Is there an early Universe solution to Hubble tension?

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We consider a low redshift (z < 0.7) cosmological dataset comprising megamasers, cosmic chronometers, type Ia SNe and BAO, which we bin according to their redshift. For each bin, we read the value of $H_0$ by fitting directly to the flat ΛCDM model. Doing so, we find that $H_0$ descends with redshift, allowing one to fit a line with a non-zero slope of statistical significance 2.1σ. Our results are in accord with a similar descending trend reported by the H0LiCOW collaboration. If substantiated going forward, early Universe solutions to the Hubble tension will struggle explaining this trend.

INTRODUCTION

Driven by successive results [1–3] favouring a higher value of the Hubble constant $H_0$, cosmology is in a state of flux. Remarkably, independent local determinations of $H_0$ based on Cepheids/Type Ia Supernovae (SNe) (SH0ES) [1], strongly-lensed quasar time delay (H0LiCOW) [2] and water megamasers (The Megamaser Cosmology Project) [3] all appear to be converging to a central value $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ that is within 2σ of all experiments [10].

Evidently some soul searching is required to convince ourselves that Hubble tension indeed implies deviations from ΛCDM. Among various ideas put forward to address the tension, the early dark energy (EDE) proposal [11] has attracted a lot of attention. The idea is to retain ΛCDM for the late-time cosmology, but reduce the sound horizon using early Universe physics as in [11–13], since this will only raise and lower the trend. Thus, we may be staring at preliminary evidence for a new cosmology at late times.

Secondly, it is tempting to adopt a different, admittedly speculative, perspective on Hubble tension. Namely, it is conceivable that Hubble tension is still down to two numbers, not the two numbers most consider, namely $H_0 ∼ 74$ km s$^{-1}$ Mpc$^{-1}$ (SH0ES) versus $H_0 ∼ 67$ km s$^{-1}$ Mpc$^{-1}$ (Planck), but rather the slope and intercept of descending line in $H_0$ with redshift. If true, this provides further hints on the missing piece of the cosmological puzzle, which may be crying out for model building beyond ΛCDM.
DATA

Let us open with the data. We make use of the following observational results in the redshift range \( z \leq 0.7 \):

- We employ distances from megamaser hosting galaxies: UGC 3789, NGC 6264, NGC 6323, NGC 5765b, CGCG 074-064 and NGC 4258 in the range 0.002 \( \leq z \leq 0.034 \) \cite{3, 19, 20}.
- We include cosmic chronometer (CC) data from \cite{21–27}, restricted to the range of interest.
- Our BAO data comprises isotropic measurements by the 6dF survey (\( z = 0.106 \)) \cite{28}, SDSS-MGS survey (\( z = 0.15 \)) \cite{29}, as well as the anisotropic measurements by BOSS-DR12 at \( z = 0.38, 0.51, 0.61 \) \cite{30}.
- We incorporate 924 Type Ia SNe from the Pantheon dataset in the range 0.01 < \( z \leq 0.7 \) \cite{31}, including both the statistical and systematic uncertainties.

Our overall dataset here is similar to \cite{10}, but differs in a number of aspects. Firstly, and most obviously, we have cut the higher redshift data \( z > 0.7 \). Secondly, instead of three masers, we now have access to six. Note, in contrast to \cite{10}, following \cite{3} we allow for errors in peculiar velocities. We have removed the strong lensing time-delay measurements by H0LiCOW \cite{32} to facilitate a later independent comparison. Since we will later bin the data, we have upgraded the compressed Pantheon data in terms of \( H(z)/H_0 \) \cite{33} (see also \cite{34}) to the full dataset. On the negative side, we have dropped the measurements of \( f\sigma_8 \), but the omission of this data is not expected to change the conclusions.

METHODOLOGY

Any trend in \( H_0 \) with redshift is model-dependent. Here we focus on flat \( \Lambda \)CDM, which is described by two parameters: the Hubble constant \( H_0 \) and matter density \( \Omega_m \). We note that CC data is expressed in terms of the Hubble parameter directly, so one can easily fit the model. For megamasers, the relevant distance is the angular diameter distance \( D_A(z) \), which can be approximated as \cite{3},

\[
D_A \approx \frac{cz}{H_0(1 + z)} \left( 1 - \frac{3\Omega_m z}{4} + \frac{\Omega_m(9\Omega_m - 4)z^2}{8} \right).
\] (1)

Following \cite{3} we convert between velocities and redshift \( v = cz \), allow for an inflated error in the velocities to take into account uncertainties in peculiar velocities \( \sigma_{pec} = 250 \text{ km s}^{-1} \) and extremize the following function:

\[
\chi^2 = \sum_{i=1}^{6} \left[ \frac{(v_i - \bar{v}_i)^2}{\sigma_{v,i}^2 + \sigma_{pec}^2} + \frac{(D_i - \bar{D}_i)^2}{\sigma_{D,i}^2} \right],
\] (2)

where the velocities \( v_i \) are treated as nuisance parameters and \( \bar{v}_i, \sigma_{v,i}, \sigma_{D,i} \) denote the velocities and galaxy distances inferred from modeling maser disks \cite{3}.

For SNe, as is common practice, we fit the distance modulus

\[
\mu = m - M = 25 + 5 \log_{10} \left( \frac{D_L(z)}{\text{Mpc}} \right),
\] (3)

where \( m \) is the apparent magnitude, \( M \) is the absolute magnitude - expected to be \( M \approx -19.3 \) - that we treat as a fitting parameter, and \( D_L(z) \) is the luminosity distance,

\[
D_L(z) = c(1 + z) \int_0^z \frac{dz'}{H(z')},
\] (4)

The BAO data involves fitting the following cosmological distances,

\[
D_A(z) = \frac{D_L(z)}{(1 + z)^2}, \quad D_H(z) = \frac{c}{H(z)}, \quad D_V(z) = [(1 + z)D_A(z)]^{\frac{1}{2}}[zD_H(z)]^{\frac{3}{2}}
\] (5)

It is important to note that BAO actually measures these quantities divided by \( r_d \) and is only sensitive to the product \( r_dH(z) \), which forms the crux of arguments for an early Universe solution to the Hubble tension. In essence, with BAO data fixed, a higher value of \( H_0 \) requires a lower value of \( r_d \) and points to some missing physics before recombination that would reduce this length scale. We refer the reader to \cite{35} for further discussion on this degeneracy.

To be fully transparent, it is worth noting that we fit all parameters subject to the following flat priors \cite{39}:

\[
H_0 \in (0, 100), \quad \Omega_m \in (0, 1), \quad r_d \in (0, 200), \quad M \in (-50, 0).
\]

![FIG. 1: Overlapping probability distribution functions for each bin plotted alongside the overall constraint.](image)

BINNING

Overall the dataset is of mixed quality and becomes sparse at higher redshift. Here we employ a non-uniform binning strategy that is designed to achieve a number of
results. Neglecting the CC data, which is not so constraining and sparse relative to Type Ia SNe, but is important in lifting a degeneracy between BAO and SNe alone, we construct the bins so that the weighted average redshifts of masers, SNe and BAO coincide. At the same time, we attempt to ensure that the data in a bin is sufficiently constraining and importantly that no data is omitted below \( z \leq 0.7 \).

While this leads to non-uniform bins, and a bin where SNe and CC appear alone, we emphasise again that this way we can confidently assign a definite redshift to each bin. The binning is summarised in Table I.

| Bin | Data                  |
|-----|-----------------------|
| 1   | Masers, SNe           |
| 2   | iso BAO, SNe, CC      |
| 3   | SNe, CC               |
| 4-6 | aniso BAO, SNe, CC    |

TABLE I: Summary of the data in each bin.

More concretely, observe that we can define a weighted average redshift of the cosmological probes in a given bin:

\[
\bar{z}_i = \frac{\sum N_k z_k (\sigma_k)^{-2}}{\sum N_k (\sigma_k)^{-2}},
\]

(6)

where \( \sigma_k \) denotes the error in the observable at redshift \( z_k \). Our strategy is simply to construct bins so that \( \bar{z}_i \) for a given data type in that bin coincide, thus allowing us to assign a definite redshift to each bin.

To this end, we can start from \( z = 0.7 \) and work backwards in redshift. The upper cut-off is a nominal value, but cannot be much greater than this value as otherwise the BAO data at \( z = 0.51 \) and \( z = 0.61 \) gets binned together. This strategy quickly leads to three bins:

- bin 4: \( \bar{z}_4 = 0.38 \in (0.321, 0.47] \),
- bin 5: \( \bar{z}_5 = 0.51 \in (0.47, 0.557] \),
- bin 6: \( \bar{z}_6 = 0.61 \in (0.557, 0.7] \),

(7)

where we have denoted the weighted average value in each bin. By construction the redshifts coincide with BAO.

To get the first, second and third bin, we identify the weighted average for the masers using \( \sigma^2_k = \sigma^2_{\nu,k} + \sigma^2_{\text{pec}} + \sigma^2_{D,k} \) [3], which includes an inflated error due to peculiar velocities \( \sigma_{\text{pec}} = 250 \, \text{km s}^{-1} \). This contribution is important as it brings the weighted average redshift into a range where SNe data exists. We are motivated to put the isotropic BAO data at \( z = 0.106 \) and \( z = 0.15 \) in the same bin to improve the constraining power, reduce the overall number of bins and ensure that the two data points mirror anisotropic BAO data, which at each redshift is also two data points. The remaining SNe we allocate to the final redshift range. Following the outlined procedure, the remaining bins are

- bin 1: \( \bar{z}_1 = 0.021 \in (0, 0.029] \),
- bin 2: \( \bar{z}_2 = 0.122 \in (0.029, 0.21] \),
- bin 3: \( \bar{z}_3 = 0.261 \in (0.21, 0.321] \).  

(8)

Having discussed the preliminaries, we come to the results. First and foremost, employing the Python package emcee [36], we identify the best-fit for the four parameters for the entire dataset through Markov Chain Monte Carlo (MCMC) [40]. The outcome is illustrated in Table II, confirming that an intermediate value of \( H_0 \sim 70 \, \text{km s}^{-1} \text{Mpc}^{-1} \) is preferred [10]. Moreover, \( \Omega_m \) and \( r_d \) agree with Planck values, \( \Omega_m = 0.315 \pm 0.007, r_d = 147.09 \pm 0.26 \) Mpc and \( M = -19.36 \pm 0.05 \) is consistent with SH0ES analysis [37].

| \( H_0 \) [\( \text{km s}^{-1} \text{Mpc}^{-1} \)] | \( \Omega_m \) | \( r_d \) [Mpc] | \( M \) |
|-----------------|------------|-------------|------|
| 69.74^{+1.60}_{-1.56} | 0.30^{+0.02}_{-0.02} | 144.83^{+1.44}_{-3.34} | -19.36^{+0.05}_{-0.05} |

TABLE II: Best-fit values of the maser+CC+SNe+BAO dataset over the redshift range \( z \leq 0.7 \).

Following similar analysis, but tailoring the MCMC to the data in the bin, we identify the best-fit values for the parameters in each bin as shown in Table III and illustrated in Figure 1. As is evident, there is a trend whereby \( H_0 \) decreases with redshift. This is primarily down to the higher \( H_0 \) value coming from the masers in the first bin, but the anisotropic BAO data is also playing a role in driving \( H_0 \) lower. In the process, the best-fit values for \( r_d \) and \( M \) start to drift outside of 1\( \sigma \) of the canonical values. Note, we have imposed no assumptions and it is simply data that is guiding us in this direction.

FIG. 2: The best-fit line against the binned data. The line is 2.1\( \sigma \) removed from the flat line null hypothesis.

To get a handle on the significance, we follow earlier H0LiCOW analysis [2] to establish a null hypothesis.
This is done by shifting the probability distribution function (pdf) for each bin to the central value favoured by the complete dataset $H_0 = 69.74$, before drawing a set of six mock $H_0$ values using the respective pdfs. Once this is done, we perform a weighted fit to identify a line and repeat $10^5$ times. Doing so, one will find a normal distribution peaked on zero slope from where one can infer confidence intervals. We fit the same linear regression binned through the data with the original $H_0$ values and find that the slope of the data falls 2.1$\sigma$ away from the slope of the null hypothesis. Concretely, we find the best-fit line has slope $m = -21.62$ with intercept $H_0 = 73.59$. We illustrate it against the binned data in Figure 2.

We have provided independent evidence (Table II), it is conceivable that the Planck result for flat $\Lambda$CDM is an “averaged” value, which is essentially to ensure our analysis only depends on late Universe physics. Nonetheless, we have checked that if one adopts a Planck prior on $r_d$, the significance of the line decreases to 1.4$\sigma$ and further decreasing $r_d$ to the values favoured by the EDE proposal, the binned values of $H_0$ are fully consistent with a horizontal line. Note, there is a tautological quality to the latter. Since BAO strongly constrains fitting, adopting a prior on $r_d$ is tantamount to fixing $H_0$ from the outset, which is precisely what we wanted to avoid.

Finally, one may be concerned that $H_0$ in the last two bins, namely $H_0 \sim 60$ km s$^{-1}$ Mpc$^{-1}$, is too low compared to Planck. Clearly, since H0LiCOW reports higher than expected values, i.e. $H_0 \sim 80$ km s$^{-1}$ Mpc$^{-1}$, at lower lens redshift, as observed, there is a discernible difference in the intercept. However, just as we have high and low values in bins, but the overall best-fit is a central value (Table II), it is conceivable that the Planck result for flat $\Lambda$CDM is an “averaged” value, which is essentially a coarse-grained value for $H_0$.

In the big picture, provided these results can be substantiated in future, they will call into question early Universe solutions to the Hubble tension. In essence, a descending feature in $H_0$ cannot be explained by fiddling with the length scale $r_d$, while $\Lambda$CDM is kept intact, since this will simply raise and lower the trend, but will not remove it. In effect, this trend, if real, is pointing to a late-time resolution to the problem whereby $\Lambda$CDM is replaced by a new cosmological model, or may even have an astrophysical resolution. Some musings on a potential explanation for such a feature will appear soon [38].

### DISCUSSION

H0LiCOW have reported a descending trend of measured $H_0$ with lens redshift, which is not the result of any obvious systematic. The deviation from a horizontal line is currently 1.7$\sigma$. In this letter using a combined dataset of masers, SNe, BAO and CC, which overall favour a central value for $H_0$, we have provided independent evidence for such a trend in a similar redshift range with statistical significance 2.1$\sigma$. While our slope is consistent with H0LiCOW, there is a curious difference in the intercept. That being said, it should be borne in mind that the underlying data is different in nature.

On the robustness of the result, it is worth noting that the correlation is driven by both bins 5 and 6. In other words, removing one of the bins will not make a difference. Alternatively, one can start removing datasets. Eliminating SNe from the analysis does not change the result, while removing BAO leaves our analysis resting on CC data, which only inflates the error bars so that a horizontal line can be fitted. We cannot remove CC as it is instrumental in breaking the degeneracies from both BAO and SNe.

Once again we reiterate that we have not assumed a prior on $r_d$ and have let the data do the talking. This is essentially to ensure our analysis only depends on late Universe physics. Nonetheless, we have checked that if one adopts a Planck prior on $r_d$, the significance of the line decreases to 1.4$\sigma$ and further decreasing $r_d$ to the values favoured by the EDE proposal, the binned values of $H_0$ are fully consistent with a horizontal line. Note, there is a tautological quality to the latter. Since BAO strongly constrains fitting, adopting a prior on $r_d$ is tantamount to fixing $H_0$ from the outset, which is precisely what we wanted to avoid.

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In this analysis, as in [3], the galaxy velocities are treated as nuisance parameters. That being said, it is heartening to see that their best-fit values from MCMC, namely 3451 $\pm$ 530 km s$^{-1}$, agree well with the corresponding values from maser disk modeling 3319 $\pm$ 229 km s$^{-1}$. Thus, our MCMC code is performing as expected. Throughout we employ standard notation for an interval in mathematics.

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