The Hubble Constant Tension Problem: An Overview

Dillon Brout

e-mail: dbrout@physics.upenn.edu

University of Pennsylvania & NASA Einstein Fellow

Presented at the 3rd World Summit on Exploring the Dark Side of the Universe
Guadeloupe Islands, March 9-13 2020

Abstract

The last two decades of progress has pushed us into an era of precision tests of the standard cosmological model. Measurements of the Hubble constant in both the early and late universe, which are now below 1% and 2% precision respectively, provide a critical test of 14 billion years of cosmic expansion history, the nature of dark matter and dark energy, the scale of departures from flat geometry, and pre-recombination physics. The value of the Hubble constant extrapolated from the cosmic microwave background measurements is in >4σ tension with the value measured directly from the local universe cosmic distance ladder. I will review the current state of the tension, lay out possible sources of systematic uncertainty, discuss numerous additional cosmological probes that have contributed to the discussion, and present the compelling story that such tension is evidence for significant deviations from the standard cosmological model.

1 Introduction

In the last decade, there has been significant progress in accuracy of measurements of the expansion rate of the universe at present day. This expansion rate, the Hubble Constant (H_0), can be determined through direct measurements of the absolute distance scale and nearby bulk flow velocities (e.g. SH0ES: Riess et al. 2016; Freedman et al. 2019), but can also be inferred from the cosmic microwave background (Planck Collaboration et al. 2018) in combination with the assumption of a cosmological model. With the former reporting 2% (stat+syst) uncertainties and the latter reporting 0.7% (stat+syst) uncertainties, a precise comparison can be made that tests the viability of the standard model of cosmology. Estimates of H_0 using the local distance ladder approach (e.g. SH0ES; Reid et al. 2019) are in 4σ tension with the value inferred from the early universe. Furthermore, there are two independent methods that corroborate both the early and late universe measurements. For the early universe, measurements of cosmic structure (BAO) in combination with big bang nucleosynthesis (BBN) data and constraints on dark matter (Ω_M) are in agreement with Planck (DES: Abbott et al 2018). However, corroborating late time H_0 measurements are the results from time-delay distances to strongly lensed quasars, which also suggest a high value in agreement with SH0ES. When analyzed in combination, these probes bring the early and late universe measurements of H_0 to greater than 5σ tension (Wong et al. 2019; Shajib et al. 2019).

The talk presented at the 3rd World Summit on Exploring the Dark Side of the Universe on March 12th was largely an overview talk. Here I briefly focus on two main aspects of the Hubble constant tension discussion: tests of exotic models and the impact of systematic uncertainties.

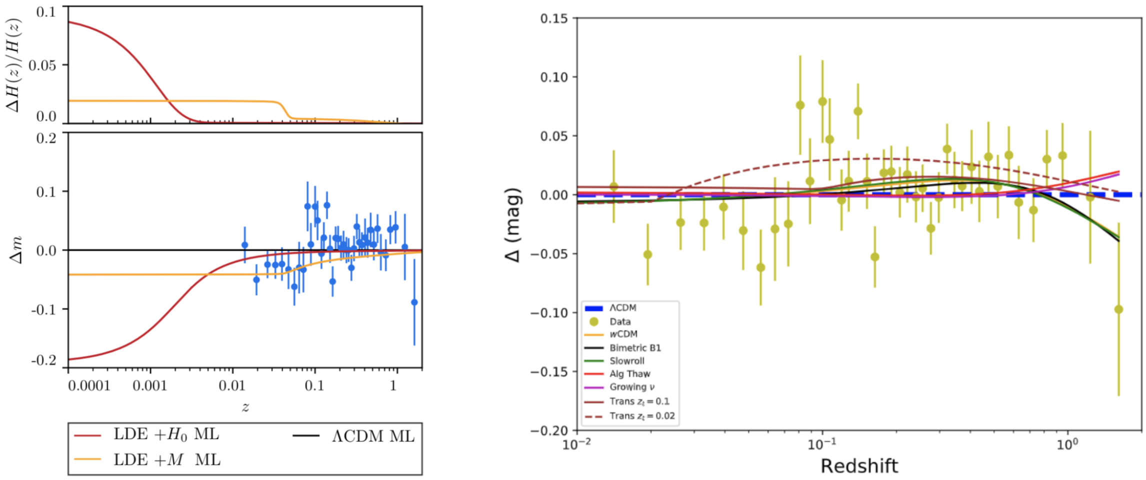

Figure 1: Constraints on exotic cosmological models and late time evolution. **Left**: Benevento, Hu, Raveri 2020 **Right**: Dahwan, et al. 2020.

2 Theoretical Resolutions are Restricted by Observations

The observed tension could be indicative of the presence of exotic physics beyond the standard model (for e.g., see Mortsell and Dhawan 2018; D'Eramo et al. 2018; Kreisch et al. 2019; Aylor et al. 2019). Many of these exotic models result in predictions that can be measured from the SN Ia rung of the distance ladder. Dahwan et al. 2020 analyze the change in the inferred value of local H_0 by altering the assumption of the cosmological model describing the expansion history of the universe. They also introduce a new formalism to account for the systematic uncertainties that affect the calibrator and Hubble flow supernovae simulataneously, motivated for calibrator and $z < 0.15$ Hubble flow SNe in previous studies (e.g. Zhang et al. 2017; Feeney et al. 2018).

While in Riess et al. (2016), the SN systematics are treated as variants in the analysis and are not combined in the same way as analyses of the latest high-z SN Ia samples (Betoule et al. 2014; Scolnic et al. 2018), Dahwan et al. 2020 adopt the formalism used for measuring dark energy properties (Brout et al. 2019b) from high-z samples and extend it to the other rungs of the cosmic distance ladder, so that covariance between the calibrator and Hubble flow SNe distances can be captured for a comprehensive list of systematics and accounted for in the H_0 inference

Dahwan et al. 2020 (shown on the right side of Figure 1) find that the assumption on the dark energy model does not significantly change the local distance ladder value of H_0, with a maximum difference between the inferred value for different models of 0.47 km/s/Mpc , i.e. a 0.6% shift in H_0, significantly smaller than the observed tension. Dahwan et al. 2020 also find that additional freedom in the dark energy models does not increase the error in the inferred value of H_0. They do find however, that including systematics covariance between the calibrators, low redshift SNe, and high redshift SNe can induce small shifts in the inferred value for H_0 and that improved systematics treatment of the SN Ia calibrators contributes 0.8% to the total uncertainty on H_0.

These findings were also backed up by the work of Benevento, Hu, Raveri 2020 (shown in left side of Figure 1), who test late time transitions in scalar field models that exhibit a sharp dip or bump in the potential within a fraction of an e-fold of the present, i.e. at redshifts between the calibrator set of SNe and the first Hubble flow SNe. They find that such potentials, including the model proposed by Mortonson, Hu, Huterer 2009, are not viable solutions to the resolution of the H_0 controversy.

3 Systematic Uncertainties

The benefit of the distance ladder approach that SH0ES takes is that potential systematic uncertainties will cancel out due to the calibration based approach. That is, if a systematic is present in more than one rung of the ladder, systematics that are demographic independent or redshift independent will nullify. The search for single rung systematics and demographic differences are at the heart of any theorized explanations for the tension.

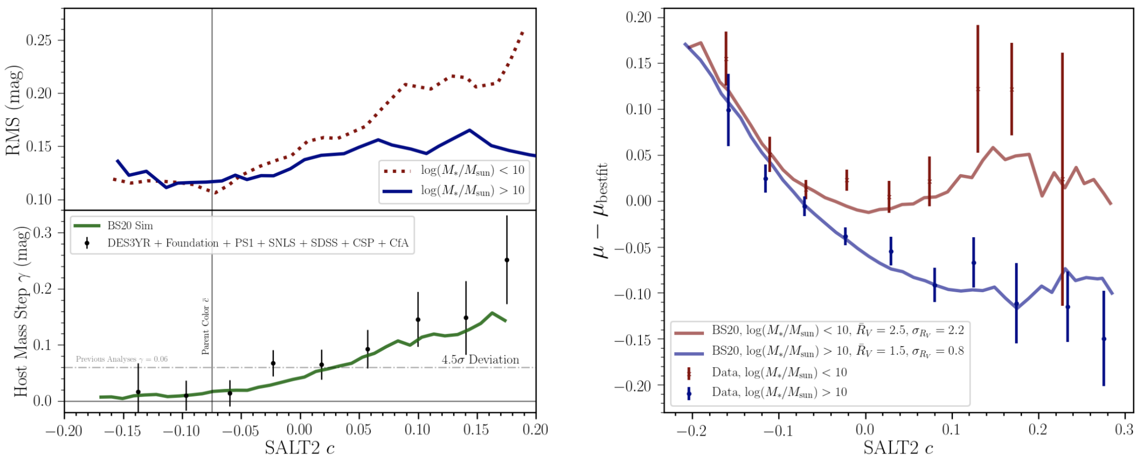

Figure 2: **Left**: (Upper) Hubble Diagram scatter binned by SALT2 observed color and compared for SNe in host galaxies with low and high mass. (Lower) Recovered values of the host stellar mass step (γ) for SNe Ia in high ($\log(M_*/M_{\rm sun}) > 10$) versus low ($\log(M_*/M_{\rm sun}) < 10$) mass hosts, binned by SALT2 observed color. Predictions from the BS20 Mass-split model is shown in green. Significance of the deviation from a constant γ of 0.06 is shown (4.5σ). b) Binned Hubble Diagram residuals versus color split on host-mass. Biases are shown for the observed data (points) and predicted using the scatter models (solid lines). The difference between the red and blue points has typically been found by marginalizing over color and finding a single step γ. The BS20 model parameters for the rolling surveys are given in the legend.

Because the absolute distance calibration only takes place in the first rung of the distance ladder, it does not retain the benefit of systematic uncertainty "cancellation". For this reason, the SH0ES measurement utilizes five independently determined, geometric distance estimators to calibrate the luminosity of Cepheids in Type Ia supernova (SN Ia) host galaxies. Independent estimates of H0 from the local, Cepheid distance ladder find no obvious source of systematic error accounting for this discrepancy (Cardona et al. 2017; Wu and Huterer 2017; Feeney et al. 2018; Follin and Knox 2017; Zhang et al. 2017; Dhawan et al. 2018).

One such systematic that could potentially plague the SNIa in the second and third rungs of the distance ladder is due to host galaxy SN Ia luminosity correlations. Global and local properties of SN Ia host galaxies such as stellar mass, star formation rate (SFR), stellar population age, and metallicity have all been shown to correlate with the distance modulus residuals after standardization (Hicken et al. 2009a; Sullivan et al. 2010; Lampeitl et al. 2010; Childress et al. 2013; Rose et al. 2019). This correlation is often parameterized as a step function in host-galaxy stellar mass and is now commonplace in SN Ia cosmology analyses despite the lack of understanding of its physical underpinning or convincing evidence for exactly which host-galaxy property is most influential on SN Ia luminosity (e.g. Jones et al. 2018a; Scolnic et al. 2020). To explain this correlation, recent studies have suggested a potential relation between the luminosity of the SN and the progenitor, which can be related to the age of the galaxy, or the local environment of the galaxy (Childress et al. 2013; Rigault et al. 2013;

Roman et al. 2018).

However, a new dust based explanation for this effect has been shown viable by Brout & Scolnic (BS20). BS20 introduce a physical model of color where intrinsic SN Ia colors with a relatively weak correlation with luminosity are combined with extrinsic dust-like colors ($E(B-V)$) with a wide range of extinction parameter values (R_V). This model captures the observed trends of Hubble residual scatter and indicates that the dominant component of SN Ia intrinsic scatter is from variation in R_V . They also find that the recovered $E(B-V)$ and R_V distributions differ based on global host-galaxy stellar mass and this explains the observed correlation γ between mass and Hubble residuals seen in past analyses as well as an observed 4.5σ dependence of γ on SN Ia color. This finding removes any need to prescribe different intrinsic luminosities to different progenitor systems.

As the H_0 measurement has different systematic sensitivity than w due to the comparison of SNe in calibrator galaxies versus Hubble flow galaxies, BS20 recommend these two samples to have similar demographics of blue and red SNe.

4 Conclusions

Several studies in the literature have found the local value of H_0 to be robust to different sources of systematic uncertainty, e.g. the statistical inference model, sample variance, Cepheid systematics and using near infrared data for SNe Ia. In addition, we have now witnessed multiple combinations of independent probes arrive at a similar conclusions for both the early and late time estimates of H_0. No longer is a single probe needed to drive the observed tension in H_0. For this reason, ever increased efforts to understand systematic uncertainties are necessary. In addition, because cosmological model independent parameterizations with additional degrees of freedom fit to the SH0ES SN Ia data result in fit parameters that are in agreement with ΛCDM, more and more precise measurements of cosmological distances will be required in order to begin the process of selecting growing field of possible explanations for the observed tension.

Acknowledgements

Thank you very much to the EDSU organizing committee for inviting me to give the overview lecture on this lively subject. Support for this work was provided by NASA through the NASA Hubble Fellowship grant HST-HF2-51430.001 awarded by the Space Telescope Science Institute, which is operated by Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS5-26555.