Studying stellar populations of luminous red galaxies to probe the Hubble parameter $H(z)$

A. L. Ratsimbazafy[1], **C. M. Cress**[2,3], **S. M. Crawford**[4], **M. Smith**[5]

[1]Centre for Space Research, North-West University, Potchefstroom 2520, SA
[2]Centre of High Performance Computing, CSIR, 15 Lower Hope St, Rosebank, Cape Town 7700, SA
[3]Physics Department, University of the Western Cape, Private Bag X17, Cape Town 7535, SA
[4]South African Astronomical Observatory, PO Box 9 Observatory, Cape Town 7935, SA
[5]School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK

E-mail: `Ando.Ratsimbazafy@nwu.ac.za`

Abstract. There have been a number of attempts to measure the expansion rate of the Universe using age–dating of Luminous Red Galaxies (LRGs). Assuming that stars in LRGs form at the same time, age–dating of two populations of LRGs at different redshifts can provide an estimate of the time difference associated with the corresponding redshift interval (dz/dt). This gives a direct estimate of the Hubble parameter $H(z)$ at the average redshift of the two populations. We explore the validity of this method by using two different sets of data. Firstly, we select a homogeneous sample of passively evolving galaxies over $0.10 < z < 0.40$ from the Sloan Digital Sky Survey Data Release Seven (SDSS-DR7) catalogue by applying a refined criteria, which is based on absolute magnitude. Secondly, we carry out a series of observations on the Southern African Large Telescope (SALT) to obtain spectra of LRGs at two narrow redshift ranges $z \simeq 0.40$ and $z \simeq 0.55$ in order to calculate the Hubble parameter $H(z)$ at $z \simeq 0.47$. We utilise different methods of age-dating including full spectral fitting on high signal-to-noise galaxy spectra from our sample. We present the $H(z)$ estimates and their cosmological constraints using the two different data sets.

1. Introduction

The expansion rate of the Universe can potentially be measured by age–dating Luminous Red Galaxies (LRGs). This technique is well known as *Cosmic Chronometers* (CC), and was originally proposed by [1]. Most cosmological probes only measure the expansion rate integrated along a line-of-sight. However, the CC method allows a measurement at a specific redshift, and this can provide tighter constraints on cosmological parameters. The Hubble parameter is given by

$$H(z) = -\frac{1}{(1+z)}\frac{dz}{dt} \tag{1}$$

where dz/dt can be approximated by determining the time interval Δt corresponding to a given Δz, where Δz is centered at redshift z. The overall method is valid when assuming that if most stars in LRGs formed near the beginning of the Universe at a similar time, then measuring the age difference between ensembles of LRGs at two different redshifts provides the differential quantity $\Delta z/\Delta t$ required to estimate the Hubble parameter $H(z)$. Using a differential quantity significantly reduces systematics associated with the age determination. Some systematic errors in the absolute age measurements have been a subject of discussion but such errors could be cancelled by using the relative ages of these galaxies, for example in Ref. [1, 2, 3]. Furthermore, only the galaxy evolution that takes place between the redshifts, where the difference is taken, is the most important while using this method.

A number of scientists have attempted to use this method to track the evolution of $H(z)$ up to redshift $z \sim 2$, and these results have been used to put constraints on cosmological parameters, for example in Ref. [2, 3, 4, 5, 6, 7, 8]. In each measurement, the authors assumed that LRGs are massive, passively–evolving elliptical galaxies that are homogeneous populations forming their stars at high redshift, and they fit single–burst equivalent ages to the galaxies.

Here, we present two different data sets including the existing archival data from the Sloan Digital Sky Survey Data Release Seven (SDSS–DR7) and data observed with the Southern African Large Telescope (SALT), $H(z)$ estimates and their cosmological constraints.

2. SDSS–LRGs

We selected a homogeneous sample of passively evolving elliptical galaxies from the SDSS catalogue by using different selection criteria which are based on the rest–frame magnitude and colour. The original sample was in the redshift range $0.10 < z < 0.40$. Further selection was applied to it to create a quiescent sample free from any emission lines and a sample which contains massive galaxies. We divided the redshift range into 15 redshift bins with a step of $\delta z = 0.02$. The full spectrum fitting was chosen to obtain Simple Stellar Population (SSP) equivalent ages and other parameters. We used the ULySS[1] (University of Lyon Spectroscopic analysis Software) package for the fits. ULySS [9] fits the entire spectrum with a model in the form of a linear combination of non–linear components, corrected for the kinematics and multiplied by a polynomial at the same time. The use of a multiplicative polynomial makes this method insensitive to the effects of the flux calibration uncertainties and the Galactic extinction.

In order to improve the fits, all galaxy spectra within a redshift bin were combined to obtain a high signal–to–noise (S/N) ratio spectrum. We used the SSP models called GALAXEV [10] (BC03). These models were generated using the STELIB library with a resolution of about 3Å FWHM across the whole spectral range 3200 – 9500 Å, the Chabrier Initial Mass function (IMF) with a mass of 0.1 to 100 $M_\odot$ and a slope of -1.35 and Padova 1994 isochrones. These models cover ages from 0.1 to 20 Gyr and [Fe/H] from -2.3 to 0.4 dex, consisting of 696 SSPs. The fitting was performed over the whole wavelength coverage of the co–added spectra, and its reliability was checked (with Monte Carlo simulations, χ^2 and convergence maps) before validating the SSP results.

Due to the lack of the number of galaxies to be combined to form the high S/N ratio spectra, only ages at high redshift $z > 0.20$ were used to measure $H(z)$. From establishing the age–redshift relation, we adopted the linear fitting procedure to fit ages in a specific redshift bin $t(z_i)$. The slope of the fit was therefore the value of dz/dt which is related to the Hubble parameter at an effective redshift $z_{eff} = (z_{max} + z_{min})/2$, according to the Equation 1. Precisely,

$$H(z_{eff}) = -\frac{1}{(1+z_{eff})}\left(\frac{dt}{dz}\right)^{-1} \tag{2}$$

The redshift difference Δz should not be too wide or too narrow in order to preserve the same number of galaxies in each redshift bin, to maximise the number of $H(z)$ measurements and to minimise the relative error bars. After testing different Δz (from lowest 0.8 to highest 0.16), the optimised Δz was set to be 0.14 with which all ages were used and the number of ages were the same. Therefore, 8 age data points were used in each subsample, leading to 3 values of $H(z)$ at

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[1] Available at http://ulyss.univ-lyon1.fr/

the following effective redshifts $z \simeq 0.32$, $z \simeq 0.30$ and $z \simeq 0.28$. The corresponding error on the $H(z)$ was obtained by using the error propagation technique. The stacking technique provides us less than 10% uncertainties in age estimates which leads to better $H(z)$ estimates compared with the values found in the literature.

The $H(z)$ results match the ΛCDM cosmology, see Figure 1. When testing different SSP models, we found some model dependence on the derived ages, hence different $H(z)$ measurements. The sensitivity and the different ingredients of models led to some changes on $H(z)$ estimates. This is one of the sources of systematic errors when adopting the CC technique. A further investigation on this is in progress. The possibility of the contribution of the young stellar populations in the relative age determination was also tested. We fitted two stellar components; one young (from 0.1 Gyr to 2 Gyr) and one old (from 2 Gyr – age of the Universe) and found that the fraction of the young population is negligible.

The comparison plot between our measurements and the other observational Hubble parameters $H(z)$ is shown in Figure 1. Data sets from Ref. [3, 4, 5, 6, 7, 11] are included to check the $H(z)$ evolution up to $z \sim 2$. Note that all $H(z)$ shown in this plot are obtained by applying the same technique of CC, except the results from [11] which are from the radial Baryonic Acoustic Oscillations (BAO) method. These data points are included in our analysis in order to compare our results on cosmological constraints (see section 4) with the previous works.

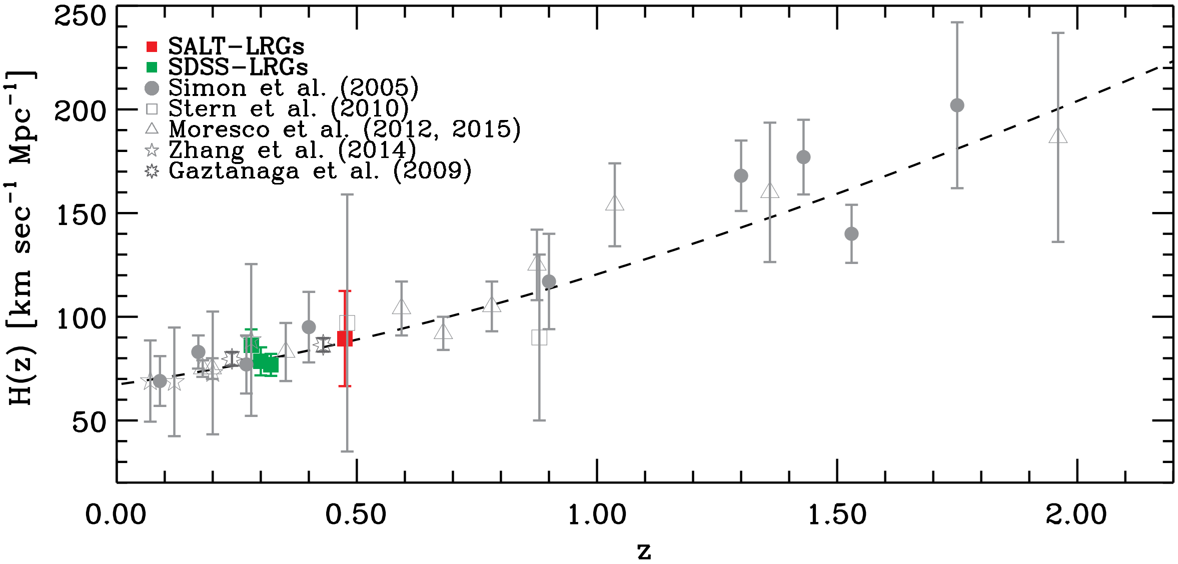

Figure 1. All available observational $H(z)$ data points. The green points are our measurements using SDSS–LRGs and the red point for using SALT–LRGs. The dashed line is the theoretical $H(z)$ of a flat ΛCDM cosmology model by *PLANCK* assuming $H_0 = 67.3$ km s^{-1} Mpc^{-1} and $\Omega_m = 0.315$. For the SDSS–LRGs : $H(z \simeq 0.32) = 86.3 \pm 7.6$ km s^{-1} Mpc^{-1}, $H(z \simeq 0.30) = 78.5 \pm 6.8$ km s^{-1} Mpc^{-1} and $H(z \simeq 0.28) = 76.8 \pm 5.3$ km s^{-1} Mpc^{-1} were estimated when fitting a straight line on the ages over $0.24 < z < 0.40$, $0.22 < z < 0.38$, and $0.20 < z < 0.36$, respectively. For the SALT–LRGs: $H(z \simeq 0.47) = 89 \pm 23$ km s^{-1} Mpc^{-1} was measured using the differential ages.

3. SALT–LRGs

We [12] found that a 3% measurement would be viable from a large redshift program targeting LRGs, and explored optimal observational set–ups for the experiment using the SALT telescope. We then obtained, reduced and analysed 16 long–slit spectra of LRGs recently observed with the SALT telescope. These galaxies were selected from the 2dF–SDSS LRG and QSO (2SLAQ) and MegaZ–LRGs catalogues at redshift $z \simeq 0.40$ and $z \simeq 0.55$. Our selection was based on stellar mass, brightness and emission lines of a galaxy in order to have a sample of old and massive passively–evolving galaxies. For all observations, the basic reductions were already performed by the semi–automated code PySALT[2] [13]. Further reduction was performed by following the standard long–slit data reduction technique with IRAF[3]. All spectra were corrected for foreground Galactic extinction.

Although in our previous work [12] we did find that LRGs may be better described by slightly extended star formation histories, we only fitted the LRGs to SSPs in order to compare this work to previous studies. We performed the full spectrum fitting after matching the resolution of both model and observed spectra. The reliability of the fits were also checked carefully. Despite the number of galaxies at $z \simeq 0.55$ (only 6 as compared to 10 at $z \simeq 0.40$), we found an age–redshift relation, that is, the mean age at $z \simeq 0.40$ is older (3.88 ± 0.20 Gyr) than that at $z \simeq 0.55$ (2.80 ± 0.18 Gyr). We found younger ages than the total sample of red galaxies in [4] at both redshifts but we note that we have a small number of galaxies in our sample. The error on the mean age was obtained by applying the standard error propagation technique.

The mean age of the sample at each redshift was used to measure the differential ages. Applying Equation 1 to the intermediate redshift between $z \simeq 0.40$ and $z \simeq 0.55$, we obtained a new observational Hubble parameter $H(z \simeq 0.47) = 89 \pm 23$ km s^{-1} Mpc^{-1} using SSP equivalent ages (see Figure 1). The most comparable measurement at the same redshift is by [4], who measured a value of $H(z) = 97 \pm 60$ km s^{-1} Mpc^{-1} at $z = 0.48$. Our value is consistent with the standard cosmology model with the parameters $\Omega_m = 0.315$, and $H_0 = 67.3$ km s^{-1} Mpc^{-1}.

We have addressed the estimated number of galaxies required to obtain the desired precision in [12]. In reality, we could not reach the estimated accuracy because of the observation constraints such as the quality of the observed spectra in terms of S/N ratio, or the fact that the number of observed objects could not complete our original estimation. A larger and better quality sample would help us to reach our main goal for the future. The relatively small sample presented here was part of an initial pilot study and further observations will be required to improve on the measurement.

4. Cosmological Constraints

We made use of our $H(z)$ measurements combined with the recent and available $H(z)$ in the literature (all data points plotted in Figure 1) to investigate their constraining power on the determination of cosmological parameters. We also combined those $H(z)$ data with other cosmological measurements: BAO, Wilkinson Microwave Anisotropy Probe (WMAP) and Hubble Space Telescope (HST) to better determine the constraints on the parameter calculations. The first calculation was done with our own code, the second one was performed by using the publicly available code `cosmoMC`. Both calculations were based on the Markov Chain Monte Carlo (MCMC) techniques to determine the cosmological parameters in the standard ΛCDM models, such as the density of matter parameter today Ω_m, the cosmological constant Ω_Λ, the spatial curvature parameter today Ω_k and the Hubble constant today H_0.

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[2] pysalt.salt.ac.za

[3] Image Reduction and Analysis Facility, a software system distributed by the National Optical Astronomy Observatories (NOAO). Available at http://iraf.noao.edu/

Our new $H(z)$ measurements impact current constraints on cosmological parameters even though only 4 data points were added to the old ones (27 data points). The 1D marginalised probability distribution of using 31 data points shows more serried distribution than using the old data sets, while they tighten each parameter contour of the confidence level in the 2D marginalisation plots. The best fit parameters are shown in Table 1 for a flat ΛCDM model.

We further combined the above observational $H(z)$ measurements with the other major data sets such as WMAP nine year data (WMAP9), BAO and H_0 HST to investigate their constraints on the determination of the cosmological parameters. The latest results of the Cosmic Microwave Background (CMB) temperature and polarization power spectra from WMAP9 [14] were used as well as the BAO measurement from:

- 6dF Galaxy Redshift Survey (6dFGRS) at z =0.106 [15]
- SDSS–LRGs DR7 sample at $z = 0.35$ [16]
- SDSS–LRGs DR9 sample at $z = 0.57$ [17]
- WiggleZ survey at $z = 0.44$, $z = 0.60$ and $z = 0.73$ [18]

The last data set used was HST measurement of the Hubble parameter today $H_0 = 73.8 \pm 2.3$ km $\mathrm{s^{-1}Mpc^{-1}}$ [19]. This value was obtained from the magnitude–redshift relation of 235 Supernovae type Ia (SNIa) observed with HST.

For a flat ΛCDM, we obtained the constraints shown in Table 2. It shows mainly the effect on cosmological parameters of adding four basic data combinations: WMAP9, WMAP9+H_0 HST, WMAP9+BAO and WMAP9+BAO+H_0 HST. Through these results, we can see that the overall joint constraints are consistent with the standard cosmological model. We find that adding the $H(z)$ data sets and H_0 HST shows noticeable constraints on H_0, Ω_m parameters. This is also due to the better constraint on the current Hubble constant H_0. WMAP9+Hz joint analysis does not provide any improvement over the WMAP9 alone since the WMAP9 constraint is much more precise than the $H(z)$ constraint. The WMAP9+BAO data alone only give very weak constraints on Ω_m. However, a combination of WMAP9+BAO with the measurements of Hubble parameter $H(z)$ significantly improves the 1-σ error on both parameters. The parameter values of $H_0 = 69.4 \pm 1.3$ km $\mathrm{s^{-1}Mpc^{-1}}$ and $\Omega_m = 0.295^{+0.011}_{-0.012}$ are consistent with results of [8], where only 25 observational $H(z)$ data points were used. More external $H(z)$ data sets (for example from the most recent BAO measurements, *PLANCK* data, latest SNIa data sets) are needed to further investigate on cosmological constraints, and determine different cosmological parameters.

Table 1. Constraints on cosmological parameters from LRG measurements of $H(z)$. Marginalised constraints on H_0, Ω_m, and Ω_Λ at 1-σ for a flat ΛCDM model

Model Parameter	27 data points	31 data points
H_0	$68.9^{+2.7}_{-2.5}$	68.6 ± 2.3
Ω_m	$0.320^{+0.047}_{-0.064}$	$0.321^{+0.048}_{-0.060}$
Ω_Λ	$0.679^{+0.047}_{-0.050}$	$0.675^{+0.060}_{-0.048}$

5. Conclusions

The differential age or *Cosmic Chronometers* technique is an interesting way to measure the expansion rate of the Universe, since it gives a direct measurement between two distinct redshifts. It uses massive and passive ellipticals. We have explored this technique by analysing both existing archival SDSS–DR7 data and new spectra obtained with the SALT telescope. The full spectrum fitting with BC03 models has been applied to extract the SSP equivalent ages.

Table 2. Combining LRG results from $H(z)$ with other measurements. Marginalised constraints at 1-σ on H_0, Ω_m parameters obtained for a flat ΛCDM model. Hz means including $H(z)$ data sets.

	H_0	Ω_m
WMAP9+Hz	$68.7^{+2.6}_{-2.3}$	$0.319^{+0.048}_{-0.062}$
WMAP9+H_0 HST+Hz	$71.3\ ^{+1.8}_{-1.6}$	$0.270^{+0.034}_{-0.043}$
WMAP9+BAO	$68.1^{+3.8}_{-4.7}$	$0.299^{+0.016}_{-0.022}$
WMAP9+BAO+Hz	69.4±1.3	$0.295^{+0.011}_{-0.012}$
WMAP9+BAO+H_0 HST	$72.5^{+0.7}_{-0.6}$	0.284±0.003
WMAP9+BAO+H_0 HST+Hz	70.4±1.1	0.290 ±0.010

Using SDSS–LRGs, three measurements of $H(z)$ were obtained at three different redshifts: $H(z \simeq 0.32) = 86.3 \pm 7.6$ km s^{-1} Mpc^{-1}, $H(z \simeq 0.30) = 78.5 \pm 6.8$ km s^{-1} Mpc^{-1} and $H(z \simeq 0.28) = 76.8 \pm 5.3$ km s^{-1} Mpc^{-1}. One additional $H(z)$ measurement was estimated using SALT–LRGs, which has a value of $H(z \simeq 0.47) = 89 \pm 23$ km s^{-1} Mpc^{-1}. The four $H(z)$ values combined with external data sets have been employed to constrain the cosmological parameters. We have obtained noticeable constraints and parameter values of $H_0 = 69.4 \pm 1.3$ km s^{-1}Mpc^{-1} and $\Omega_m = 0.295^{+0.011}_{-0.012}$, which are consistent with the standard cosmological model and very consistent with previous results.

Further investigations on cosmological constraints should be done by adding more external $H(z)$ data sets, for example from the new *PLANCK* data, latest SNIa data sets, recent BAO measurements. The systematic errors between SSP models remain a subject of discussion. Further analysis on this will be performed.

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