanSTARRS (Chambers et al. 2016), DES (Sevilla-Noarbe et al. 2021). Various selection methods have been used, with particular emphasis on machine learning (ML): in Calderone et al. (2019) candidates were selected using a canonical correlation analysis (CCA, Anderson 2003), in Guarneri et al. (2021) the Probabilistic Random Forest (PRF, Reis et al. 2019) was adopted, with modifications introduced to properly treat upper limits and missing data. In Guarneri et al. (2022) the PRF selection was further improved, in particular adding synthetic data to the training sets. In Calderone et al., (submitted) a method, dubbed Michelangelo, has been developed to significantly boost recall [3] in selection algorithms, even in the presence of severely imbalanced datasets, aimed at extending the QUBRICS survey up to $z \sim 5$.

While refining the methods of selection, a continuous effort was dedicated in QUBRICS to the follow-up spectroscopy (Boutsia et al. 2020), testing the selection procedures and leading to statistically well-defined subsamples that allowed us to address the issue of the quasar luminosity function (LF) and cosmic reionization at $z \sim 4$ (Boutsia et al. 2021) and at $4.5 < z < 5$ (Grazian et al. 2022).

A strategic feature of QUBRICS is the continuous updating, after each observation cycle, of the training set, also paying attention to identify and correct the surprisingly significant fraction of erroneous spectroscopic identifications found in the literature, in order to improve the success rate and the completeness, while keeping the list of candidates manageable.

The search for high redshift Quasars is a typical "needle in a haystack" problem and is an excellent training ground for testing and developing ML techniques that are now used in a huge number of application fields. In this way it is possible to derive a series of valuable lessons such as trying to avoid the black box syndrome (Petch et al. 2022, e.g.), heed apparently extraordinary success rates and completeness, curbe overfitting using complementary methods and dismiss stretched interpretations of non-physical features. ML is typically good for classification (i.e. giving a "label" to an object: star, galaxy, quasar...), but may be less good for regression (e.g. determining a redshift), with the interesting possibility of synergies with classical methods (e.g. model fitting) once ML has reliably identi-

[3] Recall: the fraction of relevant instances (i.e., real high-z QSOs) correctly classified by the algorithm. It is a statistical measure related to (but not the same as) the *completeness* (Guarneri et al. 2022).

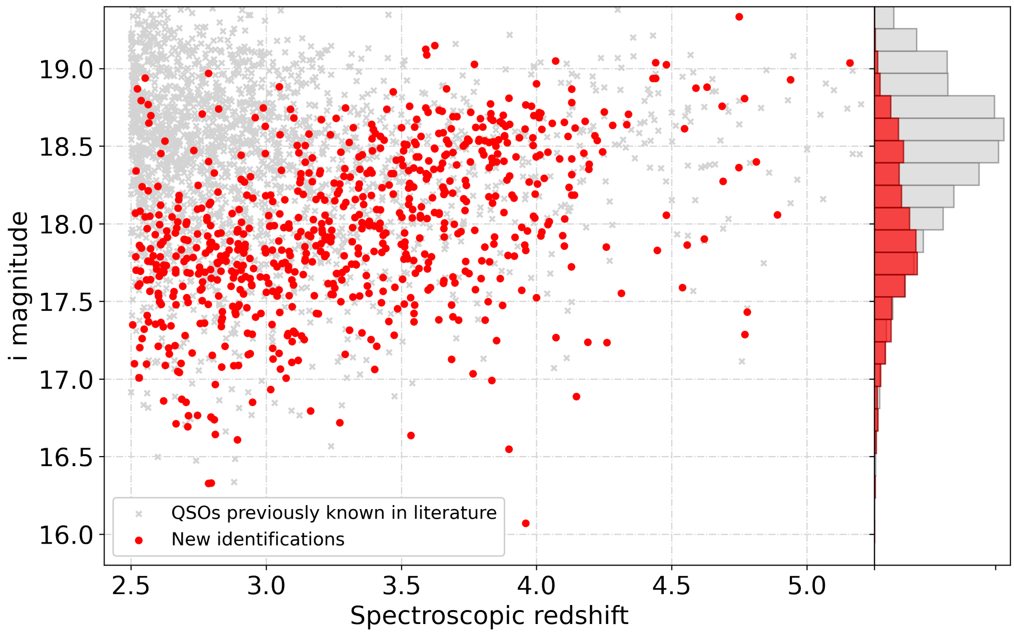

Fig. 3. i-band magnitudes versus spectroscopic redshifts for $z > 2.5$ quasars in the Southern hemisphere. Quasars discovered by QUBRICS have been highlighted in red.

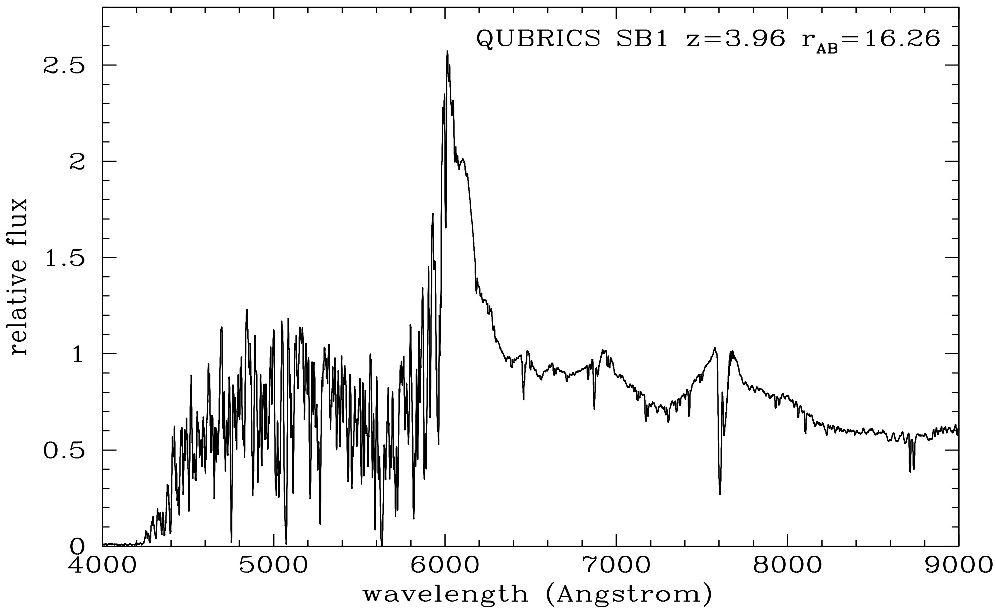

Fig. 4. Spectrum, obtained with MagE at the Magellan Telescope, of a bright quasar discovered by QUBRICS, included in the Golden Sample for the Sandage test of the redshift drift (see text).

fied the class of an object and therefore the model to apply. But above all one learns that in ML training sets are the key and biases or scarcity in the training sets can produce unfair results, in facial recognition (Buolamwini & Gebru 2018), autonomous driving, fraud detection as well as in finding high redshift quasars. Synthetic data can be a useful solution in cases where real world data is limited (Chaudhari et al. 2022; Guarneri et al. 2022).

The QUBRICS survey has produced several hundred new spectroscopically confirmed bright quasars at $z > 2.5$ (see Fig. 3). In Boutsia et al. (2020) it was shown that with a new Golden Sample of 30 quasars the redshift drift measurements, using the ANDES spectrograph at the 39m ELT, appears to be possible with less than 2500 hours of observations spread over 25 years. New bright quasars have been found since then and new optimal observation strategies are being devised, further decreasing the required investment of time. Precursor observations with ESPRESSO have been started, that, although not detecting the drift signal, aim at obtaining the first statistics-limited constraint, improving current bounds by an order of magnitude, and providing a full end-to-end proof of concept for the ANDES experiment at the ELT. An old spectroscopist's dream is starting to come true.

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