Hubble Constant at the Late Universe

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Abstract

The tension between measurements of the Hubble constant from different cosmological probes has been much debated in recent years. If it is not resolved by measurement errors, then it necessitates new physics beyond the standard flat ΛCDM model. In order to assess the significance of the tension, having independent probes of the Hubble constant is crucial. In this presentation, I describe various late-Universe probes for measuring the Hubble constant: the cosmic distance ladder, megamasers, standard sirens and strong lensing. Focussing on strongly lensed quasars and supernovae, I show that they have the potential to deliver a 1% measurement of the Hubble constant in the upcoming years.

1 Introduction

In the past decade, the so-called flat Λ cold dark matter (ΛCDM) cosmological model consisting of dark energy (with density characterised by the cosmological constant Λ) and CDM in a spatially flat Universe has emerged as the standard cosmological model. This model has provided excellent fits to various cosmological observations, especially the temperature anisotropies in the cosmic microwave background (CMB).

Despite the successes of the ΛCDM model, there is currently an intriguing tension in the measurements of the Hubble constant (H_0) from independent probes. In particular, the measurement from observations of the CMB by [1] under the flat ΛCDM model is more than 4σ lower than the local measurement from the Cepheid distance ladder by the "Supernovae, H_0, for the Equation of State of Dark Energy" (SH0ES) programme [2] . This tension, if not explained by yet unaccounted-for measurement uncertainties, has great implications for cosmology, requiring new physics beyond the standard flat ΛCDM model. By using a separate distance calibrator, the tip of the red giants (instead of Cepheids), [3] measured H_0 that is in between the values from [1] and [2] through the Carnegie-Chicago Hubble Program (CCHP) [4]. There is ongoing debate about the method, e.g. [5, 6], and the results from CCHP and SH0ES are not fully independent due to calibrating sources/data that are common among the two distance ladders. This highlights the value of having independent probes for the Hubble constant. In the following sections, we provide an overview of the various late-Universe probes of the Hubble constant.

2 Distance Ladder

The distance ladder has a long history in providing measurements of H_0. In fact, the *Hubble Space Telescope* (*HST*) Key Project was based on this method and yielded a measurement of H_0 with 10% uncertainty [7], resolving the multi-decade "factor-of-two" controversy in H_0.

By measuring distances (d) to objects in the Hubble flow (with negligible peculiar velocities) and their recessional velocities (v) via redshifts, H_0 can be inferred through the Hubble-Lemaître law $v = H_0 d$. However, direct distance measurements to such faraway objects are difficult to acquire. Thus, a practical way is to measure absolute distances to nearby objects (through e.g. parallax), and then use methods to measure relative distances (such as supernovae) to further away objects. This builds a "ladder" to obtain distances to faraway object in the Hubble flow.

In the SH0ES programme, [2] used Milky Way parallax, detached eclipsing binaries (DEB) in the Large Magellanic Cloud [8] and the maser galaxy NGC4258 to calibrate the Cepheid distance scale, that are in turn calibrating the supernova distance scale. Using all three anchors (parallax, DEB and NGC4258), [2] measured $H_0 = 74.03 \pm 1.42\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

In the CCHP, [3] calibrated the supernova distance scale using the tip of the red giant branch instead of Cepheids, and measured $H_0 = 69.8 \pm 0.8(\pm 1.1\%\ \mathrm{stat}) \pm 1.7(\pm 2.4\%\ \mathrm{sys})\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. This measurement is in between the discrepant Planck and SH0ES results, and is within 2σ of either one.

3 Megamasers

Water masers in orbit around supermassive black holes (SMBH) at centers of galaxies provide a geometric approach for measuring H_0. One could measure the velocity v_r of the masers in orbit around the SMBH (through observations of the Doppler shifts in the maser lines), and their angular positions θ_r from the central SMBH. In addition, observations of the change in velocities of the "systemic masers" (which are the masers located in front of the SMBH for nearly edge-on maser disks), the acceleration a_r could be measured. This provides a determination of the physical size of the disk r, since $a_\mathrm{r} = v_\mathrm{r}^2/r$. This physical size could then be compared to the angular size, to derive the angular diameter distance to the maser: $D = r/\theta_\mathrm{r} = v_\mathrm{r}^2/(a_\mathrm{r}\theta_\mathrm{r})$. For disks that are not viewed edge-on, there is an additional $\sin i$ factor in the numerator. Through the distance-redshift relation, the angular diameter distance then provides a measurement of H_0.

The Megamaser Cosmology Project (MCP) [9, 10] aims to determine H_0 precisely via measurements of geometric distances to galaxies in the Hubble flow. The Hubble constant based on the analysis of six megamaser galaxies in the MCP is $H_0 = 73.9 \pm 3.0\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ [11], assuming a fixed uncertainty for the velocities of 250 $\mathrm{km\,s^{-1}}$ due to peculiar motions. Peculiar motions of galaxies are currently the dominant source of uncertainty in deriving H_0 from the megamasers. Nonetheless, different peculiar velocity corrections performed by [11] do not change H_0 by more than 1σ.

4 Standard Sirens

GW170817 is the first gravitational wave (GW) source detected with electromagnetic (EM) counterpart [12], providing the first opportunity to measure H_0 through the "standard sirens" approach proposed by [13]. The gravitational wave of GW170817 originates from the merger of a binary neutron-star system. Through observations of the gravitational wave signal with the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) [14] and Virgo [15] detectors, the luminosity distance to the binary system is determined. From the EM observations, the galaxy that hosted the binary system is identified as NGC 4993. Optical observations of NGC4993 subsequently allow the determination of the recessional velocity (incorporating peculiar motion of the galaxy). By combining the luminosity distance from the GW and the recessional velocity from the EM counterpart and using the Hubble-Lemaître law, [16] made the first measurement of $H_0 = 70^{+12}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ from this standard siren.

While the measurement is statistically consistent with both the SH0ES and Planck results given its uncertainties, this very first measurement has started the era of standard sirens. The current uncertainties in GW170817 are dominated by the unknown inclination of the binary orbit of the neutron stars, since the inclination is highly degenerate with H_0. Additional gravitational wave detectors in the future would be able to constrain better the inclination. Furthermore, more sirens are expected from future observations of GW sources, providing a completely independent route of measuring H_0.

5 Strongly Lensed Quasars and Supernovae

Strong gravitational lensing occurs when there is a chance alignment of a massive object along the line of sight to a background source. The foreground massive object acts like a lens, and deflects the light rays from the background source such that multiple images of the background source appear around the foreground lens galaxy. When the source is one that varies in its luminosity, such as an activie galactic nucleus or supernova, the variability of the source manifests in each of the multiple images but delayed in time due to the different light paths. [17] proposed to use such time delays to measure H_0. This requires (1) measurements of the time delays by monitoring the lens systems over time, (2) model of the lens mass distribution, and (3) characterisation of mass distributions along the line of sight to the background source.

The H0LiCOW collaboration [18] obtained exquisite imaging and spectroscopic observations of lensed quasars with time delays from the COSMOGRAIL collaboration [19, 20] and radio monitoring [21, 22]. Through the blind analyses of 6 strongly lensed quasars[1] from the H0LiCOW and SHARP collaborations [23, 24, 25, 26, 27, 28, 29], [30] measured $H_0 = 73.3^{+1.7}_{-1.8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The newly formed TDCOSMO collaboration has performed a detailed investigations of systematic uncertainties of 7 lensed quasars [31], including a seventh lens system analysed by the STRIDES collaboration [32] in addition to the 6 H0LiCOW lenses. In contrast to [33], [31] finds no evidence of bias or errors larger than the current statistical uncertainties reported by H0LiCOW/SHARP/STRIDES.

In addition to lensed quasars, the first lensed supernovae (envisioned by [17]) are being discovered in recent years [34, 35]. Given the exciting prospects of discovering more lensed supernovae, [36] have launched the HOLISMOKES programme to study cosmology and stellar physics with lensed supernovae. With the hundreds of new lens systems expected from current and future surveys, a 1% measurement of H_0 from lensing time delays will be achievable [37, 38].

6 Conclusions

The current tension in the H_0 measurements from Planck and the SH0ES collaborations poses an exciting opportunity for potential discovery of new physics beyond the standard cosmological model. In order to verify that the tension is not due to measurement errors, it is crucial to have multiple independent probes. In this presentation, I have outlined four late-Universe methods that are promising to yield independent measurements of H_0 with uncertainties reaching 1% to address the H_0 tension in the coming years.

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[1]The analysis of the first lens system was not blind, but subsequent analyses of the other lenses were blind.

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