Draft version September 28, 2012
Preprint typeset using LaTeX style emulateapj v. 08/22/09

TESTING HOMOGENEITY WITH THE GALAXY FOSSIL RECORD

Ben Hoyle[1], Rita Tojeiro[2], Raul Jimenez[3,1,4], Alan Heavens[5], Chris Clarkson[6], Roy Maartens[7,8]

Draft version September 28, 2012

ABSTRACT

Observationally confirming spatial homogeneity on sufficiently large cosmological scales is of importance to test one of the underpinning assumptions of cosmology, and is also imperative for correctly interpreting dark energy. A challenging aspect of this is that homogeneity must be probed inside our past lightcone, while observations take place on the lightcone. The history of star formation rates (SFH) in the galaxy fossil record provides a novel way to do this. We calculate the SFH of stacked Luminous Red Galaxy (LRG) spectra obtained from the Sloan Digital Sky Survey. We divide the LRG sample into 12 equal area contiguous sky patches and 10 redshift slices ($0.2 < z < 0.5$), which correspond to 120 blocks of volume $\sim$0.04 Gpc^3. Using the SFH in a time period which samples the history of the Universe between look-back times 11.5 to 13.4 Gyrs as a proxy for homogeneity, we calculate the posterior distribution for the excess large-scale variance due to inhomogeneity, and find that the most likely solution is no extra variance at all. At 95% credibility, there is no evidence of deviations larger than 5.8%.

Subject headings: cosmology: theory, large-scale structure of universe, early universe

1. INTRODUCTION

The ΛCDM concordance model is extremely successful, as it can fit most cosmological observations with just 6 free parameters. Testing the assumptions that go into this model is vital, but it is often neglected. In particular, the model rests on the assumption of spatial homogeneity and isotropy on sufficiently large scales (for a review see Clarkson & Maartens 2010; Maartens 2011; Clarkson 2012). It is therefore appropriate and timely to devise observational tests that allow us to probe the homogeneity and isotropy assumptions. We know the isotropy assumption is well supported by detailed observations of the cosmic microwave background, which has shown that temperature variations are only one part in 10^5 across the sky. However, homogeneity is much more difficult to probe. Homogeneity is not established by observations of the CMB and the galaxy distribution: we cannot directly observe homogeneity, since we observe down our past light-cone, recording properties on 2-spheres of constant redshift and not on spatial surfaces that intersect that lightcone. What these observations can directly probe is isotropy. In order to link isotropy to homogeneity, we have to assume the Copernican Principle, i.e. that we are not at a special position in the Universe. The Copernican Principle is not observationally based; it is an expression of the intrinsic limitation of observing from one space-time location.

The importance of testing the homogeneity assumption has been highlighted by the development of inhomogeneous 'void' models which can potentially explain apparent acceleration without any exotic physics. By changing the mean density and expansion rate radially away from us, observations such as SNIa can be accommodated without any dark energy (see e.g., Biswas et al. 2010; Marra & Notari 2011; Clarkson 2012, for reviews.). However, it is difficult to fit all observations – in particular the combination of H_0 and the CMB – without requiring significant inhomogeneity or other departures from the standard model at early times as well (Nadathur & Sarkar 2011; Bull et al. 2012; Clarkson & Regis 2011; de Putter et al. 2012).

This implies that tests for homogeneity must be made throughout the history of the universe. Consistency tests which could uncover deviations from homogeneity can be used to probe consistency of observables on our past lightcone (Clarkson et al. 2008). Probing inside our past lightcone is harder, however, because we cannot observe it directly. One method is to use the Sunyaev-Zel'dovich effect to observe CMB anisotropies from distant clusters (Goodman 1995; Caldwell & Stebbins 2008). Another is to probe the thermal history in widely-separated regions of the universe (Bonnor & Ellis 1986), as it should of course be the same in the standard model.

In this letter, we apply a new method of testing homogeneity in the interior of our past lightcone for the first time, by comparing the fossil record of galaxies at different redshifts at different times along their past worldlines, thus accessing different patches of the Universe at the same cosmic time. A full proof of homogeneity would entail establishing homogeneity of the metric tensor. Here we apply a consistency test to check for violations of homogeneity, using the star formation rate as a probe, following the idea Heavens et al. (2011). The fossil record, or the star formation history (hereafter SFH),

---

[1] Institut de Ciences del Cosmos (ICC), Universitat de Barcelona (IEEC-UB), Marti i Franques 1, Barcelona 08024, Spain.
[2] Institute of Cosmology & Gravitation, University of Portsmouth, Dennis Sciama Building, Portsmouth, PO1 3FX, UK.
[3] ICREA, Barcelona, Spain.
[4] Theory Group, Physics Department, CERN, CH-1211, Geneva 23, Switzerland.
[5] Astrophysics Group, Imperial College London, Blackett Laboratory, Prince Consort Road, London SW7 2AZ, U.K.
[6] Department of Physics, University of Western Cape, Cape Town 7535, South Africa.
[7] Astrophysics, Cosmology & Gravity Centre, and, Dep. of Mathematics & Applied Mathematics, University of Cape Town, South Africa.
[8] The Institute of Cosmology & Gravitation, University of Portsmouth, Dennis Sciama Building, Portsmouth, PO1, U.K.

can be obtained by analysing the shape of the galaxy spectrum, which encodes information about the histories of the component stellar populations, dust, and star formation. Various tools have been developed to extract this information (e.g., Heavens et al. 2000; Cid Fernandes et al. 2005; Ocvirk et al. 2006; Vincoletto et al. 2012), of which we use the VErsatile SPectral Analysis[9] (hereafter VESPA, see Tojeiro et al. 2007, 2009, for more details). These approaches rely on the assumption that the evolution of the stellar populations is well understood and that the current modelling of stellar population is accurate. We use VESPA to obtain the SFH within the time bin 11.5 to 13.4 Gyrs of stacked Luminous Red Galaxy (LRG) spectra located at different positions on the sky and at different redshifts. We compare the histories of different patches of the Universe, using the local star formation rate as a proxy for homogeneity.

This letter is organised as follows; in §2 we briefly describe the applicability of the VESPA routine as a test of homogeneity, and then describe the data, simulated data and our method in §3. We present the results in §4 and conclude in §5.

To calculate distances, and to map from redshift to time, we assume a fiducial flat ΛCDM with best fit WMAP7 (Komatsu et al. 2011) cosmological parameter values. Since we are testing homogeneity, it is conservative to assume this relation, which may be different in inhomogeneous universes (Heavens et al. 2011). Any viable dark energy or modified gravity model will have a background redshift-time relation that is close to the concordance model's.

2. VESPA AND HOMOGENEITY

An illustrative diagram of our method is shown in Fig.1. Here, for illustration only, we assume that LRGs form at a similar cosmic time, and have similar SFHs, which we illustrate by the galaxies changing colour. VESPA recovers the SFH for each galaxy along its own world line (vertical lines in Fig.1), allowing us to compare the SFH at different distances but at the same cosmic time, e.g. at H1a & I1a. We note that comparing the SFH at locations I1a & I2a or I1b & I2b would be a test of isotropy only. In practice there is scatter in the SFH, due to sample variance on small scales and measurement error. We will consider these later, and seek additional variance from large-scale inhomogeneity.

3. DATA AND METHOD

Data: All of the galaxies used in this study were drawn from Sloan Digital Sky Survey (see York et al. 2000; Gunn et al. 2006; Smith et al. 2002, and references therein) Data Release 7 (Abazajian et al. 2009, hereafter SDSS DR7). We use 8.5×10^4 galaxies between the redshift range of $0.25 < z < 0.55$, selected to be Luminous Red Galaxies (Eisenstein et al. 2001, hereafter LRG) drawn from the VESPA database.

We divide the SDSS survey footprint into 12 equal area sky patches using HealPix[10] (Górski et al. 2005), and $N_z = 10$ redshift slices, whose widths are shown in Table 1, together with the total number of galaxies, and the approximate volume of the SDSS survey in each redshift slice. We hereafter refer to the galaxies in each sky patch at each redshift slice as a 'block' (B) of galaxies. We randomly select galaxies in each block into sub-samples of approximately 200 galaxies and stack the SDSS galaxy spectra for all galaxies in each sub-sample following the method presented in Tojeiro et al. (2011). We use VESPA to interpret the stacked spectrum in terms of a star formation and enforce VESPA to recover measurements in 16 time bins, τ'. The time bins are in the rest frame of the stacked-spectra, or alternatively the rest frame of the galaxy block T_B, and we refer to these quantities as the Star Formation Histories SFH(T_B, τ'). Additionally, we enforce VESPA to only allow star formation in bins whose starting times are after the start of the Universe, calculated assuming our fiducial cosmology.

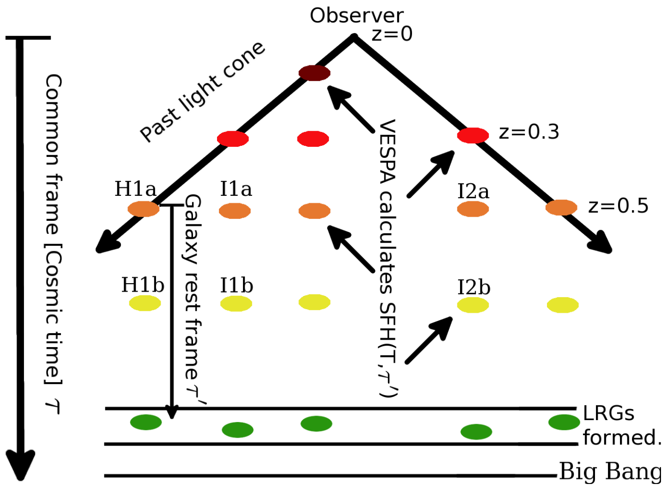

FIG. 1.— An illustration of the test of homogeneity. We assume that LRGs form at a similar cosmic time, and have similar stellar formation rate histories (SFH), which we illustrate by the galaxies changing colour. VESPA recovers the SFH for each galaxy in the galaxies rest-frame τ'. We re-bin the SFH to the common-frame τ, and compare the local SFR at, for example, locations H1a & I1a, or H1a & I2a (etc.) to test homogeneity.

Redshift ID	Range	Ngals	Vol Gpc^3
1	$0.200 < z < 0.279$	7874	0.90
2	$0.280 < z < 0.308$	9352	0.46
3	$0.309 < z < 0.327$	8532	0.34
4	$0.328 < z < 0.342$	8594	0.29
5	$0.343 < z < 0.359$	9181	0.36
6	$0.360 < z < 0.376$	8202	0.39
7	$0.377 < z < 0.398$	8754	0.55
8	$0.399 < z < 0.424$	8277	0.71
9	$0.425 < z < 0.457$	8272	1.00
10	$0.458 < z < 0.537$	8065	2.91

TABLE 1
WE SHOW THE REDSHIFT IDENTIFIER AND RANGE OF THE REDSHIFT SLICES, THE NUMBER OF SDSS LRGS WITHIN EACH SLICE, AND THE APPROXIMATE VOLUME IN GPC^3 CONTAINED BY THE REDSHIFT SLICE.

Methodology: We next add the age of the Universe, calculated using our fiducial cosmology, at the average redshift of the galaxy block T_B, to the ages of the recovered VESPA bins for the stacked-spectra. We map the values of the SFH(T_B, τ') to a common frame SFH($0, \tau$) with bins denoted by τ, the look back time with respect to the current epoch, and have chosen the lowest bin to be at $t = 0$. When we map the VESPA time bins τ' to the

---

[9] http://www-wfau.roe.ac.uk/vespa/
[10] http://healpix.jpl.nasa.gov

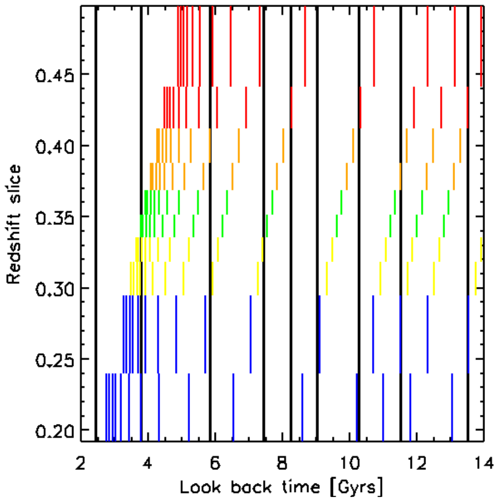

FIG. 2.— The start and end positions of the rest-frame (τ' in the text) VESPA bins in look back time, for each redshift slice. The continuous solid lines black lines show the locations of the common frame (τ) bins. We concentrate our test of homogeneity within the final bin between 11.5 and 13.4 Gyrs.

common time bin τ we choose to maintain the bin widths, to avoid over-binning the data. Fig. 2 shows the start and end times of the rest-frame τ' VESPA bins in look back time (horizontal axis), for each redshift slice (vertical axis). The continuous solid lines black lines show the locations of the common frame τ bins with start times greater than 2 Gyrs. LRGs form most of their stars very early on, and so we concentrate our test of homogeneity within the greatest time bin $\tau = 15$, which corresponds to a look-back time between 11.5 and 13.4 Gyrs. The reason for this is that all galaxies have considerable star formation in this bin. For later bins some galaxies have zero estimated star formation, which skews the distribution.

The redshift slices of the blocks (recall that a block is a redshift slice/sky patch) are chosen to contain $N_s \geq 3$ stacked spectra from N_s galaxy sub-samples. For each block B, we calculate the average A_B, and estimate the standard deviation of the block SFH, σ_B, from the sub-blocks. We determine the mean value μ of A_B, and further calculate the average value of A_B for all blocks at fixed redshift z, A_z and the standard deviation of A_z across the $N_z = 10$ redshift slices, which we denote as $\sigma_z = \sigma\big(A_z\big)$.

The dispersion σ_z is scatter arising from the re-binning of solutions $\mathrm{SFH}_{B,i}(T_B,\tau')$ of blocks at different redshifts to the common frame $\mathrm{SFH}_{B,i}(0,\tau)$. Note that block-to-block inhomogeneity would contribute to this, but only at the level of 1/12 of the variance, so it will affect our conclusions on the rms inhomogeneity by only 4%. We will, however, make this correction.

For illustration we compute the Student t-distribution t_S, for all blocks:

$$t_s = \frac{A_B - \mu}{\sqrt{\sigma_B^2 + \sigma_z^2}}.$$

which determines the number of 'combined error' $\sigma \equiv \sqrt{\sigma_B^2 + \sigma_z^2}$, or the departure the measurement A_B, is from the mean or notional value for the entire sample at each time τ.

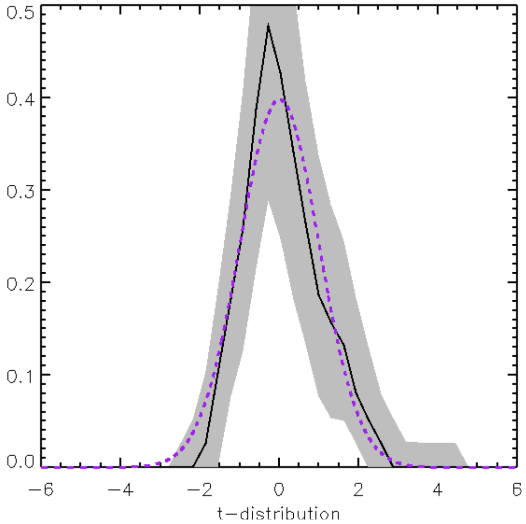

FIG. 3.— The Student-t distribution for the SDSS SFH data, assuming that the variance is due to a combination of small-scale (sub-block) sample variance, measurement error and scatter due to rebinning from the galaxy rest frame to the present epoch. The grey region give the 95% spread of Gaussian Random Samples from the data and errors. We over-plot the theoretical t_s-distribution.

We compare the probability density function obtained by the above analysis, with the theoretical probability density function $f(t)$ of the t-distribution with $\eta = 10 \times 12$ degrees of freedom, which has the analytic form given by

$$f(t) = \frac{1}{\sqrt{\eta}B(1/2,\eta/2)}\left(1+\frac{t^2}{\eta}\right)^{-(\eta+1)/2} ,$$

where $B(1/2,\eta/2)$ is the Beta function. We see in Fig. 3 that the distribution of t_s follows the expected distribution reasonably well. The grey shaded area shows the 95% range for t_s statistics from 4000 Gaussian Random Samples of the SFH and errors.

We now more formally model the data as having a gaussian distribution but with the possibility of an extra fractional variance V arising from inhomogeneity. i.e. we assume homogeneity and check for consistency using the likelihood of the data given by

$$P_B(V) = \frac{1}{\sqrt{2\pi}\sigma_V}\exp\left[-\left(A_B-\mu\right)^2/2\sigma_V^2\right],$$
$$\sigma_V^2 = \sigma_B^2 + \sigma_z^2 + V\mu^2 .$$

If we assume a uniform prior for V, then $P(V) = \Pi_B P_B(V)$ is the posterior for V given the entire block dataset. As a check, we show $P(V)$ in Fig. 4 for simulated datasets (sub-blocks) with variance $N_s\sigma_B^2$, for different star formation histories: a continuous SFH, a gaussian SFH with mean 10 and standard deviation $\sqrt{2}$ Gyr, an exponential SFH with a scale length of 0.5 Gyr, and a SFH equal to the mean of the data. SFHs are re-binned to the common frame. We see in all cases that the posterior is correctly maximised at zero, and an upper limit dependent on the SFH.

4. RESULTS

In Fig 4 we show with the solid line the posterior distribution for the additional fractional variance V in the SFH of the blocks. The most probable variance due to

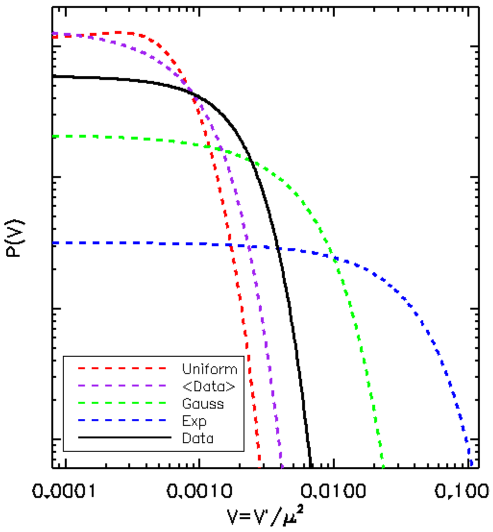

FIG. 4.— The ensemble probability that the dispersion seen in the values of A_B are drawn from a Gaussian distribution around μ, as a function of an additional error component V, which is scaled by μ^2. The colored dashed lines show the probability for each simulated SFR and the black solid line shows the data.

inhomogeneity is zero, and 95% of the posterior probability lies within $V < 0.0032$. Hence the 95% credibility interval for the additional fractional inhomogeneity r.m.s., $\sqrt{V}$ (assuming a uniform prior on V), is 5.6%, or 5.8% if we include a correction for the rebinning.

5. CONCLUSIONS

Modern cosmology is built upon the assumption of homogeneity which is inferred through the observation of isotropy (e.g. by the Cosmic Microwave Background radiation) and the Copernican principle, stating that we do not occupy a preferred location.

Deviations from homogeneity, in particular, an inhomogeneous background, for example LTB models in which massive void exist, can potentially explain the dimming of distant supernovae and thus remove the need for dark energy. Testing homogeneity is therefore an active area of research, and many tests have been devised, e.g., kinematic SZ effect.

In this letter we have performed a new observational test of homogeneity (Heavens et al. 2011) by examining the estimated Star Formation Histories in old stars (SFH) from stacked spectra of SDSS Luminous Red Galaxies (Eisenstein et al. 2001, LRG) using VESPA. The data are blocks in 10 redshift intervals $0.025 < z < 0.55$, with 12 equal-area angular bins.

We estimate the sample variance and measurement error arising from small-scale (sub-block) variations by computing the error on the mean of the sub-blocks. Additionally, we include the scatter arising from re-binning to the present-day lookback time, and then perform a Bayesian analysis of any additional variance which may exist on large scales. Our test assumes homogeneity and checks for consistency and we find no evidence for extra variance, and a 95% upper limit to the credibility interval of a fractional variation of 5.8% in SFH. The typical block size is about 0.04 Gpc^3.

The main uncertainty is in the stellar populations models employed by VESPA. However, this result can be easily extended and improved upon with future spectroscopic surveys e.g., BOSS (Dawson et al. 2012), and as our knowledge of Stellar Population Models increases. Although this is not a complete test of homogeneity, which would require investigation of the metric tensor itself, this limit on homogeneity is the first to come from within the past light cone, rather than being restricted to our past light cone. As such it is genuinely testing homogeneity rather than isotropy.

ACKNOWLEDGMENTS

BH would like to thank Aday Robiana and Roland dePutter for useful discussions, the University of Cape Town for hospitality, and acknowledges grant number FP7-PEOPLE- 2007- 4-3-IRG n 20218. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/.

REFERENCES

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543
Biswas, T., Notari, A., & Valkenburg, W. 2010, JCAP, 11, 30
Bonnor, W. B., & Ellis, G. F. R. 1986, MNRAS, 218, 605
Bull, P., Clifton, T., & Ferreira, P. G. 2012, PRD, 85, 024002
Caldwell, R. R., & Stebbins, A. 2008, Physical Review Letters, vol. 100, Issue 19, id. 191302, 100, 191302
Cid Fernandes, R., Mateus, A., Sodré, L., Stasińska, G., & Gomes, J. M. 2005, MNRAS, 358, 363
Clarkson, C. 2012, eprint arXiv:1204.5505
Clarkson, C., Bassett, B., & Lu, T. H.-C. 2008, Physical Review Letters, vol. 101, Issue 1, id. 011301, 101, 011301
Clarkson, C., & Maartens, R. 2010, Classical and Quantum Gravity, 27, 124008
Clarkson, C., & Regis, M. 2011, JCAP, 2, 13
Dawson, K. S., Schlegel, D. J., Ahn, C. P., et al. 2012, ArXiv e-prints
de Putter, R., Verde, L., & Jimenez, R. 2012, ArXiv e-prints
Eisenstein, D. J., et al. 2001, AJ, 122, 2267
Goodman, J. 1995, PRD, 52, 1821
Górski, K. M., Hivon, E., Banday, A. J., et al. 2005, ApJ, 622, 759
Gunn, J. E., Siegmund, W. A., Mannery, E. J., et al. 2006, AJ, 131, 2332
Heavens, A. F., Jimenez, R., & Lahav, O. 2000, MNRAS, 317, 965
Heavens, A. F., Jimenez, R., & Maartens, R. 2011, JCAP, 9, 35
Komatsu, E., et al. 2011, ApJS, 192, 18
Maartens, R. 2011, Royal Society of London Philosophical Transactions Series A, 369, 5115
Marra, V., & Notari, A. 2011, Classical and Quantum Gravity, Volume 28, Issue 16, pp. 164004 (2011)., 28, 164004
Nadathur, S., & Sarkar, S. 2011, PRD, 83, 063506
Ocvirk, P., Pichon, C., Lançon, A., & Thiébaut, E. 2006, MNRAS, 365, 46
Smith, J. A., et al. 2002, AJ, 123, 2121
Tojeiro, R., Heavens, A. F., Jimenez, R., & Panter, B. 2007, MNRAS, 381, 1252
Tojeiro, R., Percival, W. J., Heavens, A. F., & Jimenez, R. 2011, MNRAS, 413, 434
Tojeiro, R., Wilkins, S., Heavens, A. F., Panter, B., & Jimenez, R. 2009, ApJS, 185, 1
Vincoletto, L., Matteucci, F., Calura, F., Silva, L., & Granato, G. 2012, ArXiv e-prints
York, D. G., et al. 2000, AJ, 120, 1579