Evidence for a lower value for $H_0$ from cosmic chronometers data?

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ABSTRACT

An intriguing discrepancy emerging in the concordance model of cosmology is the tension between the locally measured value of the Hubble rate, and the ‘global’ value inferred from the cosmic microwave background (CMB). This could be due to systematic uncertainties when measuring $H_0$ locally, or it could be that we live in a highly unlikely Hubble bubble, or other exotic scenarios. We point out that the global $H_0$ can be found by extrapolating $H(z)$ data points at high-$z$ down to $z = 0$. By doing this in a Bayesian non-parametric way, we can find a model-independent value for $H_0$. We apply this to 19 measurements based on differential age of passively evolving galaxies as cosmic chronometers. Using Gaussian processes, we find $H_0 = 64.9 ± 4.2$ km s$^{-1}$ Mpc$^{-1}$ (1σ), in agreement with the CMB value, but reinforcing the tension with the local value. An analysis of possible sources of systematic errors shows that the stellar population synthesis model adopted may change the results significantly, being the main concern for subsequent studies. Forecasts for future data show that distant $H(z)$ measurements can be a robust method to determine $H_0$, where a focus in precision and a careful assessment of systematic errors are required.

Key words: cosmological parameters – cosmology: observations – cosmology: theory – dark energy – cosmology: distance scale – large-scale structure of Universe.

1 INTRODUCTION

There is a strong tension, recently quantified by Verde, Protopapas & Jimenez (2013), between the value of the Hubble constant $H_0$ derived by Planck (Planck Collaboration 2013) from anisotropies in the cosmic microwave background (CMB): 67.3 ± 1.2 km s$^{-1}$ Mpc$^{-1}$, and the value from local measurements: 73.8 ± 2.4 km s$^{-1}$ Mpc$^{-1}$ (Riess et al. 2011). While the latter measurement is based on local measurements, the former infers a global value for the Hubble constant within a cosmological model.

There remains disagreement about the local value of $H_0$ depending on the distance indicator used to measure it, which hints the discrepancy with Planck could be the result of systematic errors. Riess et al. (2011) calibrated the SNe Ia distances with three indicators: distance to NGC 4258 based on a megamaser measurement, parallax measurements to Milky Way cepheids (MWC) and cepheids observations and a revised distance to the Large Magellanic Cloud (LMC). Contrarily, calibrating the SNe Ia with the tip of red-giant branch, Tamann & Reindl (2013) provides $H_0 = 63.7 ± 2.3$ km s$^{-1}$ Mpc$^{-1}$. This shows how crucial is the first-step calibration in the distance ladder to measure $H_0$.

However, there are several local $H_0$ measurements with higher values. Riess, Fliri & Valls-Gabaud (2012) found $H_0 = 75.4 ± 2.9$ km s$^{-1}$ Mpc$^{-1}$ by using cepheids in M31. With a mid-infrared calibration for the cepheids, Freedman et al. (2012) derived $H_0 = 74.3 ± 2.1$ km s$^{-1}$ Mpc$^{-1}$, and with eight new classical cepheids observed in galaxies hosting SNe Ia Fiorentino, Musella & Marconi (2013) got $H_0 = 76.0 ± 1.9$ km s$^{-1}$ Mpc$^{-1}$. By using H II regions and H II galaxies as distance indicators, Chávez et al. (2012) obtained $H_0 = 74.3 ± 3.1$(random) ± 2.9 (syst.) km s$^{-1}$ Mpc$^{-1}$. Some of these are over $4σ$ away from the CMB-derived value. See Fig. 1 for a plot of different measurements of $H_0$.

A variety of different physical effects could explain such a discrepancy. It could just be cosmic variance: as we can observe the Universe from only one position, we are not able to realize the global parameters from the local parameters, as in the local expansion rate for instance. If we live in a locally underdense region, a ‘Hubble bubble’, a higher value for $H_0$ is obtained compared to the global value. This effect was carefully addressed by Marra et al. (2013) through a modelling of the statistics of matter distribution which provides the distribution of the gravitational potential at the observer. The outcome is that cosmic variance can alleviate the tension, but a complete elimination requires a very rare fluctuation (Marra et al. 2013; Wojtak et al. 2014), although in full agreement with observations so far (Keenan, Barger & Cowiee 2013).

Another way to look at the problem is to consider that the discrepancy may indicate new physics, such as massive neutrinos (Wyman et al. 2014), or alternative dark energy models (Salvatelli et al. 2013; Xia, Li & Zhang 2013).

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Figure 1. Different measurements of \(H_0\). The figure shows how the result obtained in this work (GaPP) is compared to other determinations of \(H_0\). The points refer to the following references: Planck (Planck Collaboration 2013), TR (Tammann & Reindl 2013), Efsl (Efstathiou 2014) with one anchor, Efsl3 with three anchors, R11 (Riess et al. 2011), R12 (Riess et al. 2012), Freed (Freedman et al. 2012), Fior (Fiorentino et al. 2013) and Chavez (Chávez et al. 2012).

Recently, some analyses were performed trying to identify sources of systematic errors in order to remove or alleviate the tension. For example, by using only the geometric maser distance to NGC 4258 of Humphreys et al. (2013) as an anchor, Efstathiou (2014) revisited Riess et al. (2011) analysis and derived \(H_0 = 70.6 \pm 3.3 \text{ km s}^{-1} \text{ Mpc}^{-1}\), while combining with LMC and MWC anchors the value is \(72.5 \pm 2.5 \text{ km s}^{-1} \text{ Mpc}^{-1}\), alleviating the tension. The Planck data were also reanalysed by Spergel, Flauger & Hlozek (2013), where it was claimed that the 217 GHz \(\times 217 \text{ GHz}\) detector is responsible for some part of the tension. Their new Hubble constant without the 217 GHz \(\times 217 \text{ GHz}\) detector is slightly higher: \(H_0 = 68.0 \pm 1.1 \text{ km s}^{-1} \text{ Mpc}^{-1}\). Moreover, the consistency of the Planck data with the cosmological standard model was tested by Hazra & Shafieloo (2014), where a lack of power for high and low multipoles may indicate new physics or systematic errors.

With so many alternatives, progress can be achieved by developing new ways to address the issue. We point out here that \(H(z)\) data which are not calibrated on a \(H_0\) estimate can be extrapolated to \(z = 0\) to provide an independent measurement of the global \(H_0\). Here, the Hubble function is reconstructed in order to derive \(H_0\) from 19 \(H(z)\) measurements of passively evolving galaxies as cosmic chronometers (Jimenez & Loeb 2002). Many of these are at relatively moderate and high redshifts so intrinsically probe the global value for \(H_0\) rather than the local one. We use Gaussian Processes (GP), which is a non-parametric method, to obtain the value of the Hubble constant in a completely cosmological model-independent way, which is in principle not affected by the local systematics. We show the value of the Hubble constant derived in this way is lower than the standard local measurements. We obtain \(H_0 = 64.9 \pm 4.2 \text{ km s}^{-1} \text{ Mpc}^{-1}\) (1σ), in agreement with the CMB-inferred value. A better understanding of systematic errors, especially the adopted stellar population synthesis (SPS) model, is required: we show that to improve this result a big effort is necessary to decrease the errors substantially in future, and a focus on precision is worthier than the number of data.

The Letter is organized as follows: in Section 2, we describe GP as well as standard parametric methods adopted to constrain \(H_0\). In Section 3, the bounds derived for the Hubble constant are displayed, followed by forecasts of constraints in Section 4. We finish the Letter in Section 5 with the conclusions.

2 METHODS

2.1 Gaussian Processes (GP)

A Gaussian distribution is a distribution over random variables, while a GP is a distribution over functions. This allows one to reconstruct a function from data without assuming a parametrization for it. Here, we use Gaussian Processes in Python (GaPP)\(^1\) (Seikel, Clarkson & Smith 2012a) in order to reconstruct the Hubble parameter as a function of the redshift from which we can infer \(H_0\). This method has been applied for several purposes, for example the reconstruction of the equation of state of dark energy (Seikel et al. 2012a) and to perform null tests of the concordance model (Seikel et al. 2012b; Yahya et al. 2014).

The reconstruction is given by a mean function with Gaussian error bands, where the function values at different points \(z\) and \(\tilde{z}\) are connected through a covariance function \(k(z, \tilde{z})\) (see Seikel & Clarkson (2013) for a discussion of choices of covariance functions). This covariance function depends on a set of hyperparameters. Here, as we expect that the Hubble parameter and all its derivatives to be smooth, we consider the general purpose squared exponential (Sq. Exp.) covariance function which is given by

\[
k(z, \tilde{z}) = \sigma_f^2 \exp\left\{-\frac{(z - \tilde{z})^2}{2l^2}\right\}.
\]

In the above equation, we have two hyperparameters, the first \(\sigma_f\) is related to typical changes in the function value while the second \(l\) is related to the distance one needs to move in input space before the function value changes significantly. We follow the steps of Seikel et al. (2012a) and determine the maximum likelihood value for \(\sigma_f\) and \(l\) in order to obtain the value of the function. In this way, we are able to reconstruct the Hubble parameter as a function of the redshift from \(H(z)\) measurements. We discuss in Section 3.1.1 the impact of different covariance functions on our results.

2.2 Parametric analyses

In order to compare the results provided by non-parametric methods with standard analyses, we also consider two parametric models. First of all, we take a flat XCDM model, where the universe is composed by dark matter and a fluid \(X\) with equation of state \(p_X = w\rho_X\), where the Hubble parameter is given by

\[
H(z) = H_0 \sqrt{\Omega_m(1 + z)^3 + (1 - \Omega_m)(1 + z)^{3\Omega_m^{1+w}}},
\]

where \(\Omega_m\) is the matter density parameter today. When \(w = -1\) this is the concordance \(\Lambda\) cold dark matter (LCDM) model which we consider separately. In order to derive \(H_0\) for the parametric models, we apply standard statistical procedures based on maximum likelihood methods.

3 CONSTRAINTS ON \(H_0\)

We use 19 \(H(z)\) measurements (Simon, Verde & Jimenez 2005; Stern et al. 2010; Moresco et al. 2012) from passively evolving galaxies as cosmic chronometers to derive the value of \(H_0\).

\(^1\) http://www.acgc.uct.ac.za/~seikel/GAPP/index.html
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3.1 Systematic errors

Some tests were performed in order to evaluate the robustness of the result. We split our analysis searching for three effects: (i) the impact of the covariance function in GaPP, (ii) a possible presence of outliers driving $H_0$ for lower values and (iii) systematic errors from the SPS models.

3.1.1 Covariance functions

The freedom in the GP approach comes in the covariance function. While in traditional parametric analyses, we choose a model to characterize what is our prior belief about the function in which we are interested, with GP we ascribe in the covariance function our priors about the expected function properties (e.g. smoothness, correlation scales etc.).

Since we expect the Hubble parameter and its derivatives to be smooth, the squared exponential covariance function was selected which is infinitely differentiable – this implies that functions drawn from the process are also infinitely differentiable. However, we considered other covariance functions to see how the results are affected. In order to do so, we considered three covariance functions from the Matérn family, namely the $v = 5/2, 7/2$ and $9/2$ (see Seikel & Clarkson 2013 for definitions and further discussion). Writing $v = p + 1/2$, each Matérn function is $p$ times differentiable as are functions drawn from it, and the squared exponential is recovered for $v \to \infty$. Increasing $v$ increases the width of the covariance function near the peak implying stronger correlations from nearby points for a fixed correlation length $\ell$.

The results are shown in Table 1, where we see slightly higher values are derived for $H_0$, together with slightly larger errors, for smaller $v$. In fact, for the Matérn$(5/2)$ the tension with local $H_0$ disappears, although the result remains in fully agreement with Planck. Interestingly, although there is some shift, the errors are relatively independent of the covariance function choice, especially when compared to the ones derived when one increases the number of parameters in parametric analyses (the error more than doubles when allowing for $w$ to be free, compared to fixing it to $-1$), showing that GP provide very stable results within different reasonable assumptions.

3.1.2 Presence of outliers

We checked if the high-redshift data were pivoting down the value of $H_0$ to smaller values. To do so, we removed all data points with redshifts greater than 1, but again the results were completely consistent with the full sample, $H_0 = 66.9 \pm 4.3$ km s$^{-1}$ Mpc$^{-1}$, thus not removing the tension. By removing low-redshift points, first and second or third and fourth, again the results did not change significantly, with $H_0 = 66.3 \pm 4.6$ km s$^{-1}$ Mpc$^{-1}$ and $H_0 = 66.4 \pm 7.1$ km s$^{-1}$ Mpc$^{-1}$, respectively. We note that the points with smaller errors dominate the final error budget, as confirmed also by the analysis done in Section 4.

We also removed point by point in the analysis. For the first 17 points, the results changed slightly, with a mean value between 64 and 65 and errors between 4 and 5. Conversely, the high-redshift points showed the biggest departure once removed, with values $H_0 \approx 71.5 \pm 5.9$ (18th out) and $H_0 = 73.2 \pm 8.7$ km s$^{-1}$ Mpc$^{-1}$ (19th out). Higher values are derived and the error blows up, although in agreement with the full sample. This shows how $H_0$ is sensitive to high-redshift values, where more data points in this redshift region might help to mitigate possible systematic errors due to outliers.

![Figure 2. Model independent reconstruction of $H(z)$ using Gaussian processes. The red points with error bars represent the 19 $H(z)$ measurements and the blue shaded contour the reconstruction within the $1\sigma$ confidence level. For comparison purposes, we also show the value obtained by Riess et al. (2011), where we see that it is compatible to the GaPP value only at 2\sigma. The inset shows a zoom in the low-redshift region.](image-url)
3.1.3 Different SPS models

One of the possible main sources of systematic errors in $H(z)$ measurements comes from the adopted SPS model. The 19 points used here were derived with Bruzual & Charlot (2003) SPS model (BC03). On the other hand, recently Moresco et al. (2012) calculated $H(z)$ for eight measurements considering BC03 and another SPS model from Maraston & Stromback (2011, MaStro). We performed the reconstruction with GaPP for this subset with both SPS models. For BC03, we derived $H_0$ in the range 64.4 ± 4.9 km s$^{-1}$ Mpc$^{-1}$, in good agreement with the full sample. In contrast, the analysis with MaStro provided $H_0 = 75.1 ± 5.2$ km s$^{-1}$ Mpc$^{-1}$, in disagreement with Planck and in good agreement with the value of Riess et al. (2011). Therefore, even with only eight data points, we identify the SPS model as the main concern for our results.

3.2 Other data sets

Another independent measurement for $H(z)$ is given by baryon acoustic oscillations (BAOs). Currently, there are seven measurements from Blake et al. (2012), Reid et al. (2012), Xu et al. (2013), Busca et al. (2013) and Chuang & Wang (2013). Combining with the other measurements, for GaPP (Sq. Exp.) we got $H_0 = 69.4 ± 4.4$ km s$^{-1}$ Mpc$^{-1}$, for a flat CDM model $H_0 = 68.4 ± 1.9$ km s$^{-1}$ Mpc$^{-1}$ and for a flat XCDM model $H_0 = 69.8 ± 4.6$, all values consistent with Planck. However, there are some drawbacks when using the BAO data. First, these data are not model independent. They are based on the CDM model to study the correlation functions and transform them to the $H(z)$ values. Moreover, generally what is inferred is the combination $H_r$, $r_s$ standing for the sound horizon whose value is given by Wilkinson Microwave Anisotropy Probe (Komatsu et al. 2009, 2011; Hinshaw et al. 2013). Also important is the point raised by Blake et al. (2012) warning that their values of $H(z)$ are derived and so they should not be used to test models.

Since the current errors do not allow a final decision about the value of $H_0$, our next step is to study whether future data can settle the issue.

4 FORECASTS

The procedure to analyse how future data can improve the determination of $H_0$ is split in two ways. First, we consider how the increase of data points of same quality can change the constraints. Secondly, the errors for $H(z)$ are shrunk and a comparison is made between the number of data and their quality.

The current errors for $H(z)$ measurements grow with redshift a few per cent up to around 15 per cent. Assuming that future data will provide measurements with the same errors, we update the method of Ma & Zhang (2011) to predict future data based on the recent measurements from Moresco et al. (2012). A value for $H(z)$ is generated by $H_{\text{sim}}(z) = H_{\text{exp}}(z) + \mathcal{N}(0, \sigma(z))$, where $H_{\text{sim}}(z)$ and $H_{\text{exp}}(z)$ are respectively the simulated and fiducial values for the Hubble parameter at redshift $z$, and $\mathcal{N}(0, \sigma(z))$ is a random number Gaussianly distributed with mean zero and variance $\sigma(z)$. To estimate $\sigma(z)$, the uncertainties of the observational points are restricted by two straight lines: $\sigma_+ = 15.76z + 3.65$ and $\sigma_+ = 13.29z + 1.62$, with two ‘outliers’ removed since they were not following the trend of the errors. Assuming that the errors of future data will be between the two lines, one can expect the mean line of the error to be $\sigma_0 = 14.52z + 2.63$. Therefore, the error of the simulated point is drawn from a Gaussianly distributed random variable $\delta(z) = \mathcal{N}(\sigma_0, \epsilon(z))$, where $\epsilon(z) = (\sigma_+ - \sigma_-)/4$ is chosen to assure the error is within $\sigma_+$ and $\sigma_-$, with 95.4 per cent probability.

Fig. 3 presents the expected future errors from considering data are equally spaced in the interval 0.1 ≤ $z$ ≤ 1.8. We present the expected error on $H_0$ from simulations with 64, 128 and 256 data points. These numbers were chosen because with 64 $H(z)$ measurements of same quality as today one can achieve the same constraints given by current SNe Ia (Ma & Zhang 2011). The black crosses represent the errors with the GaPP reconstruction, the red dots for the flat XCDM model and the blue triangles for a flat CDM model. The first panel in the left shows the behaviour of future data with the same quality as today, and the others show the trend for smaller errors for the $H(z)$ data, of 10 per cent, 5 per cent and 3 per cent (see Crawford et al. 2010 for an observational programme to achieve such values).

Some conclusions can be made from Fig. 3.

(i) For future data with the same quality as today GaPP performs very well, with errors smaller than the ones obtained with a flat XCDM model.

(ii) Current quality data provide better constraints to $H_0$ than a constant error of 10 per cent in the whole redshift range, showing that lower redshift objects with higher precision compensate the low-quality data at high redshifts.

(iii) For higher precision measurements GaPP and the XCDM model provide the same constraints, showing that a non-parametric approach is powerful to study cosmological data.

(iv) Improvement in precision is more important than increasing the number of data of poorer quality.

5 CONCLUSIONS

We have applied GaPP, a non-parametric smoothing method based on GP, to 19 $H(z)$ measurements in order to constrain the Hubble constant $H_0$. This method does not rely on a cosmological model, so...
its results can be used to infer the impact of systematic errors as well as the underlying cosmological framework. We have obtained $H_0$ to be $64.9 \pm 4.2$ km s$^{-1}$ Mpc$^{-1}$ (1$\sigma$), a value which is in agreement with Planck, but in disagreement with local measurements. This supports the notion that either there are unidentified systematic errors in the local $H_0$ data, or the local value is indeed different from the global value. A better comprehension of systematic errors, especially a thorough analysis of the impact of SPS models, can improve the robustness of our results. Simulations have shown that improvements in distant $H(z)$ measurements can help pin down the global value of $H_0$.

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