A 3% DETERMINATION OF $H_0$ AT INTERMEDIATE REDSHIFTS

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ABSTRACT

Recent determinations of the Hubble constant, $H_0$, at extremely low and very high redshifts based on the cosmic distance ladder (grounded with trigonometric parallaxes) and a cosmological model (applied to Planck 2013 data), respectively, are revealing an intriguing discrepancy (nearly 9% or 2.4σ) that is challenging astronomers and theoretical cosmologists. In order to shed some light on this problem, here we discuss a new determination of $H_0$ at intermediate redshifts ($z \sim 1$), using the following four cosmic probes: (1) measurements of the angular diameter distances for galaxy clusters based on the combination of the Sunyaev–Zeldovich effect and X-ray data (0.14 ≤ $z$ ≤ 0.89); (2) the inferred ages of old high redshift galaxies (0.62 ≤ $z$ ≤ 1.70); (3) measurements of the Hubble parameter $H(z)$ (0.1 ≤ $z$ ≤ 1.8); and (4) the baryon acoustic oscillation signature ($z = 0.35$). In our analysis, assuming a flat ΛCDM cosmology and considering statistical plus systematic errors, we obtain $H_0 = 74.1^{+2.5}_{-2.3}$ km s$^{-1}$ Mpc$^{-1}$ (1σ) which is a 3% determination of the Hubble constant at intermediate redshifts. We stress that each individual test adopted here has error bars larger than the ones appearing in the calibration of the extragalactic distance ladder. However, the remarkable complementarity among the four tests works efficiently in greatly reducing the possible degeneracy on the space parameter ($\Omega_m$, $h$), ultimately providing a value of $H_0$ that is in excellent agreement with the determination using recessional velocities and distances to nearby objects.

Key words: cosmological parameters – distance scale – galaxies: distances and redshifts

Online-only material: color figures

1. INTRODUCTION

One of the most important observational quantities for cosmology is the Hubble constant, $H_0$, the value of which determines the present-day expansion rate of the universe. The determination of $H_0$ has remained a very active research topic since the early days of physical cosmology (Jackson 2007; Riess et al. 2011; Suyu et al. 2012; Freedman et al. 2012). Several groups and ongoing missions are now focusing their efforts on a high-accuracy calibration of $H_0$ since it works like a key to quantify many astronomical phenomena in a wide range of cosmic scales. It also plays an important role in several cosmological calculations such as physical distances to objects, and the age, size, and matter–energy content of the universe (Freedman & Madore 2010; Cháves et al. 2012; Farooq & Ratra 2013; Ade et al. 2013).

Currently, more robust constraints on $H_0$ are being obtained from local tests at low redshifts (i.e., $z \ll 1$). The primary method is based on a cosmic distance ladder, interlinking different distance indicators. The basic measurements and strategies commonly adopted are Cepheids, the tip of the red giant branch, maser galaxies, surface brightness fluctuations, the Tully–Fisher relation, and Type Ia supernovae (SNe Ia). In the last decade, the Hubble Space Telescope (HST) Key Project did a magnificent job of significantly decreasing the errors on the Hubble constant (for a review, see Freedman & Madore 2010). Recently, Riess et al. (2011) used the HST observations to determine $H_0$ from Cepheids and SNe Ia. Through a rigorous analysis of the statistical and systematic errors they obtained $H_0 = 73.8 ± 2.4$ km s$^{-1}$ Mpc$^{-1}$ (1σ), corresponding to a 3.3% uncertainty. Later, using the Spitzer Space Telescope, Freedman et al. (2012) re-calibrated the HST Key Project sample and found $H_0 = 74.3 ± 2.6$ km s$^{-1}$ Mpc$^{-1}$ (1σ).

The local distance ladder may also be susceptible to unknown sources of systematics like the possible existence of a “Hubble bubble” or other local effects that would affect measurements of the nearby expansion velocity (Jha et al. 2007; Sinclair et al. 2010; Marra et al. 2013). The possibility of an observational convergence in the near future has increased in the last few years, however, additional progress, say for a determination with 2% uncertainty, will require closer scrutiny of the cosmic distance ladder (Suyu et al. 2012; Freedman et al. 2012).

On the other hand, cosmologists desire accurate measurements of the $H_0$ mainly to refine the constraints on the neutrino masses ($\sum m_\nu$), density ($\Omega_m$), and the equation of state parameter ($\omega$) of dark energy based on the cosmic microwave background (CMB) anisotropy data (Macri et al. 2006; Sekiguchi et al. 2010). It is also widely known that CMB data alone cannot supply strong constraints on $H_0$ (Spergel et al. 2007; Komatsu et al. 2009), a problem closely related to the degeneracy of the space parameter. Different grouping of the parameters ($H_0, \Omega_M, \Omega_\Lambda, \omega$, etc.) produce the same prediction for the CMB anisotropies. This degeneracy problem can be alleviated only by using a statistical prior on $H_0$ from independent probes (Hu 2005). In this regard, Komatsu et al. (2011), used CMB, SNe Ia, and baryon acoustic oscillation (BAO) data to derive a model-dependent value of $H_0$. It should also be recalled that the phenomenology underlying the CMB test operates on observations made at very high redshifts ($z \gtrsim 1070$), during the decoupling of radiation and matter. Such determination of $H_0$ involves a combination of physics and phenomena at very different scales and epochs of cosmic evolution (low, intermediate, and high redshifts) and, more importantly for the present article, due to the inclusion of SNe Ia data, the derived value of $H_0$ is also somewhat dependent on the cosmic distance ladder. Therefore, it is not only important to derive constraints on $H_0$ based on many different kinds of observations, but also to avoid the combination of phenomena occurring at very different epochs (like SNe Ia and CMB).

Hinshaw et al. (2013), using CMB experiments from the Wilkinson Microwave Anisotropy Probe (WMAP)-9, found...
H_0 = 70.0 \pm 2.2 \text{ km s}^{-1} \text{ Mpc}^{-1} (1\sigma)$, whereas Ade et al. (2013), using Planck mission analysis, reported $H_0 = 67.4 \pm 1.4 \text{ km s}^{-1} \text{ Mpc}^{-1} (1\sigma)$, corresponding to a 2.1% uncertainty. It is worth noting that the current results from different experiments working with very high redshift physics are consistent with each other; however, the CMB experiments are discrepant from the local measurements. In particular, the Planck mission tension is at a 2.4\sigma confidence level (Ade et al. 2013). In the present "era of precision cosmology," investigating this tension more fully may provide new insights into improving the determination of the Hubble constant. Naturally, if such tension is not more fully may provide new insights into improving the determination of the Hubble constant. Naturally, if such tension is not a mere consequence of systematics, and it is further strengthened by the incoming data, a new cosmology beyond CDM may also prove necessary.

Recently, some cosmological tests at intermediate redshifts ($z \sim 1$) have emerged as a promising technique to estimate $H_0$ (Simon et al. 2005; Deepak & Dev 2006; Cunha et al. 2007; Lima et al. 2009; Stern et al. 2010). The main advantage of these methods is their independence of local calibrators (Carlstrom et al. 2003; Lima et al. 2000; Friaza et al. 2005). In principle, such methods provide cross-checking for local direct estimates which are free from Hubble bubbles, since the majority of galaxy clusters are well inside the Hubble flow. All of these methods are dependent on the assumptions regarding the astrophysical medium properties, as well as on the cosmological model adopted in their analysis and, individually, are not yet competitive with the traditional methods based on the cosmic distance ladder (Freedman et al. 2001).

In this Letter, we identify a remarkable complementarity involving four different cosmological probes at intermediate redshifts ($z \sim 1$) the combination of which provides a valuable cross-check for $H_0$. The first test is based on the angular diameter distance (ADD) from galaxy clusters via the Sunyaev–Zeldovich effect (SZE) combined with measurements of the X-ray flux (the SZE/X-ray technique). Although suggested long ago, it has only recently been applied to a fairly large number of clusters (Bonamente et al. 2006; Cunha et al. 2007; Holanda et al. 2012). The second test is the age estimates of galaxies and quasars at intermediate redshifts. This became possible through new optical and infrared techniques together with the advent of large telescopes (Alcaniz et al. 2003; Lima et al. 2009). The third possibility arises from measurements of the Hubble parameter, $H(z)$, from differential ages of galaxies (Simon et al. 2005; Gaztañaga et al. 2009; Stern et al. 2010), while the fourth is the BAO signature (Eisenstein et al. 2005). The cooperation interaction among these independent tests greatly reduces the errors on $H_0$ and, more interesting, is located on a redshift zone distinct from both CMB anisotropies and the radial variations in density, temperature, and abundances. The common statistical contributions for such galaxy cluster samples are $\pm 2\%$ from galactic (and extragalactic) X-ray background, galactic $N_H \leq \pm 1\%$, CMB anisotropy $\leq \pm 2\%$, $\pm 8\%$ associated to the SZE from point sources, while statistics due to cluster asphericity amount to $\pm 15\%$. The estimates of systematic effects include X-ray temperature calibration $\pm 7.5\%$ and radio halos $\pm 3\%$, while calibrations of SZE and X-ray background flux contribute, respectively, $\pm 8\%$ and $\pm 5\%$. Different authors (Mason et al. 2001; Reese et al. 2002; Reese 2004) also believe that typical statistical errors account for nearly 20% with $+12.4\%$ and $-12\%$ for systematics (see Table 3 in Bonamente et al. 2006).

On the other hand, the age–redshift relation, $t(z)$, for a flat (CDM) model also has only two free parameters ($H_0, \Omega_M$): $t(z; h, \Omega_M) = H_0^{-1} \int_0^{z} 1/(x \sqrt{\Omega_M x^{-3} + (1 - \Omega_M)} dx)$, (2)

Note that for $\Omega_M = 1$ the above expression reduces to the well known result for the Einstein–de Sitter model (CDM, $\Omega_M = 1$) for which $t(z) = (2/3)H_0^{-1}(1 + z)^{-3/2}$. The above expression means that by fixing $t(z)$ from observations one may derive limits on the cosmological parameters $\Omega_M$ and $H_0$ (or equivalently $h$). It is also worth noting that the quantities appearing in the product defining the age parameter, $T = H_0t$, are estimated based on different (independent) observations (Lima & Alcaniz 2000; Friaza et al. 2005).

In this context, Ferreras et al. (2009) cataloged 228 red galaxies on the interval $0.4 < z < 1.3$ using HST/Advanced Camera for Surveys slitless grism spectra from the PEARs program, thereby studying the stellar populations of morphologically selected early-type galaxies from GOODS north and south fields. The first subsample adopted here consists of six passively evolving old red galaxies selected from the original Ferreras et al. sample. The second data set of old objects is also a subsample of the Longhetti et al. (2007) sample. Only nine field galaxies spectroscopically classified as early-types at $1.2 < z < 1.7$ were selected from a complete sample of the Munich Near-Infrared (IR) Cluster Survey with known optical and near-IR photometry (the age of each galaxy estimated from its stellar population). It should be stressed that for both samples, the selected data set (11 galaxies) provide the most accurate ages and the most restrictive galaxy ages.

In Figure 1(a), we display the sample constituted by the 11 data points chosen from two distinct subsamples of old objects. As discussed by Lima et al. (2009), we have added an incubation time with a conservative error bar for all galaxies. It is defined by the value of the time interval from the beginning of the structure formation process in the universe until the formation time ($t_f$) of the object itself. It will be assumed here that $t_{inc}$ varies slowly with the galaxy and redshift in our sample, thereby associating a reasonable uncertainty, $\sigma_{t_{inc}}$, in order to account for the current ignorance regarding this kind of “nuisance” parameter (Fowler 1987; Sandage 1993). Here we consider $t_{inc} = 0.8 \pm 0.4$ Gyr, and following Lima et al. (2009), we also combine statistical and systematic errors.

In Figures 1(b) and (c) we compare the age of these old objects at intermediate redshifts with the predictions of the CDM
models for different values of the free parameters ($\Omega_M$ and $h$). It is also worth noting that the current status of systematic uncertainties in this context is still under debate. Jimenez et al. (2004) studied sources of systematic errors in deriving the age of a single stellar population and concluded that they are not larger than 10%–15%. Other authors consider systematic errors to be around 20% (Percival & Salaris 2009). In this study we have adopted 15% for all data.

The third observational probe comes from $H(z)$ data, obtained from differential ages of galaxies and radial BAO (Simon et al. 2005; Gaztañaga et al. 2009). Some years ago, Jimenez et al. suggested an independent estimator for the Hubble parameter (differential ages of galaxies) and used it to constrain the equation of state of dark energy (Jimenez et al. 2003). Later, the differential ages of passively evolving galaxies were used to obtain $H(z)$ in the range of $0.1 < z < 1.8$ (Simon et al. 2005), and this sample was further enlarged by Stern et al. (2010). In addition, Gaztañaga et al. (2009) took the BAO scale as a standard ruler in the radial direction (the Peak method), thereby obtaining three more additional values: $H(z = 0.24) = 79.7 \pm 2.7$, $H(z = 0.34) = 83.9 \pm 3.2$, and $H(z = 0.43) = 86.5 \pm 3.5$, which are model and scale independent. Now, by comparing the theoretical expression, $H(z) = H_0\sqrt{\Omega_M(1 + z)^3 + (1 - \Omega_M)^{1/2}}$, with the observational data, the corresponding bounds can be readily derived. We remark that the relative age difference (the key to the method) is only of the order of 2%–3% (Stern et al. 2010). However, to be more conservative, here we are assuming systematic errors of 8% for the relative age difference and radial BAO data.

![Figure 1](image_url)

**Figure 1.** Old galaxy data at intermediate redshifts as a cosmic probe. (a) Age–redshift plane and the total sample of galaxies. Black points for $z < 1.0$ and $z > 1.2$ correspond, respectively, to the Ferreras et al. (2009) and Longhetti et al. (2007) samples. Black, red, and blue bars represent the statistical, statistical+incubation, and statistical+incubation+systematic errors, respectively. Data points correspond to the 11 galaxies of our selected subsample (see the main text). (b) Effect of $\Omega_M$. Age of the universe for some selected values of the density parameter. For smaller values of $\Omega_M$ the ages of the universe for a given redshift increase, thereby accommodating the oldest selected objects. (c) The $h$ effect on the age–redshift relation. Dotted curves are the predictions of the cosmic concordance model ($\Omega_M = 0.28$, $\Omega_{\Lambda} = 0.74$) and different values of $h$. For values smaller than $h = 0.6$ or bigger than $h = 0.9$, the curves predicted by the models move away from the data. (A color version of this figure is available in the online journal.)
A joint analysis based on the above three different probes already provides tight constraints on the value of $H_0$. However, as shown by Cunha et al. (2007), the analysis of $D_A$ data (from the SZE/X-ray technique) leads to more stringent constraints on the space parameter ($\Omega_M$, $h$) when combined with the BAO signature (Eisenstein et al. 2005; Percival et al. 2010), and the same happens when the ages of high redshift objects are considered (Lima et al. 2009). Therefore, instead of fixing a definite flat $\Lambda$CDM cosmology, it is natural to leave $\Omega_M$ free, which will be more accurately fixed by adding the BAO signature as a fourth probe to the complete joint analysis performed here. The remnant BAO peak can be interpreted as a consequence of the BAOs in the primordial baryon–photon plasma prior to recombination. It was detected from a large sample of luminous red galaxies and can be characterized by a dimensionless parameter:

$$A = \frac{\Omega_M^{1/2}}{H(z_*)^{1/3}} \left[ \frac{1}{\Gamma(z_*)} \right]^{2/3} = 0.469 \pm 0.017,$$

where $z_* = 0.35$ is the redshift at which the acoustic scale has been measured, and $\Gamma(z_*)$ is the dimensionless comoving distance to $z_*$. The above quantity is independent of the Hubble
constant and, as such, this BAO signature alone constrains only the $\Omega_M$ parameter.

3. COMPLEMENTARITY FOR $H_0$

Let us now consider a joint analysis based only on a combination of the first three probes, namely: (1) SZE/X-ray distances; (2) the age of the oldest intermediate redshift objects; and (3) the measurements of the Hubble parameter $H(z)$. Further, a complete joint analysis including the BAO signature from the Sloan Digital Sky Survey catalog will be performed. For both analyses, we stress that a specific flat $\Lambda$CDM cosmology has not been fixed a priori.

All the observational expressions adopted here have only two free parameters ($\Omega_M$, $h$). In this way, we perform the $\chi^2$ statistics over the $\Omega_M$–$h$ plane. Combining the three tests discussed above, the $\chi^2$ value reads

$$\chi^2(z; p) = \sum_i \frac{(D_A(z_i; p) - D_{\text{obs},i})^2}{\sigma_{D_{\text{obs},i}}^2 + \sigma_{\text{stat}}^2 + \sigma_{\text{syst}}^2} + \sum_j \frac{(t(z_j; p) - t_{\text{obs},j})^2}{\sigma_{t_{\text{obs},j}}^2 + \sigma_{\text{inc}}^2 + \sigma_{\text{syst}}^2} + \sum_k \frac{(H(z_k; p) - H_{\text{obs},k})^2}{\sigma_{H_{\text{obs},k}}^2 + \sigma_{\text{syst}}^2},$$

where the quantities with subindex "obs" are the observational quantities, $\sigma_{D_{\text{obs},i}}$ is the uncertainty in the individual distance, $\sigma_{\text{stat}}$ is the contribution of the statistical errors, $\sigma_{\text{inc}}$ is the incubation time error, $\sigma_{\text{syst}}$ are the contribution of the systematic errors for each sample added in quadrature, and the complete set of parameters is given by $p \equiv (\Omega_M, h)$.

In Figure 2(a), we show the dimensionless $h$ parameter versus the matter density parameter ($\Omega_M$). Our analysis combining statistical and systematic errors from galaxy ages are in black lines with 68.3%, 95.4%, and 99.7% confidence levels (c.l.s). In the same way, the green lines represent the c.l.s for the SZE/X-ray sample whereas the corresponding constraints from Hubble parameter $H(z)$ sample are shown by orange lines. As should be expected, the constraints of each sample on the ($\Omega_M$, $h$) plane are too weak when considered individually. However, due to the complementarity among them, our joint analysis for these three samples predicts $H_0 = 73.4 \pm 4.7 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$ and $\Omega_M = 0.290^{+0.078}_{-0.061}$ (1σ c.l.) for two free parameters with $\chi^2_{\text{min}} = 41.42$. The reduced values are $\chi^2_{\text{red}} = 0.702$ (including systematics) and $\chi^2_{\text{red}} \cong 1$ (no systematics).

In Figure 2(b), we display the contours on the space parameter obtained through a joint analysis involving the combination of all four probes. The dashed lines are cuts on the ($\Omega_M$, $h$) plane from BAO signature. The red, green, and blue contours are constraints with 68.3%, 95.4% and 99.7% c.l., respectively. This complete analysis provides $H_0 = 74.1_{-3.3}^{+3.3} \, \text{km s}^{-1} \, \text{Mpc}^{-1}$ (4.5% uncertainty) whereas the density parameter is $\Omega_M = 0.278^{+0.038}_{-0.028}$ for two free parameters with $\chi^2_{\text{red}} = 41.53$ ($\chi^2_{\text{red}} = 0.704$).

In Figure 2(c), we show the likelihood function for the $h$ parameter in a flat $\Lambda$CDM universe. Both curves were obtained by marginalizing on the matter density parameter. The shadow lines are cuts in the regions of 68.3% and 95.4% probability. For the solid black line the BAO signature was not considered. The constraints for the black line are $h = 0.734 \pm 0.031$ (0.064) with 1σ (2σ), respectively. For the red line the BAO signature has been included. The constraints are $h = 0.741 \pm 0.022$ (corresponding to 3% error in $h$) and 0.045 (6.1%) with 1σ and 2σ, respectively. For all of these analyses, the statistical and systematic errors were added.

In Table 1, we compare the results derived here with the latest determinations of $H_0$. Note that competitive constraints were obtained using only probes at intermediate redshifts, but the current results are nicely consistent with the latest determinations based on the HST Key Project.

| Reference | Method | $h$ (1σ) | Epoch |
|-----------|--------|---------|-------|
| Hinshaw et al. (2013) | WMAP-9 | 0.700 ± 0.022 | $z \sim 1100$ |
| Ade et al. (2013) | Planck | 0.674 ± 0.014 | $z \sim 1100$ |
| Riess et al. (2011) | Cepheid+SNe+Maser | 0.738 ± 0.024 | $z \sim 0$ |
| Freedman et al. (2012) | HST Key Project | 0.743 ± 0.026 | $z \sim 0$ |
| This Letter | SZE/X-ray+Age+$H(z)$ | 0.734 ± 0.031 | 0.1 < $z < 1.8$ |
| This Letter | SZE/X-ray+Age+$H(z)$+BAO | 0.741 ± 0.022 | 0.1 < $z < 1.8$ |

4. CONCLUSIONS

Several ongoing and future experiments (HST Key Project, SH0ES, Planck, Gaia, Spitzer/Carnegie Hubble Program, the James Webb Space Telescope, and others) are dedicated to more accurately measuring the value of $H_0$, partially because an accuracy better than 2% will provide critical information on several cosmological parameters.

We have demonstrated here that a joint analysis involving four independent cosmological tests at intermediate redshifts ($z \sim 1$) provides an independent 3% determination of $H_0$ (statistical and systematic errors combined). In the framework of a flat $\Lambda$CDM model we have obtained $h = 0.741 \pm 0.022$ (including statistical plus systematics). As shown in Table 1 this value is not only consistent, but has the same precision as a recent $H_0$ determination using nearby Cepheids and SNe (Riess et al. 2011; Freedman et al. 2012). It is also suggested here that the current determination of the Hubble constant based only on probes at intermediate redshifts provides a competitive cross-check for any determination of $H_0$.

The main advantage of the current treatment is that it does not rely on the extragalactic distance ladder being fully independent of local calibrators. Naturally, its basic disadvantage rests on the large and different systematic uncertainties appearing in each probe when separately applied. However, the remarkable complementarity among the four tests works together, thereby greatly reducing the possible degeneracy and uncertainties appearing in the current determination of the Hubble constant.
Finally, concerning the intriguing tension between the $H_0$ determinations from nearby objects and current CMB data, our analysis at intermediate $z$ clearly favors the local methods.

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